AN ABSTRACT OF THE PAPER OF

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Title: The Choice of the Optimal Sawtimber Harvesting System. (A theoretical approach based on mathematical programming.)

An extension of the sensitivity analysis of linear programming, called parametric programming is used in determining optimal sawtimber logging system mix. The five logging systems under study are manual log-length system, log-length processor and harvester systems, manual tree-length system and tree-length harvester system. In conditions where it is not exactly known how much the monetary value of the final saw wood varies as a function of the logging system used, the parametric programming approach gives the ranges for those values.

If the market value of the saw wood is the same no matter what logging system is used, it is economical to use tree-length harvesting systems under the assumptions of the study. However, if the difference in value is more than

3.90 $/m^3 (*14.85 Fmk/m^3) in favor of log-length systems, the tree-length systems are completely replaced by log-length systems in the conditions of Southern Finland. These results cannot be generalized, however, since each sawmill must be regarded as a special case. The approach developed for this study can be used to solve the problem in each particular case.

*1 U.S. dollar = 3.8 Fmk

The Choice of the Optimal Sawtimber Harvesting System

(A theoretical approach based on mathematical programming)

by

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INTRODUCTION

Problem Description

Sawtimber harvesting in Finland has traditionally been based on log-length methods. In these methods, sawtimber trunks are felled, delimbed and bucked by cutters. The length of the logs has usually been determined in accordance with the properties of the particular stems and the prevailing cutting rules of the company. Although the mechanization has changed the logging methods considerably, the basic procedure in the mechanized logging system has remained the same; the machine operator evaluates the stem and cuts it into the log-lengths according to the company's cutting rules. Logs are then hauled to the roadside by forwarders equipped with a grapple loader. Long distance transportation is usually by trailer trucks.

The cutting procedure described above has resulted in quite an excessive loss in the value of the stems due to the nonoptimal cuts into logs.

New developments in the measurement techniques of the logs and stems at the sawmill and fast real time automatic data processing with process computers have given rise to the possibility of maximizing the value of the lumber which can be gotten from a single log or stem. The latter, of course, include the optimal cut of the stem into the logs. The measurement of the stem and cutting it into the logs could also be done in a central yard from which the optimally cut logs are then sent to the sawmill.

It is estimated that if the stems can be cut optimally into the logs, the sawmill can get more output from the logs. The value of this "extra" lumber is estimated to be between 10-15 percent more than the value of the logs which are measured and cut in the woods in a non-optimal way.

Developments described above raise the question whether complete trees or tree-lengths could be brought to the sawmill or some centralized yard to be measured and cut in the optimal way and thus take advantage of the "extra" value of the lumber. The implication of this procedure would be a better utilization of the raw material.

The use of this kind of measurement and optimization technique means, however, that the preceding logging-transportation system must be adjusted to fit into the tree-length logging system. It also calls for an analysis in which kinds of conditions the tree-length logging systems are applicable and economically feasible. In the long run this may mean also that totally new machine concepts must be developed for sawtimber harvesting.

The Objectives and the Scope of the Study

The objective of this study are to:

1. Create a theoretical linear optimization model which describes the sawtimber harvesting conditions and systems in Finland.
2. Gather the best available data from the literature and other sources to be used as parameter values in the model.
3. Use the model created to choose the best possible sawtimber logging system for various conditions and thus give analytical tools for decision-making.
4. Use a crude parametric programming-type approach to study the sensitivity of the solution given by the model to the changes in the values of the parameters of the model.

The model will be limited in scope to the most relevant conditions in sawtimber logging. This means that there will be only three tree-size classes (0.225, 0.325 and 0.550 m^3/stem) and three long-distance transportation classes (0-35 km, 36-65 km and 66-120 km). Other long-distance transportation means than truck transportation will not be considered. The transportation distances are also limited to the distances less than 120 km. Two sizes of sawmills, purchasing 100,000 and 500,000 m^3 raw material annually, will be considered. Central yard processing is left outside of these considerations. Also, the hauling distance of the residual chips from the sawmill is supposed to be at most 50 km. The number of logging-transportation systems under study is restricted to five, out of which three are log-length systems and two tree-length systems.

Infrastructure and wood purchasing organizations are supposed to remain the same for both types of systems. This implies that road construction, administrations, etc. costs are the same and can thus be omitted in making comparisons and choices.

The study will continue later in Finland where new data will be collected on the factors affecting the tree-length logging. That data will be used in the model and then new runs will be done with the model to determine the optimal sawtimber logging system choice.

The potential users of the model are the sawmills and wood procurement organizations which can apply it in their conditions and use the results to help decision-making. Other researchers can use the approach developed to attack similar problems.

The approach to be taken is first to develop the theoretical background for the modeling and then apply it to the problem at hand and finally present some results of the experimental runs and critique of the model.

LITERATURE REVIEW

The possible use of tree-length systems in sawtimber harvesting in Finland is discussed by Salminen (1979). He set forth advantages of the tree-length systems over the log-length systems and also discussed the disadvantages. The advantages he sets forth are as follows: the utilization of the raw material is better, the optimal cut into the logs can be employed, special deliveries become possible, the logging machines become simpler and cheaper and finally the need for the work force in the woods decreases.

As disadvantages, Salminen sees quite high investment costs in the tree-length handling facilities at the sawmill or central yard. The technology used elsewhere is not adaptable as such into the Finnish conditions and must also be developed further to meet the modern requirements. The other disadvantages would be that there were two harvesting systems which operate on different principles in use of the same time; one for the sawtimber and the other for the pulpwood. This would increase machine costs and thus harvesting cost. Also the additional handling of the pulpwood from the tops of the tree-lengths would cause extra costs. Salminen doesn't give any direct cost figures on how much more or less the tree-length system could cost to be economically feasible or allowable when compared to the log-length system. As a conclusion, he affirms that "tree-length method cannot be regarded in Finnish conditions as a general solution. Its application is feasible directly at small sawmills or, by way of partial solution, also at large sawmills if it proves possible to solve profitably the buyers' special dimension and quick delivery requirements."

Forskningstiftelsen Skogsarbeten (Larsson, M and Nilsson, G., 1977) in Sweden, conducted a large study in 1976-1977 in which mechanized log-length system was compared to the tree-length system. In this study, the cut of the stems into the logs was done at the roadside in one alternative and a terminal after truck transportation in the other. There were several terminal size and location options under consideration. The comparison was done in monetary terms so that direct cost figures for each alternative are available. When referring to those numbers, they have changed proportionately to get rid of the bias brought by the different value of currencies in respective countries. The study showed that the log-length system was most profitable. The total logging-transportation costs were 10 percent more for at-roadside-cut-alternative and 25 to 45 percent more for the other alternatives. Logging costs were 15 percent less in tree-length systems but long distance transportation costs were 23 percent more. The terminal cost must be added to the latter alternatives and their share was 38 percent, 26 percent and 22 percent, respectively, according to the alternative. The increase of the long distance transportation cost is due to smaller loads which was caused by the loading technique used. If the same load size can be reached in both principal systems, the long distance transportation costs will be about the same. According to a more recent cost calculation tree-length logging and transportation would be three to ten percent cheaper than log-length transportation. The over-all conclusions drawn by the Swedes was that the extra value of the stems harvested by using tree-length methods should be 1.3 to 6.5 percent more for these systems to be economically justifiable.

The above study can be criticized in that it only considers one transportation distance (60 km) and also the variation of stand types it handles is small. It doesn't assign the optimal logging system to each condition but assumes systems to be used quite inflexibly in various conditions

In another Swedish study reported by Granqvist (1977) the tree-length logging transportation system was compared to processor logging and shortwood harvester logging. In both systems the transportation of logs was carried out by means of trucks. According to Granqvist the tree-length logging and transportation itself was more expensive than those log-length systems under study. On the other hand, tree-length logging gave more revenues from the logs in the form of less damages to the logs. The overall conclusion was that under the circumstances of the study, the tree-length logging system was an attractive alternative.

Tree-length skidding was studied in Canada by McMoreland (1977) in conjunction with the evaluation of the Volvo Clam-Bunk skidder. The author gives production and cost figures for this machine under conditions of interior British Columbia.

Tree-length skidding was also studied by Thesslund (1978) in accordance with the Lokomo 961T tree-length harvester. The results of this study show that tree-length logging would be about 5 mk/m^3 cheaper than log-length logging conducted by a processor-based system. This study was conducted in Finland.

In summary, the subject of tree-length and whole tree logging and transportation has been quite widely studied in the world during recent years.

These results are not directly applicable into the conditions prevailing in Finland due to different infrastructure.

Linear programming has been used earlier in minimizing wood procurement cost for integrated forest products firm by Tilghman (1967). Transportation -LP was used by Peltonen (1978) to minimize transportation cost of timber. Simulation has been used by Simpson (1970) in considering alternative wood procurement policies.

Parametric programming in this form as it is used here has not been used so far in finding out optimal logging transportation system mix.

All the investigations found in the literature dealing with the comparison of the tree-length and log-length systems have so far been such that differences in costs and other factors have been determined under certain circumstances and assumptions and then, based on those figures, the conclusions have been drawn about the feasibility of the respective systems. Even though the studies have been quite extensive and integrated, the approach which could take into account the different circumstancies and would, as a whole, assign the optimal logging system into each condition have been lacking. The study at hand will make an attempt in that direction by introducing a quantitative approach applicable in the problems described above.

MODEL FORMULATION

Theoretical Considerations

Linear Programming.

Linear programming is a mathematical tool of assigning scarce resources to the activities in such a way that some objective is optimized and the other defined conditions are still satisfied. A linear programming problem may be presented conveniently in matrix forms as follows (standard form):

$$\text{Max } Z = C^T x \tag{1}$$

such that $Ax = b$

$x \geq 0$

where C^T is a row vector of profit or cost coefficients, x is a column vector of variables, A is a coefficient matrix and finally b is the requirement column vector for the constraints of the problem. The values of x are supposed to be non-negative. The x vector in this form includes so called slack variables which are used to help solve the problem.

Solving the above linear program produces the following solution (Zionts, 1974, p. 50-57), again in the matrix terms

$$X_B^* = B^{-1}b; \quad Z^* = C_B^T B^{-1} b \tag{2}$$

where X_B^* is the column vector of the values of the variables (activities) in the optimal basic feasible solution. B^{-1} is the inverse of the coefficients of the basic variables arranged in the proper sequence, b is the same as earlier. C_B^T is the coefficient row vector of the basic variables in the original objective function and Z^* is the optimal value (maximum or minimum) of the objective function. The simplex algorithm, which will not be explained here, produces the optimal basic feasible solution to any linear programming problem, if such a solution exists.

Sensitivity Analysis

After having solved the linear programming problem described above, the task of solving the real-life problem which is modeled by using that particular linear program is usually half done. This is because the linear programs suppose deterministic values of the parameters (that is coefficients) in the model. That is not the case in most situations for there is always some inaccuracy involved. There can be three types of inaccuracies in the parameters of the model, namely; variations in the coefficients of the objective function (C^T-vector), variation in the values of the requirement vector entries (b-vector) and finally variations in the technical coefficients of the model (A-matrix). Sensitivity analysis, sometimes called postoptimality analysis, is a set of calculation procedures to take care of the situation.

In simple sensitivity analysis, it is supposed that the study of the values of the parameters is done one at a time, keeping all other constant. This sensitivity analysis gives an answer to the question how much variation is allowed in the value of a single parameter and the solution still being optimal.

The changes allowed in coefficients of the objective function can be presented as follows: (Simmons, 1972, p. 222)

$$\text{Max } Z = (C + \Theta^{(1)} S)^T X \qquad (3)$$

where $\Theta^{(1)}$ is a non-negative scalar parameter determining the values for which X_B is still optimal, S is a n-component vector for the variables under consideration. Where only one coefficient of vector C is considered, the S is a unit vector associated with the variable under consideration. After solving for $\Theta^{(1)}$ (Simmons, 1972, p. 220-230), one gets

$$\Theta^{(1)} \leq \frac{-(Z_j - C_j)}{S_B^T Y_j - S_j} \qquad (4)$$

where $(Z_j - C_j)$ = cost change for the j^{th} variable.

The formula means that X_B is optimal as long as $\Theta^{(1)}$ is small enough for the inequality to be valid.

To study the sensitivity of right hand side vectors, the following changes must be done. Let $b = b + \Theta e_j$, then solution is optimal as long as

$$B^{-1}(b + \Theta e_j) \geqq 0 \tag{5}$$

or

$$B^{-1}b + \Theta B^{-1}e_j \geq 0$$

Let $B^{-1}e_j = U_j$ be a column of updated inverse, then it follows (Simmons, p. 230) that current solution is optimal as long as

$$\Theta = \min_j \left(\frac{-X_{B_i}}{U_j}, U_j < 0\right) \tag{6}$$

By utilizing the above calculations, one can compute the ranges for the optimal solution.

Parametric programming

Because in this study, the focus is primarily on the changes of the values in the coefficients of the objective function and their effect on the optimal basic feasible solution, only the parametric programming for those coefficients will be presented. The problem is to find the consecutive values of $\Theta^{(k)}$ at which the optimal basic feasible solution changes. These are called critical values and are usually measured from zero datum. To initiate the procedure from the optimal tableau, $\Theta^{(k)} = 0$, let $\Theta^{(x)} = \alpha$ and $\Theta^{(k)} = \beta$, α and β being two consecutive critical values, $(\alpha \leq \beta)$.

Optimal basic solution is known and given by ${}^{\alpha}X_B$. The range ${}^{\beta}X_B$ being optimal was given by the formula (4) on page 12.

The next critical value is determined as follows, (Taha, 1971, pp. 286-300)

$$\beta = \alpha + \min_j \left\{ \frac{-({}^{\alpha}z_j - {}^{\alpha}c_j)}{(S_B{}^{\alpha}B^{-1}b_j - S_j)} \;\middle|\; S_B{}^{\alpha}B^{-1}b_j - S_j < 0 \right\} \quad (7)$$

When $\Theta^{(k)} > \beta$, ${}^{\alpha}X_B$ ceases to be optimal solution. At $\Theta^{(k)} = \beta$, there is an alternate optimal solution. The procedure is repeated to get the range for the basis, ${}^{\beta}X_B$ and also the next critical value. This is repeated for the consecutive critical values so long that $\Theta^{(k)}$ reaches the last value after which it can be increased to infinity without changing the basis of the then valid optimal solution.

Because there was not a computer code available on the campus, which would have allowed the calculation of the consecutive critical values directly, the following rough approach was used instead. The coefficients are decreased or increased by a certain fixed amount and the sensitivity runs for those new coefficients will give the range for that particular solution being optimal.

The following example gives an idea how the approach was used.

In the beginning, the monetary value of the saw wood for all the coefficients in the objective function was assumed to be the same. (Calculation procedure for the actual coefficients is presented in Model Formulation section.)

The optimal system mix and the ranges for objective function coefficients were obtained during the course of optimization.

In the next phase, the coefficients for tree-length systems were decreased (later on, also increased) by 5 mk (parameter - Θ decreases) and the calculation procedure was repeated.

Results were compared to find out whether the optimal system mix had changed. In case of change, the ranges for both runs were compared to find out the accurate amount by which the coefficients had to be changed to make the logging system mix change.

If there was no change, an additional 5 mk was decreased and the procedure above was repeated.

The values of the coefficients were decreased (or increased) by 5 mk as many times as was needed to pick the tree-length systems out of the optimal solution (or there was no change after several consecutive runs).

The other reason for this procedure is that the value of the several coefficients within a harvesting system will change simultaneously when the value of the timber changes. The available LP-computer code didn't allow the calculation of the effect of those changes either, so the rough approach was justified.

Still another reason for qualification is that in this case there are only two types of systems under study although there are several of each type. The rough approach is supposed to give results which are accurate enough for the comparison purposes.

Application of the Theory to the Problem

General

The harvesting-transportation system choice problem can be formulated as a linear programming problem. In this particular case the problem is to choose the system or combination of systems which will give the largest revenue from the raw material harvested in the different conditions. The solution should also give the optimal volume to be harvested by using some particular method. Let the decision variables

$$X_{ijk} \text{ and } Y_{ijk}$$

represent the volume to be harvested. X_i refers to the log-length methods and Y_i to the tree-length methods, respectively. Subscript j denotes tree size class and subscript k gives transportation distances. As already mentioned there are three tree size classes and transportation distances under consideration.

j	Tree size, m^3	k	Distance, km
1	0.225	1	0–35 km (20 km)
2	0.325	2	36–65 km (50 km)
3	0.550	3	66–120 km (90 km)

As an example: X_{332} is Pika 75' harvester, operating on large trees (0.550 m^3) and within 36–65 km's distance.

The use of different harvesting systems is subject to various restrictions. Restrictions to be considered here are the following:

- Total volume to be harvested
- Availability of certain tree size
- Availability within certain transport distance
- Manpower
- Machine hours
- Investment money
- Quality of the tree-lengths and logs in form of
  - mechanical damages
  - blue-stain damages
  - damages caused by insects
- Decrease in value of the logs due to nonoptimal cut
- Landing space requirements.

To create a basis for the comparisons of the different harvesting systems, the following assumptions have been made.

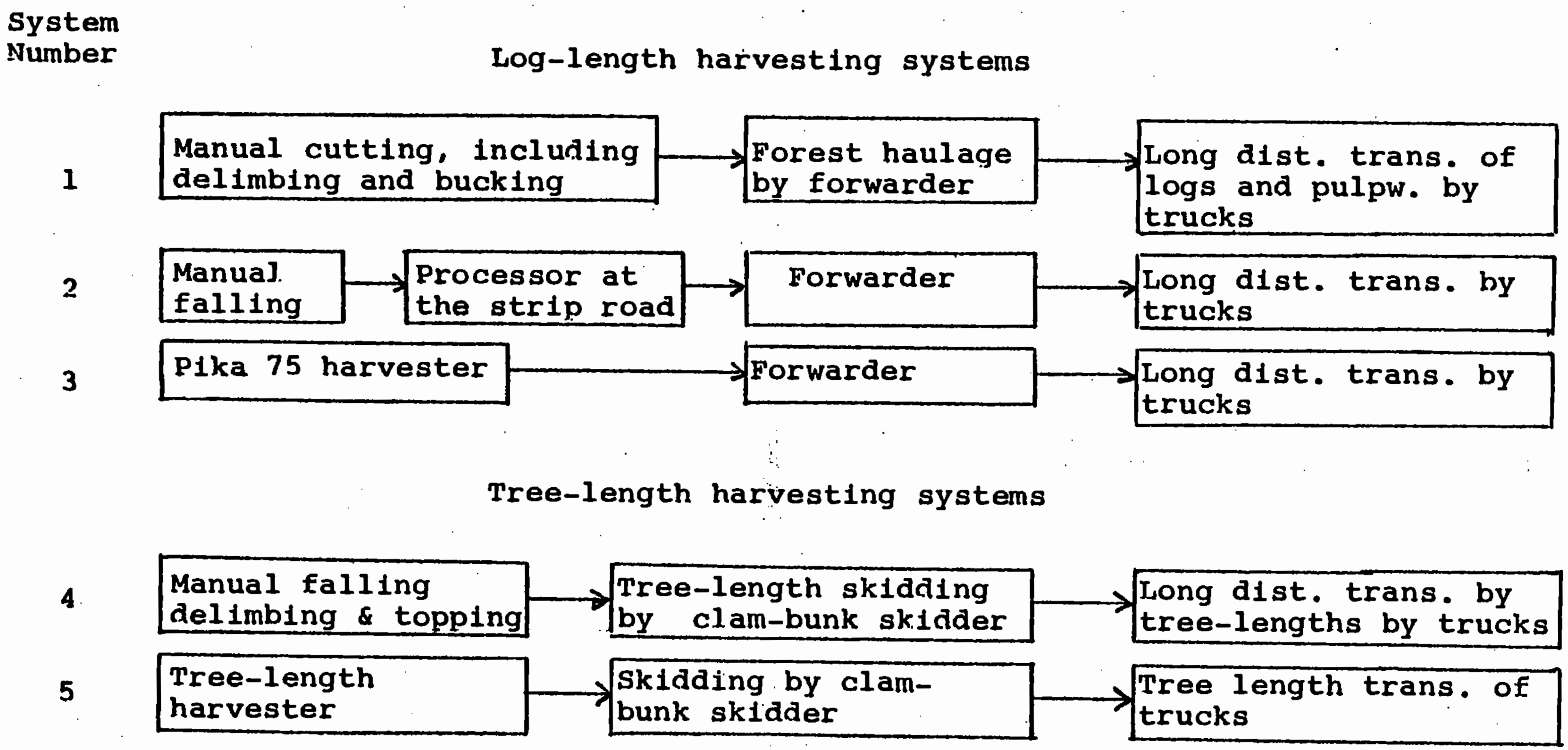
In basic form, it is supposed that the value of the timber gotten out of logs is the same no matter what logging-transportation system has been used. This is called 0-alternative in the following pages. To generate additional alternatives, the value of the timber logged by using tree-length methods has been decreased or increased in proportion to the value of the timber logged by log-length methods. These alternatives are called -30-,-20-,-10 alternatives or +5-, +10-, +20 alternatives and so on; the number indicating how much the value in marks has been decreased or increased from the 0-alternative.

Logging Systems Under Study

In this study, the logging transportation systems to be compared were chosen regarding their potential usefullness; each of the log-length systems under consideration has proven to be reliable but have not yet been employed to the full extent except the manual log-length system which is the main system in use today.

The manual tree-length system has proven to be good elsewhere and the mechanized tree-length system chosen is the only one for which there are reliable machines available. The schematic picture on the next page gives an idea of the systems under consideration.

Figure 1. Logging-Transportation Systems of the Study



Assumptions for the Hypothetical Experiment Lay-out

The use of the tree-length systems in Finland can never reach the hundred percent extent due to the large number of small woodlot owners and variety of forest management practices; as Salminen (1979) puts it, ". . . (tree-length harvesting) application is feasible chiefly at small sawmills, or by way of partial solution, also at large sawmills . . .". Because of that fact, two sawmill sizes, purchasing at most 100,000 m^3 and 500,000 m^3 of logs annually, will be considered. The first represents small sawmills and the other can be classified as large. Both sawmills are supposed to locate in Southern Finland, so the cost figures used in the following calculations are valid for that part of the country. For the purpose of simplicity, it is also assumed that all the activities (i.e., logging, forest haulage and long distance transportation) are carried out under summer conditions. The time span for any one logging-transportation operation is supposed to last at most two months. It is also a one period operation and no inventories are allowed during the progress of the logging-transportation. Calculations are conducted on a yearly bases.

As far as the volume to be procured is concerned, the following restrictions are valid for the small sawmill:

- no more than 20% is available in tree-size class 0.550 m^3

- no more than 50% is available in tree-size class 0.325 m^3,
- no more than 30% is available within 35 km's transport distance,
- no more than 40% is available within 65 km's transport distance.

Other restrictions are

- there are two forwarders, 1440 days/year, which must be employed,
- 9 cutters, @ 220 hrs/year, must be employed,
- no other restrictions in the basic form.

Assumptions for the large sawmill are

- there is raw material coming from each tree size class and transportation distance class as follows:

Distance km	tree size, m^3 0.225	0.325	0.550
	% of volume		
0- 35	> 2	> 6	> 3
36- 65	> 4	>12	> 6
66-120	> 4	>12	> 6

- no more than 30% in tree size class 0.550
- no more than 70% in tree size class 0.350
- no more than 20% nearer than 35 km
- no more than 60% nearer than 65 km

Other restrictions for the large sawmill

- 10 forwarders must be employed @ 1440 hrs/year

- 70 cutters must be employed (@ 220 days/year)
- no other restrictions

Objective Function

Out of each m^3 of sawed wood after having been processed at the sawmill and sold on the market, an average revenue of 560 mk occurs. (Yearbook of Forest Statistics, 1978) Every cubic meter of sawtimber requires 2.15 m^3 sawlogs. Hence, the revenue generated by evey cubic meter of sawlogs is approx. 260 mk.

From the sawmill's point of view, the pulpwood which is also produced when sawlogs are produced is a by-product. The value assigned to a cubic meter of pulpwood is in this case 80 mk, since the sawmill must sell it further and that is the current market value of pulpwood per cubic meter.

The coefficients for the objective function are given in the following tableau, assuming that there is a certain log-content in the tree-lengths of different size.

Table 1. Values of the Raw Material

Item	Log-length methods					
	0.225 m^3		0.325 m^3		0.550 m^3	
	%	mk/m^3	%	mk/m^3	%	mk/m^3
Logs	52	135	76	198	82	213
Pulpwood	48	39	24	19	18	15
Total	100	174	100	217	100	228
	Tree-length methods					
Logs	57	148	82	213	86	224
Pulpwood	43	35	18	15	14	11
Total	100	185	100	228	100	235

The log content when utilizing tree-length methods is assumed to be slightly higher than that of log-length methods.

To get the real net revenues, one must subtract from the objective function the cost of the logging and transportation of the raw material and the value of damages caused in logging. The objective function along with the restrictions for the 0-alternative for the small sawmill is presented in Appendix 1.

Basic data for the Technical Coefficients

Value of the Damages in Logging

The monetary values of the mechanical damages, blue stain and insect damages per cubic meter logged is presented in the following table. Calculations are based on percentages given by Makela and Pennanen (1980).

These values are used as technical coefficients to calculate their effect to the objective function as will be explained in "Requirement Vectors."

The value of the raw material has decreased in log-length methods due to nonoptimal cut of the stems into the logs. Estimates which are used here are given by Eskelinen and Pennanen (1979).

Monetary losses used are given in the following chart.

	System		
	Manual log-length	Processor system	Pika harvester system
Monetary loss mk/m^3	2.61	3.96	4.22

Table. The Values of Mechanical, Blue Stain and Insect damages, mk/m^3, Sawlogs. (After Eskelinen and Pennenen 1979)

System	Decrease in value %	Tree size, m^3 0.225	0.325	0.550
	Mechanical Damages			
		Decrease, mk/m^3		
(1) Manual log-length system	0.3	0.41	0.59	0.64
(2) Mechanized Processor system	1.6	2.16	3.16	3.41
(3) Pika 75 harvester system	0.1	0.14	0.20	0.21
(4) Manual tree-length system	0.1	0.15	0.21	0.22
(5) Tree-length harvester	0.7	1.04	1.49	1.57
	Blue Stain Damages			
(1) Manual log-length system	1.3	1.76	2.57	2.77
(2) Mechanized Processor system	0.7	0.95	1.38	1.49
(3) Pika 75 harvester system	0.7	0.95	1.38	1.49
(4) Manual tree-length system	1.3	1.93	2.77	2.91
(5) Tree-length harvester	0.1	0.15	0.21	0.22

Table 2. (continued)

System	Insect Damages			
	Decrease in value %	Tree size, m^3		
		0.225	0.325	0.550
		Decrease, mk/m^3		
(1) Manual log-length system	4.8	6.49	9.40	10.20
(2) Mechanized Processor system	3.7	5.00	7.31	7.89
(3) Pika 75 harvester system	2.7	3.65	5.34	5.76
(4) Manual tree-length system	4.8	7.11	10.20	10.70
(5) Tree-length harvester	3.6	5.34	7.68	8.05

Manhour Input and Labor Cost Data

Each system under consideration requires certain amounts of labor input in every phase of the logging, forest haulage and long distance transportation. The input required is different in different systems and depends on the productivity of that particular system. Productivities are based on Kahala's (1969) investigations and on the productivities used in the wage agreements for both logging and transportation. When calculating the actual cost, one must add the social security cost which is 46% at the present time in Finland.

Here is an example how the cost of the manual cutting of spruce is calculated in 0.325 tree size class. From the wage tables, one gets the unit cost of different workphases.

Work phase	Cost, mk/m^3
Directional falling	1.36
Delimbing, topping	9.85
Bucking	1.00
Bunching of pulpwood	2.83
Moving to another tree	.30
Terrain class correction	.87
Subtotal	16.21
Social security	+7.46
Total	23.67

Similar calculations give the cost for cutting pine and hardwoods, at the cost of 17.49 mk/m^3 and 15.55 mk/m^3 respectively. If the share of the spruce is 53%, that of pine 35% and that of hardwood 12%, the expected average cost for the stand is $23.67 * 0.53 + 17.49 * 0.35 + 15.55 * 0.12 =$ 20.53 mk/m^3. That is the unit cost used for the manual cutting in the 0.325 m^3/stem size stand. The production in that tree size class is 11.4 m^3/day so the manday input required is the inverse of that number, being 0.0877 mandays/m^3. To get rid of round-off errors in the computer, the latter figure was multiplied by 100.

Machine Input and Cost Data

Production figures used are based on the most recent studies on forwarder hauling logs and pulpwood by Kahala (1979), processors working on the strip road by Myllyniemi (1979), Pika 75 harvester working on the spruce stand by Makela (1979). Tree-length harvester production is based on the study done by Mikkonen-Peltonen-Silvennoinen (1979). Machine hour input required is, of course, the inverse of the production per hour in the adequate conditions.

Truck transportation productivities are calculated by using Myllyniemi's (1980) loading times and the following average roundtrip speeds of the trucks

Transport distance	Average roundtrip speed, km/h
20 km	55
50 km	65
90 km	75

The following machine utilizations and hourly costs are implicitly included in the calculations

	Utilization, %	Hourly cost, mk
- forwarder	80	125:-
- processor	67	225:-
- Pika 75 harvester	65	260:-
- clam bunk skidder	63	278:-
- tree length harvester	65	350:-
- trucks	95	-

Other data which was used in the calculations is presented in the table on the next page.

The production of the forwarder is 6% lower in pulpwood hauling which must be taken into account when calculating average production. The productivity of the forwarder when hauling logs and pulpwood after multipurpose machines is 10% and 8% higher, respectively.

The unit cost of production of the multipurpose machines and the forwarder are taken from the actual payment agreements and they represent real cost of logging with those machines in the conditions of the study.

Because there are not payment agreements available for the clam-bunk skidding the unit costs were evaluated by using the following formula (McMoreland, 1977)

$$\text{unit cost/PMH} = \left[\frac{I - R}{L}\left[1 + \frac{i(N+1)}{2}\right] + \frac{iRN}{L} + M + W\right]\frac{100}{U} + F$$

where I = Purchase price, 850,000 mk

R = Salvage value, 170,000 mk

L = Machine life in scheduled machine hours = 11,200

i = Interest and insurance factor = .1282 (interest 11.25%)

N = Depreciation period, 5 years

M = Maintenance cost/SMH = 27.00 mk

W = Operator cost/SMH = 37.38 mk

Table 3. Basic data used in the calculations. It is supposed that stand density is 500 stems/ha.

Machine type	Initial investment mk	Salvage value %	Depreciation time		Average annual production m^3	Man hour required per one machine hour	Volume/ha		
							120	170	
							Tree size m^3		
			hours	yrs			0.225	0.325	0.550
							Production m^3/hr		
Forwarder	750,000	30	6480	4.5	20,736	1.4	11.5	11.5	11.5
Processor	1,200,000	25	7500	5.0	40,725	1.7	21.0	27.5	42.0
Pika 75 Harvester	1,100,000	20	6875	5.0	18,500	1.7	9.7	13.5	20.3
Clam-Bunk Skidder	850,000	20	7050	5.0	25,400	1.4	15.0	17.4	23.9
Tree-length Harvester	1,500,000	20	11150	5.0	80,600	1.7	27.1	36.6	55.1
							20 km	50 km	90 km
Truck & trailer	450,000	22	9975	5.0	38,335	1.5	28.7	21.9	17.5

U = Machine utilization = 63%

F = fuel & lubricant cost/PMH = 24.00 mk

PMH = Productive machine hours

The formula gives 278 mk/PMH. The production in different tree size classes was 15.0, 17.4 and 23.9 m^3/PMH. Hence the unit cost of production are 18.50, 15.97 and 11.62 mk/m^3, tree size being 0.225, 0.325 and 0.550 m^3/stem, respectively.

There are not production numbers available for the transportation of tree-lengths on trucks for the conditions in Southern Findland. These numbers were evaluated by using the formula given by Granqvist (1977).

$$\text{round trip time} = \left[\frac{2*d_i}{v_i} + \frac{V*L_k}{60} + T\right] \frac{1}{U}$$

where
d_i = one way hauling distance, km
v_i = average speed, km/hr
V = Capacity of the truck = 50 m^3
L_k = Loading time, min/m^3
U = Utilization factor for the truck = 0.95
T = terminal time to unload

The loading times used were 1.63 min/m^3, 1.63 min/m^3 and 1.53 min/m^3 for the different tree sizes. Velocities were as earlier mentioned. Calculations gave the following round-trip times and production figures for the tree-length transportation, assuming 50 m^3 load size.

Table 4. Round trip times and production in tree-length hauling

Distance km	Tree size, m^3					
	0.225		0.325		0.550	
	HRS	m^3/hrs	HRS	m^3/hrs	HRS	m^3/hrs
20	2.87	17.4	2.87	17.4	2.78	18.0
50	3.77	13.3	3.77	13.3	3.68	13.6
90	4.73	10.6	4.73	10.6	4.64	10.8

Unit costs of hauling tree-lengths were supposed to be the same as hauling poles. Those costs were picked up from the payment tables of the transport agreement.

Capital Input Data

All the costs which occur in logging or transportation of timber are implicitly included in the payment tables. To get the capital input part of it, the calculations must be carried out separately. Neglecting the effect of compound interest, the calculations are trivial. The following formula gives the capital input requirement per cubic meter logged.

$$\text{Capital input} = \frac{I - R}{P_L}$$

where I = Purchase value of the machine

R = Residual or salvage value

P_L = Expected lifetime production

Applying the formula on the previous page, the capital input requirements for different systems in different conditions were calculated.

Requirement Vectors

The requirement vectors, except those for volume requirements, were formulated in the equality form. This was done by subtracting an additional variable from that constraint and giving it a proper name. Thus the simplex procedure worked as an "internal counter" in the alternatives having no direct restriction value assigned to that particular restriction.

Combining those additional variables it was also easy to formulate adequate restrictions for the particular alternative under consideration.

RESULTS OF THE EXPERIMENTAL RUNS

The Optimal Logging in 0-Alternative

Table 5. The Assignment of Logging Systems to the Conditions

Transport Distance	Stem size, m^3		
	0.225	0.325	0.550
20 km	--	Tree-length harvester system 30,000 m^3	--
50 km	Processor system 5,700 m^3	tree-length harvester system 20,000, m^3	tree-length harvester 14,3000, m^3
90 km	Manual log-length 17,9000 m^3 Processor system 6,4000 m^3	--	Pika-75 system 5,700, m^3

Table 5 shows that if the decision maker is not required to log in the conditions of the empty entries in the table, he should not do so.

The most profitable systems for small trees are processor systems and manual log-length systems. The reason there is that much manual-log length system in use is due to restriction that 9 cutters must be employed and it is cheapest to use them in the area of long transport distance and small tree size where the manual labor is cheapest when compared to the mechanized work.

Additional runs at this point showed that if all the restrictions were relaxed except volume requirement of 100,000 m^3, the most economical system to use would have been Pika 75 system on the large trees and short distances. When distance restriction was added, Pika-system was still most economical, now on all the transport distances.

When the rest of five restrictions for the 0-alternative were added, one got the results of table 5.

There was an alternate optima for this solution. One could have brought in the manual log-length system on small trees and medium distances at the same "price."

The opportunity cost at this point showed that next cheapest system to bring in would have been tree-length harvester system on large trees and short distances. The next one after that would have been manual tree-length system on medium size trees and 50 km's transport distance followed by Pika-system on large trees and medium distances. All of those had an opportunity cost less than 0.15 mk/m^3.

The print-out of results is presentd in appendix 2.

Effect of Changing Objective Function Coefficients

The behavior of the optimal solution when the coefficients for tree-length systems in the objective function are changed is presented in table 6.

Table 6. The change of optimal solution by alternative.

Alternative, mk/m^3 Change in Market value	20 km						50 km						90 km					
	0.225 m^3		0.325 m^3		0.550 m^3		0.225 m^3		0.325 m^3		0.550 m^3		0.225 m^3		0.325 m^3		0.550 m^3	
	Sys	%	Sys	%	Sys	%	Sys	%	Sys	%	Sys	%	Sys	%	Sys	%	Sys	%
-30.0			X_3	30.0			X_1 X_2	17.9 12.1	X_3	10.0					X_3	10.0	X_3	20.0
-20.0			X_3	30.0			X_1 X_2	17.9 12.1	X_3	10.0					X_3	10.0	X_3	20.0
-14.85			Y_2	30.0			X_1 X_2	17.9 12.1	Y_2	10.0					X_3	10.0	X_3	20.0
-12.00			Y_2	30.0			X_1 X_2	17.9 12.1	Y_2	20.0			X_1	10.0			X_3	20.0
-10.00			Y_2	30.0			X_2	5.7	Y_2	20.0	Y_2	14.3	X_1 X_2	17.9 6.4			X_3	5.7
-5.00			Y_2	30.0			X_2	5.7	Y_2	20.0	Y_2	14.3	X_1 X_2	17.9 6.4			X_3	5.7
±0			Y_2	30.0			X_2	5.7	Y_2	20.0	Y_2	14.3	X_1 X_2	17.9 6.4			X_3	5.7
+5.00			Y_2	30.0			X_2	5.7	Y_2	20.0	Y_2	14.3	X_1 X_2	17.9 6.4			X_3	5.7
+10.00			Y_2	30.0			X_1	4.2	Y_2	20.0	Y_2	15.8	X_1	25.8			X_3	4.2
+30.00			Y_2	30.0			X_1	4.2	Y_2	20.0	Y_2	15.8	X_1	25.8			X_3	4.2

Systems: X_1 = Manual log-length system; X_2 = Processor system; X_3 = Pika 75 system; Y_1 = Manual tree length system; Y_2 = Tree length

When the proportional value of the raw material from the tree-length harvester system is lowered, the tree-length system in the optimal solution tends to be replaced by Pika system. The break-point or critical value (Θ) for all the tree-length systems being replaced is -14.85 mk/m^3. This means that if the value of the raw material for the sawmill harvested using tree-length systems decreases more than 14.85 mk/m^3 from the 0-alternative (raw material equally valuable) it would not be economically feasible to use tree-length systems under any conditions.

Similarly, when increasing the value of the raw material (parameter Θ increases) the optimal solution reaches the basis which seem not to change after +10 alternative. The actual break-point is somewhere between +5 mk/m^3 and +10 mk/m^3. The rough procedure used could not give the accurate point.

Table 7 and figures 2 and 3 give more information on the behavior of the optimal solution. The information is self-explanatory and need not be commented on in more detail.

The reason that all the other systems except tree-length harvester systems are not eliminated from the basis is due to other restrictions, mainly employment and forwarder hour requirements.

Two additional runs were done at this point to figure out the effects of strict invest money availability and higher employment requirement. Results are presented in tables 8 and 9.

Table 7. The values of the different parameters as a function of the alternative.

Item	Alternative, mk/m^3 change							
	-20.00	-14.85	-12.00	-10.00	±0	+5	+10	+30
Log content, %	70.0	72.4	73.0	73.6	73.6	73.6	73.6	73.6
Av. stem size, m^3	0.340	0.340	0.340	0.340	0.340	0.340	0.340	0.340
Av. transp. distance, km	53	53	53	53	53	53	53	53
Av. harvest, cost, mk/m^3	48.61	47.34	47.14	46.78	46.78	46.78	47.11	47.11
Av. damage cost, mk/m^3	11.36	10.68	10.51	10.24	10.24	10.24	10.12	10.12
The % share of								
- manual log-length system	17.9	17.9	17.9	17.9	17.9	17.9	30.0	30.0
- manual tree-length system	-	-	-	-	-	-	-	-
- mechanized log-length system	82.1	42.1	32.1	17.8	17.8	17.8	4.2	4.2
- tree-length harvester system	-	40.0	50.0	64.3	64.3	64.3	65.8	65.8

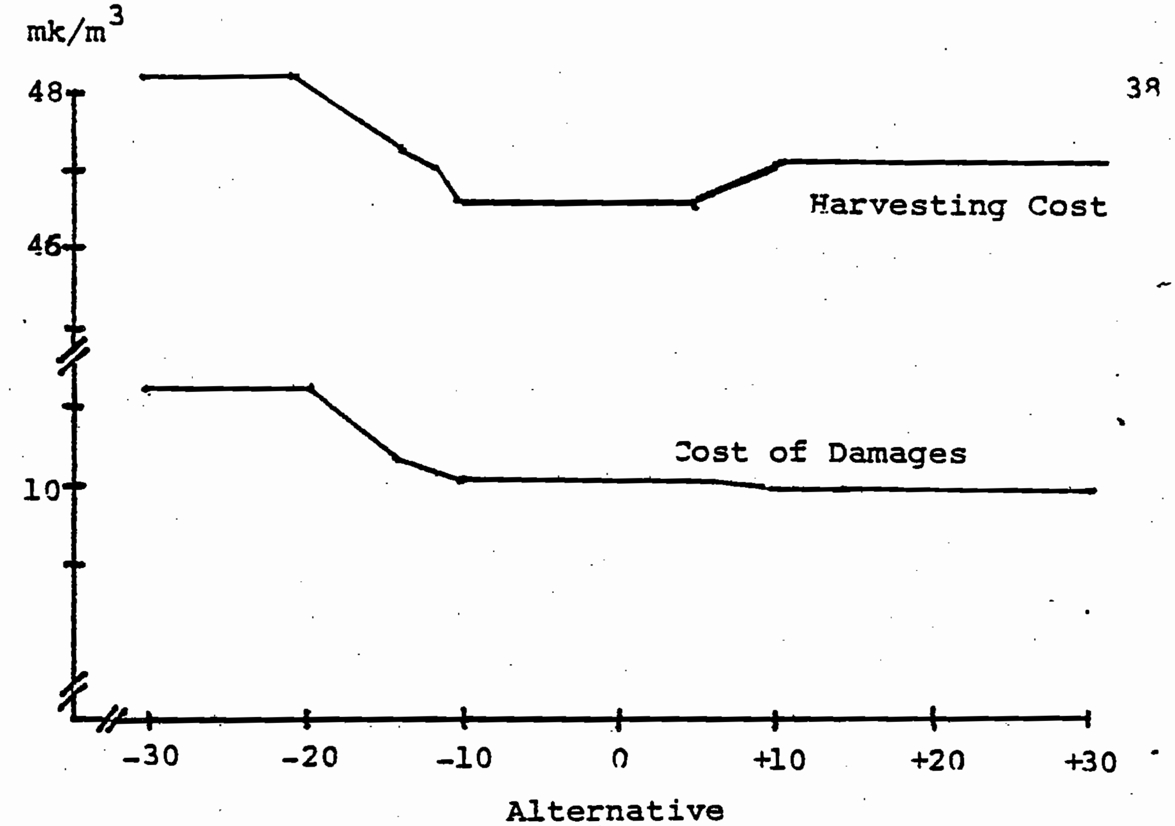


Figure 2. The behavior of the average harvesting cost and the average value of damages by alternative.

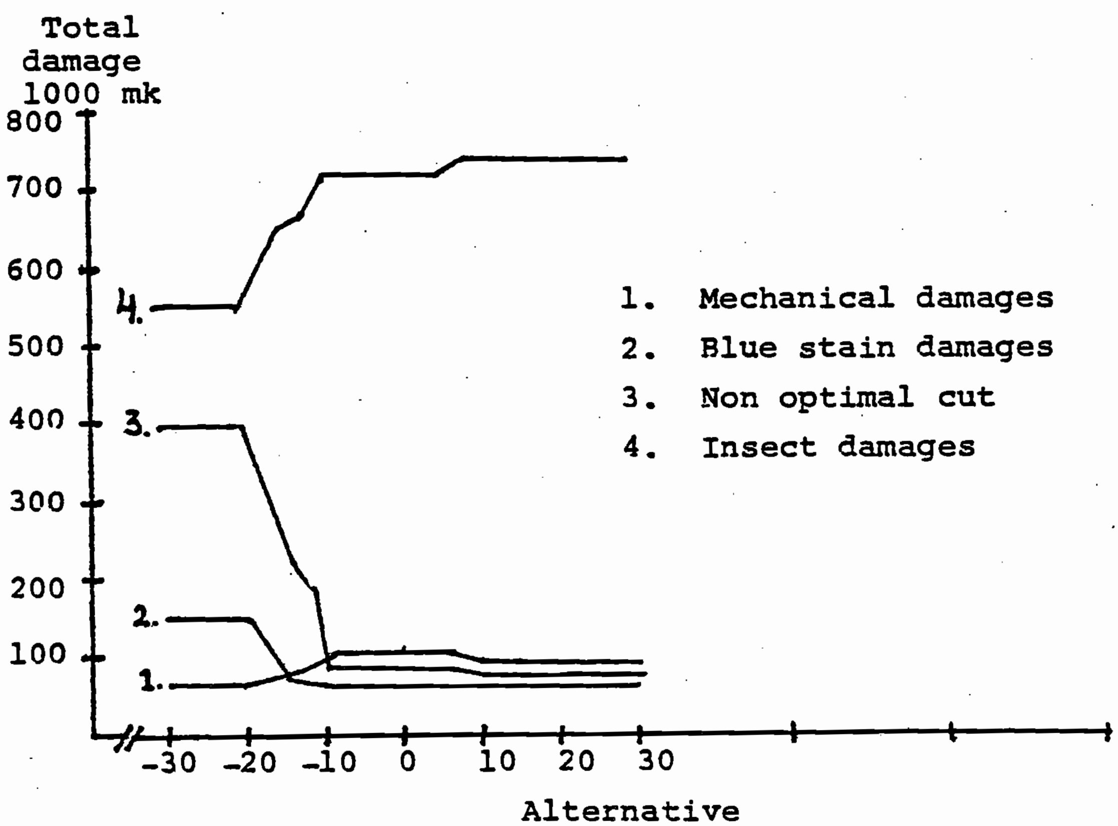


Figure 3. The behavior of the cost of the different damage components by alternative.

Table 8. The effect of the larger employment level and scarcer investment money on the mix of the optimal logging systems.

Solution	Distance km	Stem size, m^3 0.225	0.325	0.550
Optimal solution, no extra restrictions on b-vector	20		Tree-length harv. sys.	
	50	Processor system	Tree-length harv. sys.	Tree-length harv. sys.
	90	Proc. sys. & manual log-length		Pika-75 system
Must employ a larger number of cutters (30 instead of 9)	20		Tree-length harv. sys.	
	50	Man. log-length system	Tree-length harv. sys. & manual tree-length system	Tree-length harv. sys.
	90	Man. log-length sys.	Man. log-length sys.	
Investment money restriction (8.50 mk/m^3)	20		Tree-length harv. sys.	Tree-length harv. sys.
	50		Man. log-length sys.	
	90	Man. log-length system		

Table 9. The average log-content transportation distance, and stem size of the solutions in table 8.

Item	Alternative		
	No restrictions	Employment restrictions	Investment restrictions
Log content, %	73.6	73.6	74.2
Av. Stem size, m^3	0.340	0.340	0.357
Av. trans. dist., km	53	53	48
Av. harvest cost/m^3	46.78	48.53	41.14
Av. damage cost/m^3	10.24	10.69	10.96
The % share of			
- manual log-length m.	17.9	33.6	65.6
- manual tree-length m.	--	11.5	--
- mech. log-length m.	17.8	--	--
- tree-length harvester	64.3	54.9	34.4

Tighter restrictions on those issues would cut down the use of processors and Pika 75 harvester. The investment restriction was initially set so low that it restricted the total volume to be cut. One additional goal programming type run was carried out to find out how low the investment requirement can get not prohibiting the volume required to be harvested. This limit was found to be 9.60 mk/m^3.

One additional issue studied by using the model was the effect of mechanical damages on logs when using processors. Initially it was supposed that processors are equipped with feed rollers having conical spikes. Because it is apparent that the rollers of that type will disappear from use in the near future, the value of the mechanical damages was lowered to half in the processor system. This did not in any way affect the optimal logging system mix.

The Effects of Changing Requirement Vector Values

As explained earlier, one aim of this study was to find out how the logging-transportation system mix for large sawmills would behave. The requirement vectors for the large purchase were presented on pages 25-26.

Four different alternatives for the large purchase were developed and main results are given in tables 10 and 11.

From table 10, one can see that the behavior of the optimal system mix is similar to that of the small purchase.

Table 10. Optimal harvesting system mix for the large sawmill by alternative.

Alt.	Transp. Distance	Stem size 0.225, m^3		Stem size 0.325, m^3		Stem size 0.350, m^3	
		System	%	System	%	System	%
-20	20 km	Man. log-length sys.	2.0	Processor System	15.0	Pika 75 System	3.0
	50 km	Man. log-length sys.	4.0	Processor System	30.0	Pika 75 System	6.0
	90 km	Man. log-length sys.	4.0	Man. log-length sys. Proc. sys.	13.6 1.4	Pika 75 System	21.0
-15	20 km	Man. log-length system	2.0	Tree length harv. sys.	15.0	Pika 75 System	3.0
	50 km	Man. log-length system	4.0	Man. log-length system proc. sys	3.0 27.0	Pika 75 System	6.0
	90 km	Man. log-length system	4.0	Man. log-length system	15.0	Pika 75 System	21.0

Table 10. (Cont.) Optimal harvesting system mix for the large sawmill by alternative.

0	20 km	Man. log-length system	2.0	Tree length harv. sys.	15.0	Tree length harv. sys.	3.0
	50 km	Man. log-length system	4.0	Man. Tree-length sys., tree length harv. sys.	2.0 13.0	Tree length harv. sys.	21.0
	90 km	Man. log-length system	4.0	Man. log-length sys., tree length harv. sys.	22.3 7.7	Tree length harv. sys.	6.0
+10	20 km	Man. log-length system	2.0	Man. Tree-length sys., tree length harv. sys.	2.0 13.0	Tree length harv. sys.	3.0
	50 km	Man. log-length system	4.0	Tree length harv. sys.	22.7	Tree length harv. sys.	13.3
	90 km	Man. log-length system	4.0	Man. log-length system	22.3	Tree length harv. sys.	13.7

Alternative-20 = Assumed value of the tree-length raw material 20 mk/m^3 down from the original comparative value

Table 10. (continued)

Alternative-15 = Assumed value of the tree-length raw material 15 mk/m^3 down from the original comparative value

Alternative 0 = Original comparison

Alternative+10 = 10 mk up frwm the 0-alternative

In the 0-alternative, the manual system is employed on small stems, tree length system on medium size and large stem, the special feature being that manual tree-length system is also employed in the medium distances.

When lowering the value of the raw material, the tree-length harvester systems would be replaced by Pika 75-system on large stems and processor system on medium size stems.

An increase in value would not change the optimal system mix. The table gives, thus, the optimal logging system to be used in every circumstance defined.

Table 11 is self explanatory. Logging cost figures represent actual cost per cubic meter logged by that particular method and thus one cannot add them up to get the total average cost. The average total harvesting cost can be calculated by multiplying the cost of each work phase in table 11 by the share of the respective system and then adding up the cost.

Computational Experience

This model in its basic form had 126 variables and 88 constraints. The solution on CDC's Cyber 7000 computer using MPOS LP-package required 16.23 seconds of CPU time. The density of the model was 11.5% and the number of artificial variables was large due to 80 equality constraints. Solution required 167 iterations.

Table 11. Additional information given by the model in the optimal mix for the various alternatives for the large sawmill.

Item	20 mk down	15 mk down	±0	10 mk up
	mk/m^3			
Total value of damages	14.03	13.06	11.10	11.10
out of which				
- mechanical	1.64	1.29	1.18	1.18
- blue-stain	1.61	1.29	0.95	0.95
- insects	7.06	7.21	8.13	8.13
- non opt. cut	3.72	3.07	0.84	0.84
Average total harv. cost/m^3	47.12	47.40	47.65	47.65
out of which				
- manual logg.	9.49	12.51	21.01	21.01
- mechanical logging	12.74	11.72	8.08	8.08
Forest transp				
- forwarding	10.75	10.75	10.48	10.48
- skidding	--	12.18	11.05	11.05
long dist. trans.				
- logs	18.30	20.64	21.75	21.75
- pulpwood	18.91	16.14	21.72	21.72
- stems	--	14.20	20.31	20.31
- chips	--	8.00	9.36	9.36
Storage area *cost	2.00	2.09	2.47	2.47

*It was assumed that per each m^3 harvested, 2 mk cost in storage or landing area occurs. Different systems have different landing requirements, that is why the different cost.

Table 11. Additional information given by the model in the optimal mix for the various alternatives for the large sawmill.

Total labor input, mandays	28,367	29,526	29,293	29,296
- manual logging	15,400	15,400	15,400	15,400
- mechanical logging	4,241	3,564	1,620	1,620
- forest trans.	5,246	6,631	4,805	4,805
- long. dist. trans.	3,480	3,931	6,483	6,483
Machine hour input/year				
- forwarders	40,283	34,504	14,400	14,400
- skidders	--	3,285	13,045	13,045
- processors	12,589	7,336	--	--
- Pika harv.	7,395	7,395	--	--
- tree-length harvesters	--	2,048	7,584	7,584
Truck hours in long distance tr.	24,256	26,626	37,200	37,200
Initial investment required per m^3 logged per year, mk	11.23	9.21	10.70	10.70

To find the optimal solution by using dual-simplex method required, in this case, 503 iterations and 38.9 seconds CPU time. Obviously, regular simplex is more efficient algorithm for a problem formulation of this type.

THE CHOICE OF THE OPTIMAL SAWTIMBER HARVESTING SYSTEM

The Implications of the Parametric Approach

One of the most important features of the parametric programming approach is that it allows several consecutive optimal solutions to be developed. This is important when there is an uncertainty involved in the parameters of the model. Thus the decision maker knows what course of action to take to get the optimal solution if the initial value of the parameter under consideration was not the right one or there is a sudden change in the value of that parameter.

In this particular case, the parametric approach, though a rough one, gives a sequence of optimal harvesting systems and the cost and other input factors associated with them. It relates those to monetary values and hence the decision maker can make his best estimate under his assumptions whether it is feasible to start to use tree-length harvesting systems or not.

The Sensitivity of the Solution

Since the parametric programming is an extension of the sensitivity analysis, the ranges for the different optimal solutions are also produced when the parametric programming is carried out.

In this case the optimal solution was not very sensitive for the changes. It means that there is an optimality range of several marks or percents for each basis.

On the other hand, this means that this kind of rough approach can be employed in determining optimal logging-transportation system mix for various conditions.

CONCLUSIONS AND SUGGESTIONS

Future Research

During the course of the study, it became apparent that such a computer code is needed which would allow the parametric programming of several parameters at the same time.

As far as the subject issue itself goes, the model should be developed so that a wider range of circumstances could be included and thus the model describing the reality would be less restrictive.

The third area of future research would be to develop this kind of operation research model applications into a general every-day management tool for the harvesting practioners.

Implementation of the Model

This model can be used directly for the creation of basic data for the investment comparision calculations at a sawmill. It also can be used in determining the future courses of actions in sawtimber harvesting and all the technical development associated with it.

Thirdly, it shows to the other researchers that OR-models can be successfully applied in the difficult forestry environment and thus, hopefully, gives its contribution to the wider range of applications of those models in harvesting.

BIBLIOGRAPHY

Anonym, , 1978. Long-Distance Off and On-Road Transport. FERIC. Technical Report No. TR-26. Quebec, Canada.

Anonym, , 1980. Payment tables for the transportation of timber 1.1 1980 - 31.12. 1980. Metsā-alan Kuljetuksenantajat. Off-set printing. Helsinki, Finland.

Anonym, , 1980. Payment tables for forest haulage of timber in South-Finland. 1.2. 1980 - 31.1. 1981. Metsā-alan Kuljetuksenantajat. Off-set printing. Helsinki, Finland.

Anonym , 1980. Wage agreement for logging and floating industry and wage tables based upon it. South Finland. 6.4. 1979 - 29.2. 1980. Kar-Print 1979. Helsinki, Finland.

Anonym , 1975. Yearbook of Forest Statistics 1977-1978. Official Statistics of Finland. Folia Forestalia 375. Helsinki, Finland.

Cohen, C. and J. Stein. 1976. Multipurpose Optimization System. Version 4. Northwestern University. Evanston, Illinois, USA.

Eskelinen, A. and O. Pennanen. 1979. Marking for bucking of softwood and distribution into timber assortments in the different harvesting methods. Metsāteho Report No. 358. Helsinki, Finland.

Granqvist, Å, 1977. Tree-length Logging and Central Processing at Sawmills, Royal College of Forestry. Department of Operational Efficiency. Research Notes No. 117. Garpenberg, Sweden.

Gustafson, B.; S. Linden and R. Palm. 1974. The Influence of Saw-log Length on Trucking Costs - A Theoretical Analysis. Royal College of Forestry. Department of Operational Efficience. Research Notes No. 79. Garpenberg, Sweden.

Hypes, Trenor L. 1980. The impact of tree size on the performance of longwood harvesting functions and systems in clearcut harvesting of Southern Pine. M.S. Thesis. School of Forestry and Wildlife Resources. VPI & SU Blacksburg, Virginia. USA.

Johnson, L. and Biller, C. 1974. Wood chipping and a balanced logging system. Simulation can check the combinations. ASAE Transact. Vol. 17, No. 4. USA.

Kahala, M. 1979. Forwarder Transport of Timber and Tractors Influencing it. Metsateho Report No. 355. Helsinki, Finland.

Laasasenaho, J. 1975. Dependence of the Amount of Harvestable Timber Upon the Slump Height and the Top-logging diameter. Folia Forestalia No. 233, Helsinki Finland.

Larsson, M. and G. Nilsson. 1977. Driving, Transport och Terminalhantering av stammar i Sverige. Redogorelse No. 9/177. Forskningstiftelsen Skogsarbeten. Stockholm, Sweden.

Lavoie, J.-M., 1979. The Transportation of Tree Lengths by Truck Trains. FERIC. Technical Report No. TR-33. Quebec Canada.

Makela, M. 1979. Effect of work difficulty factors on the output of Pika-75 harvester. Metsāteho Report No. 354. Helsinki, Finland.

Makela, M. 1980. Time study on processors. Unpublished manuscript. Metsāteho. Helsinki, Finland.

Makela, M. and O. Pennanen. 1980. Damage to sawlogs during processing and storage in the different delimbing methods. Metsāteho Report No. 361. Helsinki, Finland.

McMoreland, B. 1977. Evaluation of Volvo BM 971 Clam Bunk Skidder. FERIC. Technical Report No. TR-16. Quebec, Canada.

Mikkonen, E. 1977. Timber sorting with multipurpose machines. Metsāteho Report No. 344. Helsinki, Finland.

Mikkonen, E.; J. Peltonen and U. Silvennoinen. 1979. Lokomo 961T-harvester. Metsāteho Review 1A/1979. Helsinki Finland.

Myllyniemi, A. 1977. Effect of work difficulty factors on the output of multipurpose machines operating in the cutting area. Metsāteho Report No. 345. Helsinki, Finland.

Myllyniemi, A. 1980. Loading onto truck of long pulpwood bucked by eye. Metsateho Review 3/1980. Helsinki Finland.

Peltonen, J. 1980. The technical conditions of harvesting in Finland in 1979. Typewriting. Helsinki, Finland.

Salminen, J. 1979. Purchasing sawtimber by the tree-length method. Metsāteho Review 15/1979. Helsinki, Finland.

Simmons, D. 1972. Linear programming for operations research. Holden-Day, Inc. San Francisco.

Simpson, M. L. Jr. 1970. A computer simulation model for use in considering alternative wood procurement policies. Unpublished master of forestry paper. Virginia Polytechnic Institute. Virginia, USA.

Smith, D. G., and Tse, P. P. 1977. Logging Trucks: Comparison of productivity and costs. FERIC. Technical Report No. TR-18. Quebec. Canada.

Taha, H. 1972. Operations Research. McMillan, New York, USA.

Thesslund, O. 1978. Tree-length harvesting system based on Lokomo 933T-harvester. Unpublished manuscript. National Board of Forestry, R & D Section. Hirvas, Finland.

Tilghman, W. G. 1967. Linear programming approach to minimizing wood procurement cost for integrated forest products firm. Unpublished master of forestry paper. Virginia Polytechnic Institute. Virginia USA.

Williams, H. P. 1978. Model Building in Mathematical Programming. John Wiley & Sons, New York, USA.

Zionts, S. 1974. Linear and Integer Programming. Prentice-Hall, Inc. Englewood Cliffs. New Jersey, USA.

COMPUTER INPUT

Appendix 1

List of Auxliary Variables:

LOGCONT = total volume of sawtimber

MECHDAM = value of mechanical damages, mk

BLSTAIN = value of blue-stain damages, mk

INSECTS = value of insect damages, mk

NOPTCUT = value of nonoptimal cut, mk

MANCOST = cost of manual logging, mk

MECCOST = cost of mechanized logging, mk

FWLCOST = forwarding cost of logs, mk

FWPCOST = forwarding cost of pulpwood, mk

SKDCOST = skidding cost of tree-lengths, mk

LLDCOST = long distance transportation cost of logs, mk

PLDCOST = long distance transportation cost of pulpwood, mk

TRTCOST = transportation cost of tree-lengths, mk

CHPCOST = cost of secondary transportation of chips, mk

STOCOST = landing cost of the systems

MDSCUT1, MDSCUT2, MDSCUT4 - labor input in cutting in mandays in systems 1, 2, and 4

MDSFWL1 = mandays required in forwarding logs. Similarly, all the variables formed in this way where:

MDS indicates manday input
FW = forwarder
L = logs
P = pulpwood
LLD = long. dist. transp. of logs
PLD = long. dist. transp. of pulpwood
PRC = processor
SKD = skidding
HARV = harvester
(number indicates the system used)

In general, variable having

- FW indicates forwarder
- SKD indicates skidder
- TR or TRUCK indicates trucks
- TRL indicates tree-lengths
- LOG or L indicates logs
- PLW or P indicates pulpwood
- CHSAW indicates chainsaw
- I, IN or INV indicates investments
- HRS indicates machine hours

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TITLE
TREE-LENGTH LOGGING STUDY
REGULAR
MAXIMIZE
174X111+174X112+174X113+217X121+217X122+217X123+228X131+228X132+228X133
+174X211+174X212+174X213+217X221+217X222+217X223+228X231+228X232+228X233
+174X311+174X312+174X313+217X321+217X322+217X323+228X331+228X332+228X333
+183Y111+183Y112+183Y113+228Y121+228Y122+228Y123+235Y131+235Y132+235Y133
+183Y211+183Y212+183Y213+228Y221+228Y222+228Y223+235Y231+235Y232+235Y233
-MECHDAM-BLSTAIN-INSECTS-NOPTCUT-MANCOST-MECCOST-FWLCOST-FWPCOST
-SKDCOST-LLDCOST-PLDCOST-TRTCOST-CHPCOST-2STOCOST
CONSTRAINTS
1.  X111+X112+X113+X121+X122+X123+X131+X132+X133
    +X211+X212+X213+X221+X222+X223+X231+X232+X233
    +X311+X312+X313+X321+X322+X323+X331+X332+X333
    +Y111+Y112+Y113+Y121+Y122+Y123+Y131+Y132+Y133
    +Y211+Y212+Y213+Y221+Y222+Y223+Y231+Y232+Y233  .LE.  100000
2.  .52X111+.52X112+.52X113+.76X121+.76X122+.76X123+.82X131+.82X132+.82X133
    +.52X211+.52X212+.52X213+.76X221+.76X222+.76X223+.82X231+.82X232+.82X233
    +.52X311+.52X312+.52X313+.76X321+.76X322+.76X323+.82X331+.82X332+.82X333
    +.57Y111+.57Y112+.57Y113+.82Y121+.82Y122+.82Y123+.86Y131+.86Y132+.86Y133
    +.57Y211+.57Y212+.57Y213+.82Y221+.82Y222+.82Y223+.86Y231+.86Y232+.86Y233
    -LOGCONT  .EQ.  0
3.  X131+X132+X133+X231+X232+X233+X331+X332+X333
    +Y131+Y132+Y133+Y231+Y232+Y233                .LE.  20000
4.  X121+X122+X123+X221+X222+X223+X321+X322+X323
    +Y121+Y122+Y123+Y221+Y222+Y223                .LE.  50000
5.  X111+X121+X131
    +X211+X221+X231
    +X311+X321+X331
    +Y111+Y121+Y131
    +Y211+Y221+Y231  .LE.  30000
6.  X111+X121+X131
    +X211+X221+X231
    +X311+X321+X331
    +Y111+Y121+Y131
    +Y211+Y221+Y231
    +X112+X122+X132
    +X212+X222+X232
    +X312+X322+X332
    +Y112+Y122+Y132
    +Y212+Y222+Y232  .LE.  70000
7.  X111+X112+X113+X121+X122+X123+X131+X132+X133
    +X211+X212+X213+X221+X222+X223+X231+X232+X233
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     +X311+X312+X313+X321+X322+X323+X331+X332+X333
     +1.3Y111+1.3Y112+1.3Y113+1.3Y121+1.3Y122+1.3Y123+1.4Y131+1.4Y132+1.4Y133
     +1.3Y211+1.3Y212+1.3Y213+1.3Y221+1.3Y222+1.3Y223+1.4Y231+1.4Y232+1.4Y233
     -STOCOST  .EQ. 0
  8. 0.41X111+0.41X112+0.41X113+0.59X121+0.59X122+0.59X123+0.64X131+0.64X132+0.64X133
     +2.16X211+2.16X212+2.16X213+3.16X221+3.16X222+3.16X223+3.4X231+3.4X232+3.4X233
     +0.14X311+0.14X312+0.14X313+0.20X321+0.20X322+0.20X323+0.2X331+0.2X332+0.2X333
     +0.15Y111+0.15Y112+0.15Y113+0.2Y121+0.2Y122+0.2Y123+0.22Y131+0.22Y132+0.22Y133
     +1.04Y211+1.04Y212+1.04Y213+1.5Y221+1.5Y222+1.5Y223+1.57Y231+1.57Y232+1.57Y233
     -MECHDAM  .EQ.  0
  9. 1.76X111+1.76X112+1.76X113+2.57X121+2.57X122+2.57X123+2.77X131+2.77X132+2.77X133
     +.95X211+.95X212+.95X213+1.38X221+1.38X222+1.38X223+1.49X231+1.49X232+1.49X233
     +.95X311+.95X312+.95X313+1.38X321+1.38X322+1.38X323+1.49X331+1.49X332+1.49X333
     +1.96Y111+1.96Y112+1.96Y113+2.77Y121+2.77Y122+2.77Y123+2.9Y131+2.9Y132+2.9Y133
     +.15Y211+.15Y212+.15Y213+.21Y221+.21Y222+.21Y223+.22Y231+.22Y232+.22Y233
     -BLSTAIN  .EQ.  0
 10. 6.49X111+6.49X112+6.49X113+9.5X121+9.5X122+9.5X123+10.2X131+10.2X132+10.2X133
     +5.0X211+5.0X212+5.0X213+7.31X221+7.31X222+7.31X223+7.89X231+7.89X232+7.89X233
     +3.65X311+3.65X312+3.65X313+5.3X321+5.3X322+5.3X323+5.76X331+5.76X332+5.76X333
     +7.1Y111+7.1Y112+7.1Y113+10.2Y121+10.2Y122+10.2Y123+10.7Y131+10.7Y132+10.7Y133
     +5.34Y211+5.34Y212+5.34Y213+7.68Y221+7.68Y222+7.68Y223+8.05Y231+8.05Y232
     +8.05Y233  -INSECTS  .EQ.  0
 11. 2.61X111+2.61X112+2.61X113+2.61X121+2.61X122+2.61X123+2.61X131+2.61X132+2.61X133
     +3.96X211+3.96X212+3.96X213+3.96X221+3.96X222+3.96X223+3.96X231+3.96X232
     +3.96X233
     +4.22X311+4.22X312+4.22X313+4.22X321+4.22X322+4.22X323+4.22X331+4.22X332
     +4.22X333   -NOPTCUT  .EQ. 0
 12. 22.75X111+22.75X112+22.75X113+20.53X121+20.53X122+20.53X123+17.55X131
     +17.55X132+17.55X133
     +3.69X211+3.69X212+3.69X213+3.39X221+3.39X222+3.39X223+3.18X231+3.18X232
     +3.18X233
     +19.86Y111+19.86Y112+19.86Y113+17.67Y121+17.67Y122+17.67Y123+14.32Y131
     +14.32Y132+14.32Y133  -MANCOST  .EQ. 0
 13. 16.00X211+16.00X212+16.00X213+11.70X221+11.70X222+11.70X223+8.50X231+8.50X232
     +8.50X233
     +26.78X311+26.78X312+26.78X313+19.27X321+19.27X322+19.27X323+12.82X331
     +12.82X332+12.82X333
     +12.91Y211+12.91Y212+12.91Y213+9.56Y221+9.56Y222+9.56Y223+6.33Y231+6.33Y232
     +6.33Y233  -MECCOST  .EQ. 0
 14. 5.73X111+5.73X112+5.73X113+8.28X121+8.28X122+8.28X123+8.98X131+8.98X132+8.98X133
     +5.40X211+5.40X212+5.40X213+7.81X221+7.81X222+7.81X223+8.47X231+8.47X232
     +8.47X233
     +5.11X311+5.11X312+5.11X313+7.38X321+7.38X322+7.38X323+8.01X331+8.01X332
     +8.01X333 -FWLCOST  .EQ.  0
 15. 5.39X111+5.39X112+5.39X113+2.86X121+2.86X122+2.86X123+2.22X131+2.22X132+2.22X133
     +5.68X211+5.68X212+5.68X213+3.01X221+3.01X222+3.01X223+2.33X231+2.33X232
     +2.33X233
     +5.68X311+5.68X312+5.68X313+3.01X321+3.01X322+3.01X323+2.33X331+2.33X332
     +2.33X333  -FWPCOST  .EQ. 0
 16. 18.50Y111+18.50Y112+18.50Y113+15.97Y121+15.97Y122+15.97Y123+11.62Y131+11.62Y132
     +11.62Y133
     +15.18Y211+15.18Y212+15.18Y213+12.18Y221+12.18Y222+12.18Y223+8.62Y231+8.62Y232
     +8.62Y233  -SKDCOST .EQ.  0
 17. 6.11X111+8.86X112+12.01X113+8.82X121+12.81X122+17.35X123+9.58X131+13.90X132
     +18.83X133
     +6.11X211+8.86X212+12.01X213+8.82X221+12.81X222+17.35X223+9.58X231+13.90X232
     +18.83X233
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     +6.11X311+8.86X312+12.01X313+8.82X321+12.81X322+17.35X323+9.58X331+13.90X332
     +18.83X333  -LLDCOST  .EQ.  0
18.  5.99X111+8.41X112+11.43X113+3.03X121+4.26X122+5.79X123+2.21X131+3.11X132
     +4.22X133
     +5.99X211+8.41X212+11.43X213+3.03X221+4.26X222+5.79X223+2.21X231+3.11X232
     +4.22X233
     +5.99X311+8.41X312+11.43X313+3.03X321+4.26X322+5.79X323+2.21X331+3.11X332
     +4.22X333  -PLDCOST .EQ.  0
19.  14.20Y111+20.43Y112+28.01Y113+14.20Y121+20.43Y122+28.01Y123+14.20Y131+20.43Y132
     +28.01Y133
     +14.20Y211+20.43Y212+28.01Y213+14.20Y221+20.43Y222+28.01Y223+14.20Y231
     +20.43Y232+28.01Y233  -TRTCOST  .EQ.  0
20.  3.39Y111+4.29Y112+4.29Y113+1.44Y121+1.82Y122+1.82Y123+1.07Y131+1.36Y132+1.36Y133
     +3.39Y211+4.29Y212+4.29Y213+1.44Y221+1.82Y222+1.82Y223+1.07Y231+1.36Y232
     +1.36Y233  -CHPCOST  .LE.  0
21.  9.71X111+9.71X112+9.71X113+8.77X121+8.77X122+8.77X123+7.51X131+7.51X132+7.51X133
     -MDSCUT1  .EQ. 0
22.  0.80X111+0.80X112+0.80X113+1.16X121+1.16X122+1.16X123+1.25X131+1.25X132+1.25X133
     -MDSFUL1  .EQ. 0
23.  0.76X111+0.76X112+0.76X113+0.40X121+0.40X122+0.40X123+0.31X131+0.31X132+0.31X133
     -MDSFUP1  .EQ. 0
24.  0.34X111+0.45X112+0.56X113+0.34X121+0.45X122+0.56X123+0.34X131+0.45X132+0.56X133
     -MDSLLD1  .EQ.  0
25.  0.32X111+0.21X112+0.19X113+0.32X121+0.21X122+0.19X123+0.32X131+0.21X132+0.19X133
     -MDSPLD1  .EQ.  0
26.  4.57X111+4.57X112+4.57X113+6.60X121+6.60X122+6.60X123+7.16X131+7.16X132+7.16X133
     -FRWLOG1  .EQ.  0
27.  4.36X111+4.36X112+4.36X113+2.31X121+2.31X122+2.31X123+1.79X131+1.79X132+1.79X133
     -FRWPLW1  .EQ. 0
28.  1.84X111+2.40X112+3.00X113+2.65X121+3.47X122+4.34X123+2.88X131+3.76X132+4.71X133
     -TRUCKL1  .EQ.  0
29.  1.75X111+2.26X112+2.71X113+0.89X121+1.14X122+1.42X123+0.65X131+0.83X132+1.03X133
     -TRUCKP1  .EQ.  0
30.  0.89X111+0.89X112+0.89X113+0.89X121+0.89X122+0.89X123+0.89X131+0.89X132+0.89X133
     -CHSAWI1  .EQ.  0
31.  3.70X111+3.70X112+3.70X113+5.34X121+5.34X122+5.34X123+5.80X131+5.80X132+5.80X133
     -FRWLIN1  .EQ.  0
32.  3.52X111+3.52X112+3.52X113+1.87X121+1.87X122+1.87X123+1.45X131+1.45X132+1.45X133
     -FRWPIN1  .EQ.  0
33.  1.26X111+1.63X112+2.03X113+1.26X121+1.63X122+2.06X123+1.26X131+1.63X132+2.03X133
     -TRUCIN1  .EQ.  0
34.  2.15X211+2.15X212+2.15X213+1.97X221+1.97X222+1.97X223+1.85X231+1.85X232+1.85X233
     -MDSCUT2  .EQ. 0
35.  1.51X211+1.51X212+1.51X213+1.15X221+1.15X222+1.15X223+0.75X231+0.75X232+0.75X233
     -MDSPRC2  .EQ.  0
36.  0.69X211+0.69X212+0.69X213+1.00X221+1.00X222+1.00X223+1.09X231+1.09X232+1.09X233
     -MDSFUL2  .EQ.  0
37.  0.71X211+0.71X212+0.71X213+0.37X221+0.37X222+0.37X223+0.29X231+0.29X232+0.29X233
     -MDSFUP2  .EQ.  0
38.  0.34X211+0.45X212+0.56X213+0.34X221+0.45X222+0.56X223+0.34X231+0.45X232+0.56X233
     -MDSLLD2  .EQ.  0
39.  0.32X211+0.21X212+0.19X213+0.32X221+0.21X222+0.19X223+0.32X231+0.21X232+0.19X233
     -MDSPLD2  .EQ.  0
40.  7.09X211+7.09X212+7.09X213+5.43X221+5.43X222+5.43X223+3.55X231+3.55X232+3.55X233
     -PROHRS2  .EQ.  0
41.  3.97X211+3.97X212+3.97X213+5.74X221+5.74X222+5.74X223+6.23X231+6.23X232+6.23X233
     -FRWLOG2  .EQ.  0
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42.  4.03X211+4.03X212+4.03X213+2.14X221+2.14X222+2.14X223+1.66X231+1.66X232+1.66X233
     -FRWPLW2  .EQ.  0
43.  1.84X211+2.40X212+3.00X213+2.65X221+3.47X222+4.34X223+2.88X231+3.76X232+4.71X233
     -TRUCKL2  .EQ.  0
44.  1.75X211+2.26X212+2.71X213+0.89X221+1.14X222+1.42X223+0.65X231+0.83X232+1.03X233
     -TRUCKP2  .EQ.  0
45.  0.23X211+0.23X212+0.23X213+0.23X221+0.23X222+0.23X223+0.23X231+0.23X232+0.23X233
     -CHSAWI2  .EQ.  0
46.  5.71X211+5.71X212+5.71X213+4.42X221+4.42X222+4.42X223+2.86X231+2.86X232+2.86X233
     -PROCIN2  .EQ.  0
47.  3.22X211+3.22X212+3.22X213+4.65X221+4.65X222+4.65X223+5.05X231+5.05X232+5.05X233
     -FRWLIN2  .EQ.  0
48.  3.27X211+3.27X212+3.27X213+1.73X221+1.73X222+1.73X223+1.35X231+1.35X232+1.35X233
     -FRWPIN2  .EQ.  0
49.  1.26X211+1.63X212+2.03X213+1.26X221+1.63X222+2.06X223+1.26X231+1.63X232+2.03X233
     -TRUCIN2  .EQ.  0
50.  2.19X311+2.19X312+2.19X313+1.57X321+1.57X322+1.57X323+1.05X331+1.05X332+1.05X333
     -MDSHAR3  .EQ.  0
51.  0.69X311+0.69X312+0.69X313+1.00X321+1.00X322+1.00X323+1.09X331+1.09X332+1.09X333
     -MDSFWL3  .EQ.  0
52.  0.71X311+0.71X312+0.71X313+0.37X321+0.37X322+0.37X323+0.29X331+0.29X332+0.29X333
     -MDSFWP3  .EQ.  0
53.  0.34X311+0.45X312+0.56X313+0.34X321+0.45X322+0.56X323+0.34X331+0.45X332+0.56X333
     -MDSLLD3  .EQ.  0
54.  0.32X311+0.21X312+0.19X313+0.32X321+0.21X322+0.19X323+0.32X331+0.21X332+0.19X333
     -MDSPLD3   .EQ.  0
55.  10.3X311+10.3X312+10.3X313+7.41X321+7.41X322+7.41X323+4.93X331+4.93X332+4.93X333
     -HARHRS3  .EQ.  0
56.  3.78X311+3.78X312+3.78X313+5.46X321+5.46X322+5.46X323+5.93X331+5.93X332+5.93X333
     -FRWLOG3  .EQ.  0
57.  4.03X311+4.03X312+4.03X313+2.14X321+2.14X322+2.14X323+1.66X331+1.66X332+1.66X333
     -FRWPLW3   .EQ.  0
58.  1.84X311+2.40X312+3.00X313+2.65X321+3.47X322+4.34X323+2.88X331+3.76X332+4.71X333
     -TRUCKL3   .EQ.  0
59.  1.75X311+2.26X312+2.71X313+0.89X321+1.14X322+1.42X323+0.65X331+0.83X332+1.03X333
     -TRUCKP3  .EQ.  0
60.  13.3X311+13.3X312+13.3X313+7.00X321+7.00X322+7.00X323+6.35X331+6.35X332+6.35X333
     -HARVIN3  .EQ.  0
61.  3.07X311+3.07X312+3.07X313+4.43X321+4.43X322+4.43X323+4.81X331+4.81X332+4.81X333
     -FRWLIN3  .EQ.  0
62.  3.27X311+3.27X312+3.27X313+1.73X321+1.73X322+1.73X323+1.35X331+1.35X332+1.35X333
     -FRWPIN3   .EQ.  0
63.  1.26X311+1.63X312+2.03X313+1.26X321+1.63X322+2.06X323+1.26X331+1.63X332+2.03X333
     -TRUCIN3   .EQ.  0
64.  8.47Y111+8.47Y112+8.47Y113+7.56Y121+7.56Y122+7.56Y123+6.13Y131+6.13Y132+6.13Y133
     -MDSCUT4  .EQ.  0
65.  1.16Y111+1.16Y112+1.16Y113+1.01Y121+1.01Y122+1.01Y123+0.73Y131+0.73Y132+0.73Y133
     -MDSSKD4   .EQ.  0
66.  1.08Y111+1.40Y112+1.76Y113+1.08Y121+1.40Y122+1.76Y123+1.04Y131+1.37Y132+1.74Y133
     -MDSTRL4  .EQ.  0
67.  0.42Y111+0.54Y112+0.54Y113+0.18Y121+0.23Y122+0.23Y123+0.13Y131+0.17Y132+0.17Y133
     -MDSCHP4  .EQ.  0
68.  6.58Y111+6.58Y112+6.58Y113+5.75Y121+5.75Y122+5.75Y123+4.18Y131+4.18Y132+4.18Y133
     -SKDHRS4  .EQ.  0
69.  5.75Y111+7.52Y112+9.43Y113+5.75Y121+7.52Y122+9.43Y123+5.56Y131+7.35Y132+9.26Y133
     -TRLTHR4  .EQ.  0
70.  2.22Y111+2.87Y112+2.87Y113+0.95Y121+1.22Y122+1.22Y123+0.71Y131+0.91Y132+0.91Y133
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     -TRCHHR4  .EQ.  0
71.  0.78Y111+0.78Y112+0.78Y113+0.78Y121+0.78Y122+0.78Y123+0.78Y131+0.78Y132+0.78Y133
     -CHSAWI4  .EQ.  0
72.  6.42Y111+6.42Y112+6.42Y113+5.53Y121+5.53Y122+5.53Y123+4.03Y131+4.03Y132+4.03Y133
     -SKDINV4  .EQ.  0
73.  2.06Y111+2.70Y112+3.38Y113+2.06Y121+2.70Y122+3.38Y123+1.99Y131+2.64Y132+3.32Y133
      -TRITRL4   .EQ.  0
74.  1.85Y111+2.37Y112+2.37Y113+1.85Y121+2.37Y122+2.37Y123+1.85Y131+2.37Y132+2.37Y133
     -TRICHP4  .EQ.  0
75.  0.82Y211+0.82Y212+0.82Y213+0.58Y221+0.58Y222+0.58Y223+0.39Y231+0.39Y232+0.39Y233
     -MDSHAR5   .EQ.  0
76.  0.96Y211+0.96Y212+0.96Y213+0.77Y221+0.77Y222+0.77Y223+0.54Y231+0.54Y232+0.54Y233
     -MDSSKD5  .EQ.  0
77.  1.08Y211+1.40Y212+1.76Y213+1.08Y221+1.40Y222+1.76Y223+1.04Y231+1.37Y232+1.74Y233
     -MDSTRL5  .EQ.  0
78.  0.42Y211+0.54Y212+0.54Y213+0.18Y221+0.23Y222+0.23Y223+0.13Y231+0.17Y232+0.17Y233
     -MDSCHP5  .EQ.  0
79.  3.69Y211+3.69Y212+3.69Y213+2.73Y221+2.73Y222+2.73Y223+1.81Y231+1.81Y232+1.81Y233
     -TRLHAR5  .EQ.  0
80.  5.46Y211+5.46Y212+5.46Y213+4.38Y221+4.38Y222+4.38Y223+3.10Y231+3.10Y232+3.10Y233
     -SKDHRS5  .EQ.  0
81.  5.75Y211+7.52Y212+9.43Y213+5.75Y221+7.52Y222+9.43Y223+5.56Y231+7.35Y232+9.26Y233
     -TRLTHR5  .EQ.  0
82.  2.22Y211+2.87Y212+2.87Y213+0.95Y221+1.22Y222+1.22Y223+0.71Y231+0.91Y232+0.91Y233
     -TRCHHR5  .EQ.  0
83.  3.97Y211+3.97Y212+3.97Y213+2.94Y221+2.94Y222+2.94Y223+1.95Y231+1.95Y232+1.95Y233
     -RHARIN5  .EQ.  0
84.  5.23Y211+5.23Y212+5.23Y213+4.20Y221+4.20Y222+4.20Y223+2.97Y231+2.97Y232+2.97Y233
     -SKDINV5  .EQ.  0
85.  2.06Y211+2.70Y212+3.38Y213+2.06Y221+2.70Y222+3.38Y223+1.99Y231+2.64Y232+3.32Y233
     -TRITRL5  .EQ.  0
86.  1.85Y211+2.37Y212+2.37Y213+1.85Y221+2.37Y222+2.37Y223+1.85Y231+2.37Y232+2.37Y233
     -TRICHP5  .EQ.  0
87.  FRWLOG1+FRWLOG2+FRWPLW1+FRWPLW2+FRWLOG3+FRWPLW3  .GE.  300000
88.  MDSCUT1+MDSCUT2+MDSCUT4   .GE. 200000
     RNGOBJ
     RNGRHS
     OPTIMIZE
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USING REGULAR
TREE-LENGTH LOGGING STUDY

Appendix 2

SUMMARY OF RESULTS

VAR NO	VAR NAME	ROW NO	STATUS	ACTIVITY LEVEL	OPPORTUNITY COST	BOUND VALUE
1	X111	--	NB	--	1.4400000	INF
2	X112	--	NB	--	0.0000000	INF
3	X113	--	B	17923.2804231	--	INF
4	X121	--	NB	--	8.0618996	INF
5	X122	--	NB	--	6.6718996	INF
6	X123	--	NB	--	6.5718996	INF
7	X131	--	NB	--	8.7241459	INF
8	X132	--	NB	--	7.3341459	INF
9	X133	--	NB	--	7.2041460	INF
10	X211	--	NB	--	1.4400000	INF
11	X212	--	B	5709.0051671	--	INF
12	X213	--	B	6367.7144086	--	INF
13	X221	--	NB	--	5.1995186	INF
14	X222	--	NB	--	3.8095186	INF
15	X223	--	NB	--	3.7095186	INF
16	X231	--	NB	--	5.2390631	INF
17	X232	--	NB	--	3.8490631	INF
18	X233	--	NB	--	3.7190631	INF
19	X311	--	NB	--	5.6729141	INF
20	X312	--	NB	--	4.2329141	INF
21	X313	--	NB	--	4.2329141	INF
22	X321	--	NB	--	4.8950725	INF
23	X322	--	NB	--	3.5050725	INF
24	X323	--	NB	--	3.4050725	INF
25	X331	--	NB	--	1.5200000	INF
26	X332	--	NB	--	.1300000	INF
27	X333	--	B	5709.0051668	--	INF
28	Y111	--	NB	--	2.1832732	INF
29	Y112	--	B	0.0000000	--	INF
30	Y113	--	NB	--	1.4100000	INF
31	Y121	--	NB	--	2.7952444	INF
32	Y122	--	NB	--	.0919712	INF
33	Y123	--	NB	--	1.5019712	INF
34	Y131	--	NB	--	2.7932732	INF
35	Y132	--	B	0.0000000	--	INF
36	Y133	--	NB	--	1.4100000	INF
37	Y211	--	NB	--	2.5113199	INF
38	Y212	--	NB	--	3.0313199	INF
39	Y213	--	NB	--	4.4413199	INF
40	Y221	--	B	30000.0000001	--	INF
41	Y222	--	B	19999.9999997	--	INF
42	Y223	--	NB	--	1.4100000	INF
43	Y231	--	NB	--	.0900000	INF
44	Y232	--	B	14290.9948333	--	INF
45	Y233	--	NB	--	1.4100000	INF
46	MECHDAM	--	B	132012.9221777	--	INF

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* PROBLEM NUMBER  1 *
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USING REGULAR
TREE-LENGTH LOGGING STUDY

SUMMARY OF RESULTS

VAR NO	VAR NAME	ROW NO	STATUS	ACTIVITY LEVEL	OPPORTUNITY COST	BOUND VALUE
47	BLSTAIN	--	B	65168.2936965	--	INF
48	INSECTS	--	B	708632.0659632	--	INF
49	NOPTCUT	--	B	118695.5732244	--	INF
50	MANCOST	--	B	452317.7248447	--	INF
51	MECCOST	--	B	834878.9567448	--	INF
52	FWLCOST	--	B	213643.8139253	--	INF
53	FWPCOST	--	B	178504.2307143	--	INF
54	SKDCOST	--	B	732188.3754629	--	INF
55	LLDCOST	--	B	449817.2009497	--	INF
56	PLDCOST	--	B	349750.8061863	--	INF
57	TRTCOST	--	B	1126565.0244377	--	INF
58	CHPCOST	--	B	99035.7529728	--	INF
59	STOCOST	--	B	120716.3979337	--	INF
60	LOGCONT	--	B	73571.6397912	--	INF
61	MDSCUT1	--	B	174035.0529102	--	INF
62	MDSFWL1	--	B	14338.6243378	--	INF
63	MDSFWP1	--	B	13621.6931220	--	INF
64	MDSLLD1	--	B	10037.0370368	--	INF
65	MDSPLD1	--	B	3405.4232806	--	INF
66	FRWLOG1	--	B	81909.3915220	--	INF
67	FRWPLW1	--	B	78145.5026473	--	INF
68	TRUCKL1	--	B	53769.8412709	--	INF
69	TRUCKP1	--	B	48572.0899484	--	INF
70	CHSAWI1	--	B	15951.7195768	--	INF
71	FRWLIN1	--	B	66316.1375580	--	INF
72	FRWPIN1	--	B	63089.9470914	--	INF
73	TRUCIN1	--	B	36384.2592596	--	INF
74	MDSCUT2	--	B	25964.9470878	--	INF
75	MDSPRC2	--	B	18235.8465594	--	INF
76	MDSFWL2	--	B	8332.9365073	--	INF
77	MDSFWP2	--	B	8574.4708988	--	INF
78	MDSLLD2	--	B	6134.9723940	--	INF
79	MDSPLD2	--	B	2408.7568227	--	INF
80	PROHRS2	--	B	85623.9417920	--	INF
81	FRWLOG2	--	B	47944.5767157	--	INF
82	FRWPLW2	--	B	48669.1798902	--	INF
83	TRUCKL2	--	B	32804.7556270	--	INF
84	TRUCKP2	--	B	30158.8577251	--	INF
85	CHSAWI2	--	B	2777.6455024	--	INF
86	PROCIN2	--	B	68958.0687775	--	INF
87	FRWLIN2	--	B	38887.0370339	--	INF
88	FRWPIN2	--	B	39490.8730127	--	INF
89	TRUCIN2	--	B	22232.1386719	--	INF
90	MDSHAR3	--	B	5994.4554251	--	INF
91	MDSFWL3	--	B	6222.8156318	--	INF
92	MDSFWP3	--	B	1655.6114984	--	INF

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* PROBLEM NUMBER  1 *
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USING REGULAR
TREE-LENGTH LOGGING STUDY

SUMMARY OF RESULTS

VAR NO	VAR NAME	ROW NO	STATUS	ACTIVITY LEVEL	OPPORTUNITY COST	BOUND VALUE
93	MDSLLD3	--	B	3197.0428934	--	INF
94	MDSPLD3	--	B	1084.7109817	--	INF
95	HARHRS3	--	B	28145.3954724	--	INF
96	FRWLOG3	--	B	33854.4006392	--	INF
97	FRWPLW3	--	B	9476.9485769	--	INF
98	TRUCKL3	--	B	26889.4143357	--	INF
99	TRUCKP3	--	B	5880.2753218	--	INF
100	HARVIN3	--	B	36252.1828092	--	INF
101	FRWLIN3	--	B	27460.3148523	--	INF
102	FRWPIN3	--	B	7707.1569752	--	INF
103	TRUCIN3	--	B	11589.2804886	--	INF
104	MDSCUT4	--	NB	--	.3115876	INF
105	MDSSKD4	--	B	0.0000000	--	INF
106	MDSTRL4	--	B	0.0000000	--	INF
107	MDSCHP4	--	B	0.0000000	--	INF
108	SKDHRS4	--	B	0.0000000	--	INF
109	TRLTHR4	--	B	0.0000000	--	INF
110	TRCHHR4	--	B	0.0000000	--	INF
111	CHSAWI4	--	B	0.0000000	--	INF
112	SKDINV4	--	B	0.0000000	--	INF
113	TRITRL4	--	B	0.0000000	--	INF
114	TRICHP4	--	NB	--	5.1986024	INF
115	MDSHAR5	--	B	34573.4879850	--	INF
116	MDSSKD5	--	B	46217.1372100	--	INF
117	MDSTRL5	--	B	79978.6629215	--	INF
118	MDSCHP5	--	B	12429.4691216	--	INF
119	TRLHAR5	--	B	162366.7006482	--	INF
120	SKDHRS5	--	B	263302.0839831	--	INF
121	TRLTHR5	--	B	427938.8120239	--	INF
122	TRCHHR5	--	B	65904.8052982	--	INF
123	RHARIN5	--	B	174867.4399249	--	INF
124	SKDINV5	--	B	252444.2546548	--	INF
125	TRITRL5	--	B	153528.2263596	--	INF
126	TRICHP5	--	B	136769.6577547	--	INF
127	--SLACK	87	NB	--	1.4927536	INF
128	--SLACK	88	NB	--	.1206004	INF
129	--SLACK D-	1	NB	--	117.9213199	INF
130	--ARTIF D-	2	NB	--	0.0000000	INF
131	--SLACK D-	3	NB	--	61.5286801	INF
132	--SLACK D-	4	NB	--	47.9286801	INF
133	--SLACK D-	5	NB	--	6.6100000	INF
134	--SLACK D-	6	NB	--	6.1700000	INF
135	--ARTIF D-	7	NB	--	2.0000000	INF
136	--ARTIF D-	8	NB	--	1.0000000	INF
137	--ARTIF D-	9	NB	--	1.0000000	INF
138	--ARTIF D-	10	NB	--	1.0000000	INF

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* PROBLEM NUMBER 1 *
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USING REGULAR
TREE-LENGTH LOGGING STUDY

SUMMARY OF RESULTS

VAR NO	VAR NAME	ROW NO	STATUS	ACTIVITY LEVEL	OPPORTUNITY COST	BOUND VALUE
139	--ARTIF	D- 11	NB	--	1.0000000	INF
140	--ARTIF	D- 12	NB	--	1.0000000	INF
141	--ARTIF	D- 13	NB	--	1.0000000	INF
142	--ARTIF	D- 14	NB	--	1.0000000	INF
143	--ARTIF	D- 15	NB	--	1.0000000	INF
144	--ARTIF	D- 16	NB	--	1.0000000	INF
145	--ARTIF	D- 17	NB	--	1.0000000	INF
146	--ARTIF	D- 18	NB	--	1.0000000	INF
147	--ARTIF	D- 19	NB	--	1.0000000	INF
148	--SLACK	D- 20	NB	--	1.0000000	INF
149	--ARTIF	D- 21	NB	--	-.1206004	INF
150	--ARTIF	D- 22	NB	--	0.0000000	INF
151	--ARTIF	D- 23	NB	--	0.0000000	INF
152	--ARTIF	D- 24	NB	--	0.0000000	INF
153	--ARTIF	D- 25	NB	--	0.0000000	INF
154	--ARTIF	D- 26	NB	--	-1.4927536	INF
155	--ARTIF	D- 27	NB	--	-1.4927536	INF
156	--ARTIF	D- 28	NB	--	0.0000000	INF
157	--ARTIF	D- 29	NB	--	0.0000000	INF
158	--ARTIF	D- 30	NB	--	0.0000000	INF
159	--ARTIF	D- 31	NB	--	0.0000000	INF
160	--ARTIF	D- 32	NB	--	0.0000000	INF
161	--ARTIF	D- 33	NB	--	0.0000000	INF
162	--ARTIF	D- 34	NB	--	-.1206004	INF
163	--ARTIF	D- 35	NB	--	0.0000000	INF
164	--ARTIF	D- 36	NB	--	0.0000000	INF
165	--ARTIF	D- 37	NB	--	0.0000000	INF
166	--ARTIF	D- 38	NB	--	0.0000000	INF
167	--ARTIF	D- 39	NB	--	0.0000000	INF
168	--ARTIF	D- 40	NB	--	0.0000000	INF
169	--ARTIF	D- 41	NB	--	-1.4927536	INF
170	--ARTIF	D- 42	NB	--	-1.4927536	INF
171	--ARTIF	D- 43	NB	--	0.0000000	INF
172	--ARTIF	D- 44	NB	--	0.0000000	INF
173	--ARTIF	D- 45	NB	--	0.0000000	INF
174	--ARTIF	D- 46	NB	--	0.0000000	INF
175	--ARTIF	D- 47	NB	--	0.0000000	INF
176	--ARTIF	D- 48	NB	--	0.0000000	INF
177	--ARTIF	D- 49	NB	--	0.0000000	INF
178	--ARTIF	D- 50	NB	--	0.0000000	INF
179	--ARTIF	D- 51	NB	--	0.0000000	INF
180	--ARTIF	D- 52	NB	--	0.0000000	INF
181	--ARTIF	D- 53	NB	--	0.0000000	INF
182	--ARTIF	D- 54	NB	--	0.0000000	INF
183	--ARTIF	D- 55	NB	--	0.0000000	INF
184	--ARTIF	D- 56	NB	--	-1.4927536	INF

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* PROBLEM NUMBER  1 *
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USING REGULAR
TREE-LENGTH LOGGING STUDY

SUMMARY OF RESULTS

VAR NO	VAR NAME	ROW NO	STATUS	ACTIVITY LEVEL	OPPORTUNITY COST	BOUND VALUE
185	--ARTIF	D- 57	NB	--	-1.4927536	INF
186	--ARTIF	D- 58	NB	--	0.0000000	INF
187	--ARTIF	D- 59	NB	--	0.0000000	INF
188	--ARTIF	D- 60	NB	--	0.0000000	INF
189	--ARTIF	D- 61	NB	--	0.0000000	INF
190	--ARTIF	D- 62	NB	--	0.0000000	INF
191	--ARTIF	D- 63	NB	--	0.0000000	INF
192	--ARTIF	D- 64	NB	--	-.4321880	INF
193	--ARTIF	D- 65	NB	--	0.0000000	INF
194	--ARTIF	D- 66	NB	--	0.0000000	INF
195	--ARTIF	D- 67	NB	--	0.0000000	INF
196	--ARTIF	D- 68	NB	--	0.0000000	INF
197	--ARTIF	D- 69	NB	--	0.0000000	INF
198	--ARTIF	D- 70	NB	--	0.0000000	INF
199	--ARTIF	D- 71	NB	--	0.0000000	INF
200	--ARTIF	D- 72	NB	--	0.0000000	INF
201	--ARTIF	D- 73	NB	--	0.0000000	INF
202	--ARTIF	D- 74	NB	--	-5.1986024	INF
203	--ARTIF	D- 75	NB	--	0.0000000	INF
204	--ARTIF	D- 76	NB	--	0.0000000	INF
205	--ARTIF	D- 77	NB	--	0.0000000	INF
206	--ARTIF	D- 78	NB	--	0.0000000	INF
207	--ARTIF	D- 79	NB	--	0.0000000	INF
208	--ARTIF	D- 80	NB	--	0.0000000	INF
209	--ARTIF	D- 81	NB	--	0.0000000	INF
210	--ARTIF	D- 82	NB	--	0.0000000	INF
211	--ARTIF	D- 83	NB	--	0.0000000	INF
212	--ARTIF	D- 84	NB	--	0.0000000	INF
213	--ARTIF	D- 85	NB	--	0.0000000	INF
214	--ARTIF	D- 86	NB	--	0.0000000	INF
215	--ARTIF	D- 87	NB	--	-1.4927536	INF
216	--ARTIF	D- 88	NB	--	-.1206004	INF

MAXIMUM VALUE OF THE OBJECTIVE FUNCTION =   15577393.426548

CALCULATION TIME WAS   16.5560 SECONDS FOR 164 ITERATIONS.

1   MPOS VERSION 3.2   NORTHWESTERN UNIVERSITY