Optimal Operation Planning for Integrated Forest Harvesting and Transport Operations from the Forest to the Mill

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ABSTRACT

Forest harvesting systems vary from place to place. This paper concentrates on the study of one of the most complex systems, multistage timber production, which is very popular in vast forest regions of China and Russia. Based on case studies from the Heilongjiang Forest Region, in the northeast part of China, optimal operation planning for forest harvesting, and the impact of harvesting on the forest environment, economic benefit and working safety, is carried using a multi-objective optimization model. The results of the case studies, optimizing operation time schedules, show that the models are quite applicable and helpful to practical operations.

Keywords: *integrated forest operations, multi-objective planning, multiple-use forestry.*

INTRODUCTION

Generally speaking, harvesting systems can be classified into the following three groups according to the operation location and operation organization:

	Operations on cutting sites	Timber transport	Operations at storage yards
Group 1	included	excluded	excluded
Group 2	included	included	excluded
Group 3	included	included	included

We discuss the last group, the most complex one, in this paper. The typical production flow chart for this group is seen in Figure 1.

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Moving timber (skidding or forwarding, transport and conveying) consumes most of the energy (80-85%) put into harvesting [5]. Skidding, transport and conveying are like the valves in the flow line of timber production and play critical roles in the overall operation system. They control the flow rate of the production line on the three different working sites. Together with the other two key parts, wood storage on the cutting sites and wood storage before conveying at the yards, they are the five key macro-variables reflecting the state and change of a harvesting system. Thus, a group 3 forest harvesting system, according to System Dynamics [1], can be illustrated simply as in Figure 2.

Differences among operation location, environment, cost, efficiency, damage to the residual stands, damage to soil, and so on, vary much from stage to stage over a year. For example, the operation results of stage 1 change significantly between the four seasons, while the difference of stage 3 is small during the same period. Thus, it is difficult to assign the amount of timber production among the four seasons for each of the stages. This is the main reason for discussing the operational planning problem for harvesting in this region.

The goal of an operational yearly harvesting plan [7] is to make decisions on how to harvest and how much to harvest in each year. We must rationally distribute the total amount of timber to be produced into each of the seasons in order to obtain the most satisfactory results for the operations from both an economical and environmental point of view.

CLASSIFICATION OF OPERATIONAL SEASONS FOR HARVESTING

Classification of time periods within a year is an important part of harvesting operation planning. The reason is that forest harvesting operations in the Heilongjiang Forest Region are significantly influenced by climate (Figure 3)[5]. From month to month, the operation results, such as cost, productivity and damage to forest environment, are different. But variation of the results is not very significant between some months. To simplify the planning problem and to illustrate it more precisely, we use a method of Fuzzy Set Theory [9], which is the analysis of fuzzy correlation of time-sequence groups, to divide the whole annual operation period into four operation seasons. The criteria used here for classifi-

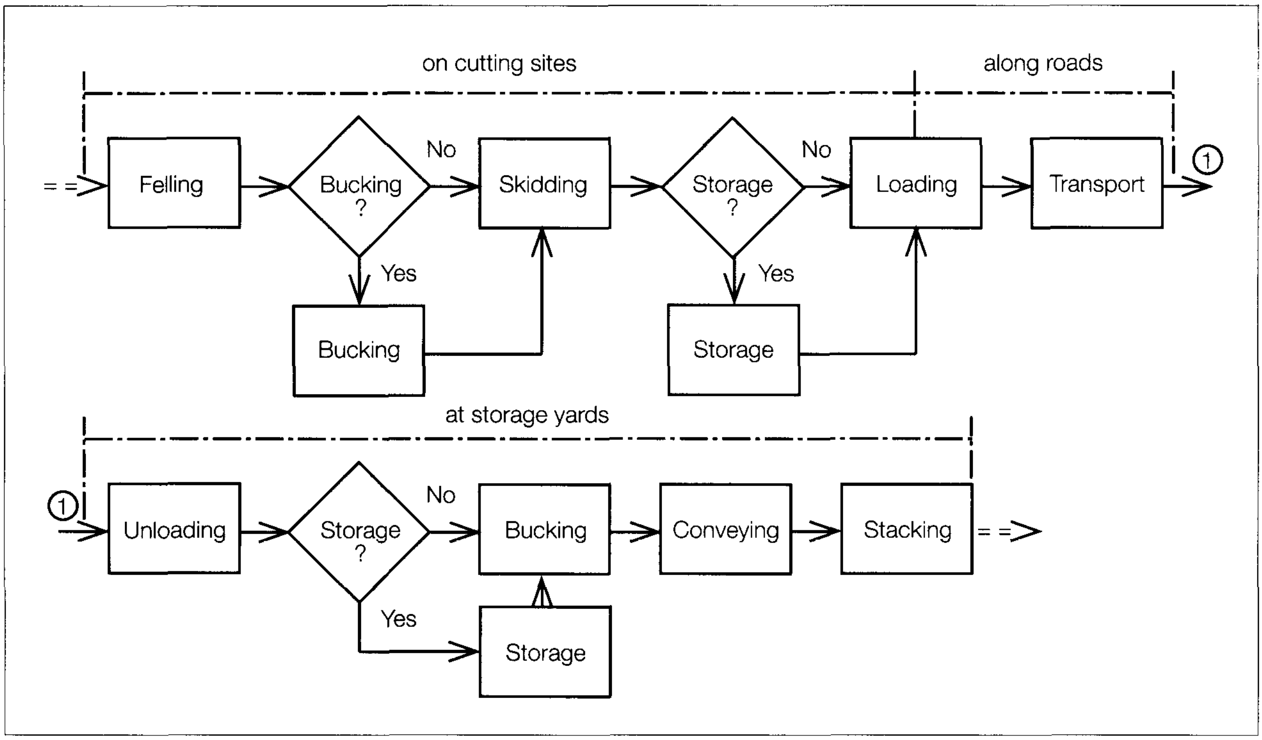
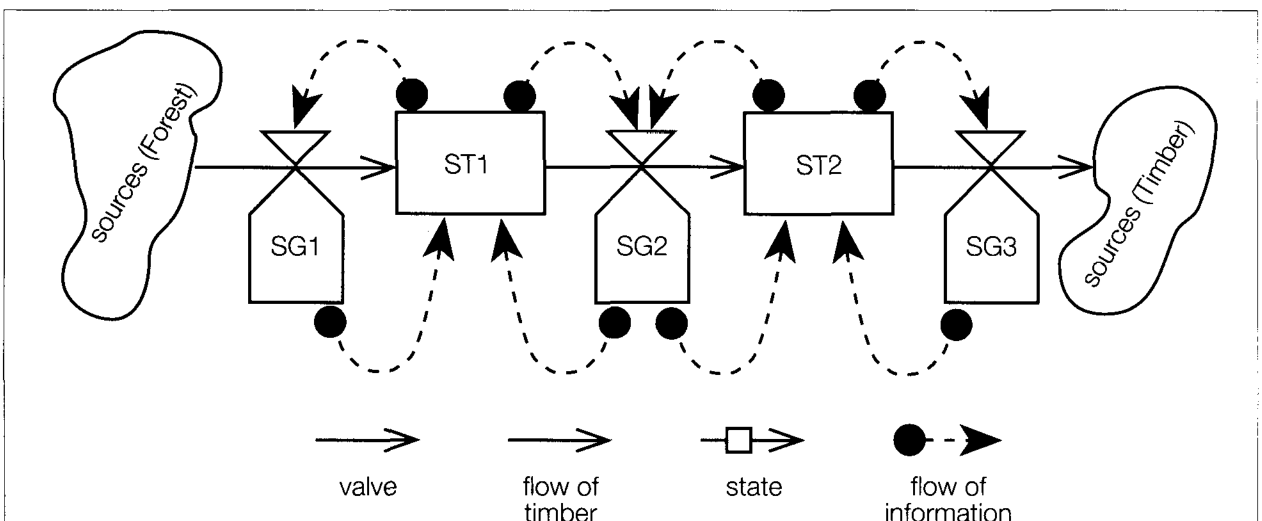


Figure 1. Typical timber production system of group 3.



SG1: stage 1, operations from felling to loading on the cutting sites;
SG2: stage 2, operations of timber transport;
SG3: stage 3, operations from unloading to stacking at a terminal yard;
ST1: state 1, amount of wood storage on the cutting sites;
ST2: state 2, amount of wood storage before conveying at a terminal yard.

Figure 2. Flow chart of a group 3 timber production system.

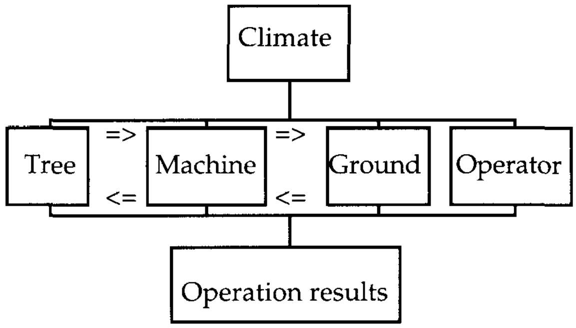


Figure 3. Harvesting operation factors influenced by climate.

cation of the time (monthly) sequences are cost, productivity, soil-bearing capacity, a tree's resistant capacity to damage, temperature, precipitation, and the degree to which the operators are influenced by changing climate. Taking 0.72 as the significant level of correlation between any two time sequences, the result of classification might be spring (April-May), summer (June-August), autumn (September-October), and winter (November-March)[5].

SELECTION OF CRITERIA FOR COMPREHENSIVE EVALUATION OF HARVESTING OPERATIONS

Harvesting operational plans are the tactical components of long-term harvesting policy. Within the limitation of harvesting policy, harvesting operational plans mainly answer the questions of how, where, how much, and when to do harvesting in order to gain the maximum comprehensive benefit, which is the synthesis of economic and ecological benefits of harvesting operations. Because the decision as to where to harvest is made by harvesting policy in the Heilongjiang Forest Region, this will be our only concern for the remainder of this paper.

The appraisal criteria play the most important role in the evaluation of harvesting plans. They depend on our knowledge about forests and human society as well as the relationships between them. With increased knowledge, the criteria for evaluating harvesting have become more and more explicit, comprehensive, and accurate. For example, the criteria for evaluating forest harvesting have changed from the efficiency of simply gathering food, firewood, and establishing living settlements in the ancient times, to the multicriteria for multifunctional forestry nowadays. The forest today is no longer the endless resource that people thought it was in ancient times. The more we know about the forest and its importance to human beings, the more carefully we harvest.

We recommend the use of the following rules to choose the criteria for evaluation of harvesting plans:

- authoritative: that is, the criteria should exactly illustrate the system or action that we are studying;
- observable: under these criteria the system (or action) should be qualitatively observable;
- measurable: under these criteria the system (or action) should be easy to quantitively measure by prediction, inference, or comparison;
- independent: each criterion should be independent of the other criteria, or they should at least have no significant correlation between them.

Based on these rules and the knowledge that we have about forests, forest harvesting, and its impact on the environment, the following criteria should be selected for comprehensively evaluating today's harvesting plans :

(1) Operation Cost C1: Organizers of harvesting want to know how much profit they would gain from production based on the prediction of operation cost.

(2) Ratio of Input of Forest Resources and Output of Products C2: Harvesting, as a kind of system production, is composed of three parts: input, processing, and output. Forest resources are becoming more and more expensive. So, the ratio of input of forest resources and output of products is the key criterion to evaluate the degree of utilization for the purpose of timber production. That is:

$$\text{Ratio} = \frac{\text{total amount of forest resources}}{\text{total amount of timber (to be) produced}}$$

(3) Degree of Working Safety C3: Degree of working safety is a symbol of the development level of harvesting in both social and economic aspects. It has been attracting more and more attention in recent decades, and has become one of the key criteria for evaluating production.

(4) Degree of Harvesting Damage to the Residual Stands on the Operation Sites C4: The trees maintained on the operation sites also play an important role in regeneration after harvesting.

Besides supplying seeds, they can influence the density of sunlight, strength of rainfall, and microclimate in the stand area.

(5) Degree of Harvesting Damage to Soil and Vegetation in the Operation Sites C5: Poor harvesting methods often result in serious damage to soil and vegetation. High soil compaction and large amounts of productive soil runoff significantly hinder the regeneration after cutting [6]. In the long term, it would accelerate the succession of a forest ecosystem to a lower community.

THE COMPREHENSIVE OPTIMAL MODEL FOR HARVESTING OPERATION PLANNING

A forest harvesting operation is theoretically restrained by the multicriteria mentioned above. How may one incorporate the multicriteria into one planning model ? There are two typical approaches used in industry planning. One is to take one of the criteria as the objective of planning while taking the other criteria as constraints [8]. Another is to use the method called multi-objective programming [10]. Here we develop a new method, which is a combination of Analytic Hierarchy Process (AHP [3]) and Linear Programming (LP). The structure of the planning model may be graphically illustrated as follows:

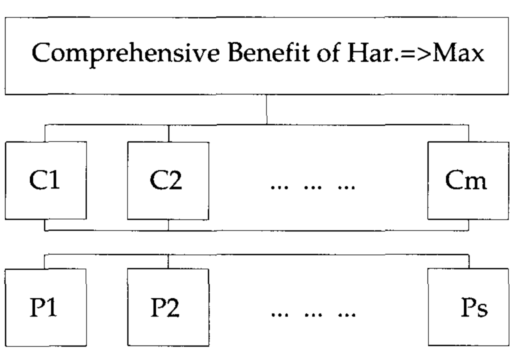


Figure 4. Structure model of harvesting operation planning.

We solve this optimization problem by the LP method. The objective coefficients in the LP model represent the comprehensive benefit of harvesting operations.

1. Evaluation of Comprehensive Benefit of Harvesting Operations for Each Approach

The benefit of harvesting operations under each criterion varies greatly from season to season in the Heilongjiang Forest Region. This is the main reason why yearly planning becomes necessary and important for harvesting enterprises in that region. According to the AHP [3], the reference values of comparison for harvesting comprehensive benefits among four seasons are shown in Table 1. In order to apply as much knowledge as possible from experts about harvesting and its impact on the forest environment, and to make the planning more general, 36 experts engaged in forest harvesting, ergonomics, silviculture, and forest ecology in different institutions were involved in the comparison of comprehensive harvesting operation benefits among the four seasons. Table 2 shows the results of this comparison, and the average comparison values of each possible operation among four seasons. The comparison only happens independently within one stage (state) under each criterion among four seasons.

Table 1. Reference values of comparison.

Value	worst	worse	good	better	best
Benefit	1	3	5	7	9

Weight coefficient distribution for each criterion might be one of the important problems of the planning optimization. Based on Table 2, we gain the weight distribution in the following method, called Weight Coefficient Differentiating (WCD) [5].

Assume Table 2 as matrix $\{X\}_{20X6}$, that is, x_{ij} is the value of operation approach i under criterion j (i=1,2,...,20; j=1,2,...,6). Harvesting operation of each procedure (stage or state) during one of the seasons is one approach. For example, operation of stage 1 during spring is approach 1, and that during summer is approach 2.

Let b, which can fit the following non-linear programming, be the coefficient of weight distribution:

Table 2. Comparison of operation benefits among the four seasons.

		C1	C2	C3	C4	C5
Stage 1	spring	5	4	6	4	3
	summer	1	1	5	7	1
	autumn	3	5	9	9	3
	winter	9	9	1	1	9
State 1	spring	3	5	6	6	3
	summer	1	1	7	7	1
	autumn	5	5	9	9	3
	winter	9	9	1	1	9
Stage 2	spring	1	5	6	7	3
	summer	3	1	7	1	1
	autumn	5	6	9	9	5
	winter	9	9	1	7	9
State 2	spring	3	3	5	0	0
	summer	1	1	5	0	0
	autumn	5	7	9	0	0
	winter	9	9	1	0	0
Stage 3	spring	9	0	5	0	0
	summer	7	0	5	0	0
	autumn	7	0	9	0	0
	winter	1	0	1	0	0

$$\text{Max } J = \frac{b^T W b}{b^T b} \tag{1}$$

where: $b == (b_1, b_2, \ldots, b_6)^T$, a matrix of transpose of B ($B = (b_1, b_2, \ldots, b_6)$).

$$W = \{\Sigma(X_{ij} - \bar{X}_j)(X_i - X_k), (j, k = 1, 2, \ldots, 6)\}_{6x6}$$

$$X_j = 1/n\, \Sigma X_{ij}, (j = 1, 2, \ldots, 6)$$

Table 3. Weight distribution.

Criterion	C1	C2	C3	C4	C5
Distribution bj	0.2408	0.1959	0.1953	0.1522	0.2158

Through matrix calculation (Equation (1)) and further processing, we have weight distribution b_j ($j = 1, 2, \ldots, 6$) shown in Table 3.

Based on Table 2 (matrix {X}) and Table 3 (as matrix {C}), we finally obtain the comprehensive benefit of harvesting operation among the four seasons by matrix calculation:

$$\{E\}_{20X1} = \{X\}_{20X6}\{C\}_{6X1} \tag{2}$$

and the result is shown in Table 4.

2. The Comprehensive Optimal Model for Harvest Operation Planning

Let X_{ij} ($i = 1, 2, 3, 4, 5; j = 1, 2, 3, 4$) be the proportion of operation level of the total amount of production planned for procedure *i* during season *j*. On the basis of Table 4, we can develop the comprehensive optimal model for harvesting operation planning in a linear programming form as follows [2, 4]:

Objective: to maximize the comprehensive benefits of harvesting operations (CBHO in short) over a year,

$$\begin{aligned}\text{Max CBHO} = {} & 6.22\, X_{11} + 4.4156\, X_{12} + 2.9644\, X_{13} + 5.4768\, X_{14} + 6.22\, X_{21} + 4.4343\, X_{22} + 3.085\, X_{23} \\ & + 5.9584\, X_{24} + 7.1332\, X_{31} + 4.1049\, X_{32} + 2.6534\, X_{33} + 6.5859\, X_{34} + + 4.1256\, X_{41} + 2.2866\, X_{42} + \\ & 1.4132\, X_{43} + 4.333\, X_{44} + 0.4361\, X_{51} + 3.1437\, X_{52} + 2.6621\, X_{53} + 3.4433\, X_{54}\end{aligned} \tag{3}$$

Constraints:

(a) Operation level of timber production at each stage must be equal to the total amount of timber production planned by long-term planning:

$$\begin{aligned} X_{11} + X_{12} + X_{13} + X_{14} &= 1 \\ X_{31} + X_{32} + X_{33} + X_{34} &= 1 \\ X_{51} + X_{52} + X_{53} + X_{54} &= 1 \end{aligned} \tag{4}$$

(b) The total amount of wood storage at each state can not exceed the total of timber production for a whole year:

$$\begin{aligned} X_{21} + X_{22} + X_{23} + X_{24} &<= 1 \\ X_{41} + X_{42} + X_{43} + X_{44} &<= 1 \end{aligned} \tag{5}$$

Table 4. Comprehensive benefits of harvesting operations among four seasons.

	Winter	Spring	Summer	Autumn
SG1 cutting & skidding	6.2200	4.4156	2.9644	5.4768
ST1 storage at sites	6.2200	4.4343	3.0850	5.9584
SG2 transport	7.1332	4.1049	2.6534	6.5859
ST2 storage at yard	4.1256	2.2866	1.4132	4.3330
SG3 processing at yard	0.4361	3.1437	2.6621	3.4433

Table 5. Optimal solution without specific constraint (%).

	Winter	Spring	Summer	Autumn
Stage 1	100	0	0	0
State 1	34	33	33	0
Stage 2	67	0	0	33
State 2	67	17	16	0
Stage 3	0	50	0	50

Table 6. Optimal solution under the constraint of unchangeable production capacity at stage 3 (%).

	Winter	Spring	Summer	Autumn
Stage 1	100	0	0	0
State 1	16	16	16	0
Stage 2	84	0	0	16
State 2	42	25	0	0
Stage 3	42	17	25	16

Table 7. Optimal solution under constraints of stage 3 and state 2 (%).

	Winter	Spring	Summer	Autumn
Stage 1	100	0	0	0
State 1	37	37	16	0
Stage 2	63	0	21	16
State 2	21	4	0	0
Stage 3	42	17	25	16

Table 8. Optimal solution under constraints of state 1, state 2, and stage 3 (%).

	Winter	Spring	Summer	Autumn
Stage 1	75	0	22	3
State 1	12	8	13	0
Stage 2	63	4	17	16
State 2	21	8	0	0
Stage 3	42	17	25	16

(c) Dynamic constraints of states for overall system:

$$\begin{aligned}
&X_{11} - X_{21} + X_{24} - X_{31} = 0\\
&X_{31} - X_{41} + X_{44} - X_{51} = 0\\
&X_{12} + X_{21} - X_{22} - X_{32} = 0\\
&X_{13} + X_{22} - X_{23} - X_{33} = 0\\
&X_{14} + X_{23} - X_{24} - X_{34} = 0\\
&X_{32} + X_{41} - X_{42} - X_{52} = 0\\
&X_{33} + X_{42} - X_{43} - X_{53} = 0\\
&X_{34} + X_{43} - X_{44} - X_{54} = 0\\
&X_{24} <= S_1,\ X_{44} <= S_2
\end{aligned} \quad (6)$$

where: S_1 and S_2 are initial values of state 1 and state 2 respectively. According to the harvesting practice in the Heilongjiang Forest Region, assume: $S_1 = S_2 = 0$.

(d) Non-negative constraints:

$$X_{ij} >= 0 \quad (i = 1, 2, 3, 4, 5; j = 1, 2, 3, 4) \quad (7)$$

RESULTS AND DISCUSSION

The constraints for the model above are general for the planning of harvesting operations in Heilongjiang Forest Region. In the case study, some specific constraints, also typical and popular in that region, are considered together. So the results of the model for different constraints are as follows:

(1) Optimal solution without specific constraint of production capacity for each operation, shown in Table 5.

(2) Optimal solution under a specific constraint of unchangeable production rate of stage 3, shown in Table 6.

(3) Optimal solution under constraints of both unchangeable production rate of stage 3 and storage capacity limitation of state 2 (less than 50% of total amount of production during the same season) around a year, shown in Table 7.

(4) Optimal solution under constraints of
  i) unchangeable production rate at stage 3;
  ii) storage capacity limitation (less than 50% of total production during the same season) at state 1;
  iii) storage capacity limitation (less than 50% of total production during the same season) at state 2

is shown in Table 8.

It is clear from the results obtained above that winter (November-March) is the best season for harvesting operations in Heilongjiang Forest Region, especially for the operations in cutting sites. It has been proved by practice that conducting logging operations during winter in that region is very helpful to both economic and environmental considerations. In other words, logging operations during that period result in high operation efficiency, low cost and less damage to forest environments because of the frozen ground. Loggers in that area call the winter period "the golden season for logging". Spring is the worst season for timber transport operations. This conclusion is consistent with the running results of many forest enterprises in that region. During springtime, the bearing capacity and the roughness of both standard roads and non-standard roads are much worse than in the other seasons. By comparison, winter is also the best season for timber transport operations. Wood storage in cutting sites and at yards certainly results in higher total operation costs. But this contributes more to the comprehensive benefits of the overall operation of harvesting. For many forest enterprises in Heilongjiang Forest Region logging operations and most of the timber transportation is done in winter time, and therefore appropriate wood storage will be the most effective measure to improve the comprehensive benefits of harvesting operations.

Based on Figure 2 and the optimal planning for harvesting operations obtained above, we can control the real operations according to the differences of two state dynamic levels between planning and real operations. The objective of control is to decrease the difference to a minimum. The control measures are to adjust the production rate at stage 1, stage 2 and stage 3. The information flow (feedback) also plays an important role in the control of harvesting operations.

The method of comprehensively optimizing operation benefits of harvesting developed in this paper synthesizes the considerations for harvesting operations, such as cost, efficiency, ratio of resources input to product output, working safety, damage to the residual stands, and damage to soil. Although this attempt might not completely be correct, we are sure it is a step in the right direction. More than30 experts engaged in forest harvesting, ergonomics, silviculture, and forest ecology were requested to evaluate and comment on the final results and conclusion of the case study. Most of them think the results are scientific, reliable, and applicable in this forest region.

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