Multi Period Operational Planning in Woody Biomass System

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Abstract

Strategic decisions of such systems have been previously studied by the authors. In this work, we present the operational planning decisions of such systems. In particular, we consider an integrated multi-period problem of woody biomass operations in a three echelon supply chain system, which includes many geographically dispersed harvesting sites, several pretreatment facilities, and the power plant. The objective of the operational planning model is to compute an optimal assignment of harvesting teams at the beginning of each period and an optimal allocation of biomass flows so that the total cost of harvesting, transportation, preprocessing, storage, and conversion over a finite planning horizon is minimized. The constraints include restrictions on supply at each harvesting site, capacity constraints at pretreatment and storage facilities, flow balance between sites and facilities, and demand satisfaction at the power plant. Other considerations affecting operations such as forest regeneration, cutting cycle, and biomass degradation during storage are also modeled. We propose a dynamic programming model to address the described problem and present a decomposition approach to solve it. A case study shows that our approach can be efficiently used in the woody biomass system.

Keywords
renewable energy, woody biomass, logistics, GIS

1. Introduction

Recent trends in the United States show increasing interest in renewable energy, which provides a variety of benefits for the environment, economy, and energy security. Woody biomass as one of the renewable energy sources has no technology barrier, contains one of the highest energy content (25 million BTUs per ton) of all biomass sources [1], and has an extensive amount of supply in the U.S. However, cost efficiency, sustainability, and uncertainties of the woody biomass-based energy logistics system are largely responsible for impeding the utilization of woody biomass. Integration is the key to solve these problems. Yet, to the best of our knowledge, the integration of woody biomass-based energy logistics system with considerations of sustainability and uncertainties has not been widely studied.

In order to ensure the constant supply from the forest and produce woody biomass-based energy in a sustainable manner while conserving the availability and quality of the resources in forests, the logistics system must be designed to have minimum impact on the environment and have potential for forest health and yield improvement. There are several criteria and indicators for forest sustainability, including biological diversity, growing stock, soil and water quality, etc. One important factor that affects forest sustainability is the cutting cycle, which is the time required between two consecutive harvesting operations in the same forest.

Uncertainties play an important role in the design of biomass-based energy logistics system because they exist in almost every echelon of the system from beginning to end. For example, the yield of biomass, delay in transportation due to congestion, and variation in demand.

Therefore, the design of a cost-efficient woody biomass-based energy logistics system, with the environmentally sustainable production and uncertainties considered, demands integration and coordination.

2. Related Literature

The design of a woody biomass based energy logistics system include two major decisions: long-term strategic decision and short-term operational decision. In [2] a model was proposed for the optimal location of lignocellulosic ethanol refineries integrated with a powerplant. A mixed integer linear programming model was implemented in [3]
to determine the best locations and capacities of the biorefinery in a biofuel supply chain. In [4] a mixed integer linear programming model for strategic decisions such as locations and scales of biorefineries and modes of transportation was develop. A mixed integer linear programming model in [5] was applied to determine the operational decisions of the production, harvest, storage and transportation of lignocellulosic biomass. A generic mixed integer model was proposed in [6] that coordinates both strategic decisions and operational decisions. In [7] Cundiff characterized the weather-affected supply uncertainty by assigning probabilities to four possible scenarios, each of which is a combination of good/poor weather conditions. A dynamic programming model was given in [8] to find the lowest cost from harvest to end use in a agricultural supply chain. Several uncertainties through the process of biofuel supply chain were considered in [9] including biomass availability, acquisition cost, yield of intermediate/final product, maximum demands, and sale price.

3. Geo-database Preparation
Geographic information system (GIS) is introduced into the decision support system for woody biomass-based energy logistics, because it provides more accuracy in computing distances and configuring the spatial network for the logistics system. Geographical objects (such as harvesting sites, pretreatment facilities and power plants), attributes (such as availability of biomass, capacity of pretreatment facilities and feasibility of facility locations), and methods (such as spatial analysis and network analysis) can be created, stored, retrieved, updated, and presented in GIS easily. This was done in our previous paper.

4. Problem Statement
With geo-database prepared, the next step is to make decisions on the operational level consisting of sequential operations in the biomass energy supply chain process from woody biomass harvesting to energy conversion. In this section, attention is focused on the operational planning with the assumptions that locations of processing facilities are known. Since most of the parameters and decisions in operational problems are time dependent the modeling of the operational planning problem needs to capture the characteristics in the temporal dimension where system transition issue is considered.

To do this we consider an integrated multi-period problem of different woody biomass operations in a three-echelon supply chain system in this section. The higher echelon consists of many geographically dispersed harvesting sites, each of which has different amount of available supplies in different time. The intermediate echelon includes several pretreatment facilities, where woody biomass is preprocessed and stored. The lower echelon is the power plant, which has specific demands in different periods. This is shown in Figure 1.

The objective of the operational planning model is to compute 1) an optimal assignment plan of harvesting teams at the beginning of each period, and 2) an optimal allocation of biomass flows between levels to minimize cost. The constraints we consider include restrictions on supply at each harvesting site, capacity constraints at pretreatment and storage facilities, flow balance between sites and facilities, demand satisfaction at the power plant, etc. Other considerations affecting the operations such as forest regeneration, cutting cycle and biomass degradation during storage are also included.

5. Linear Mixed Integer Programming Model
In this section, we develop a linear mixed integer programming model.

5.1 Decision Variable
Let $u^t_{ij}$ denote the amount of harvested woody biomass transported from harvesting site $i$ to preprocessing facility $j$ during period $t$, $v^t_j$ the amount of biomass to transport from preprocessing facility $j$ to power plant during period $t$. In addition, let decision variable $w^{kj}_{ij}$ indicate the locations of harvesting teams. $w^{kj}_{ij}$ indicates the movement of a harvesting team from one forest to another at the end of each period. Specifically, we define

$$w_{ij}^{kj} = \begin{cases} 1, & \text{if team } k \text{ moves from forest } i \text{ to forest } j \text{ at the end of period } t; \\ 0, & \text{otherwise}. \end{cases} \tag{1}$$

These decision variables can also be written in matrix forms such as $U = \{u^t_{ij}\}$, $V = \{v^t_j\}$ and $W = \{w^{kj}_{ij}\}$.
5.2 Model Formulation

The complete mixed integer linear programming model is described as follows:

\[
\begin{align*}
\min_{U,V,W} & \sum_{t=1}^{T} \left( \sum_{j=1}^{I} c_j \left( \sum_{k=1}^{K} \sum_{i=1}^{I} w_{ij}^k \right) + \sum_{j=1}^{J} c_j y_j + \sum_{j=1}^{J} \sum_{i=1}^{I} c_{ij} u_{ij} + \sum_{j=1}^{J} \left( \beta c_j + c_j^f \right) v_j \right) \\
& + \sum_{k=1}^{K} \sum_{i=1}^{I} d_{ij} \omega_{ij}^k \\
\text{s.t.} & \quad x_i^t = \begin{cases} 
0, & \text{if } t = 1 \\
\tau \sum_{k=1}^{K} \sum_{j=1}^{J} w_{ij}^k - \sum_{i'=3}^{t} \sum_{k=1}^{K} \sum_{j=1}^{J} w_{ij}^{k(t'-2)}, & \text{if } 3 \leq t \leq \tau + 2 \\
\sum_{i=1}^{I} \alpha^{t-1} \left( \sum_{l=1}^{L} u_{ij}^l - y_j^t \right), & \text{if } t > \tau + 2 
\end{cases} \\
& \quad y_j^t = \begin{cases} 
0, & \text{if } t = 1 \\
\sum_{t'=1}^{t-1} \alpha^{t'-t} \left( \sum_{l=1}^{L} u_{ij}^l - v_j^t \right), & \text{if } 2 \leq t \leq T 
\end{cases} \\
& \quad 0 \leq y_j^t \leq B_j \\
& \quad \sum_{j=1}^{J} u_{ij}^t \leq Q_j \sum_{k=1}^{K} \sum_{i=1}^{I} w_{ij}^k \\
& \quad \sum_{j=1}^{J} v_j^t \geq D_j \\
& \quad x_i^t / M \leq 1 - \sum_{k=1}^{K} \sum_{i=1}^{I} w_{ij}^k \\
& \quad \sum_{j=1}^{J} w_{ij}^k = \sum_{j=1}^{J} w_{ji}^{k(t-1)} \\
& \quad \sum_{i=1}^{I} w_{ij}^k = 1 \\
& \quad \sum_{k=1}^{K} \sum_{j=1}^{J} w_{ij}^k \leq 1
\end{align*}
\]

5. Biomass-based energy supply chain

Figure 1: Biomass-based energy supply chain

Yu, Klein, Jang
The objective function minimizes the total cost of the logistics system over the planning horizon. Period 1 denotes the initial period of the planning horizon, and period \( T \) denotes the last period. We assume that all forest are available and there is no inventory at the beginning of the planning horizon. Therefore, \( X^1 = 0, Y^1 = 0 \), and the initial locations of harvesting teams are assumed to be known. The first term in (2) shows the harvest cost for all teams to harvest at their current locations during period \( t \). The second term denotes the storage cost at all preprocessing facilities. The third term is the cost of transporting biomass from forest to preprocessing facilities. The fourth term denotes the transportation and pretreatment cost for the biomass moving from preprocessing facilities to power plant. The last term is the reallocation cost of all harvesting teams. The first equation in (3) shows that all forests are available at the beginning of the first period. The second equation means that the forest which were harvested in the first period will need \( \tau \) periods to reenter at the beginning of the second period. The third and fourth equations represent all the possible states of a single forest \( i \) when period \( 3 \leq t \leq \tau + 2 \) and \( t > \tau + 2 \), respectively. Constraint (5) denotes that storage level cannot exceeds the capacity constraint for each processing facility. Constraint (6) shows the total amount of outbound biomass equals the maximum amount of available woody biomass harvested at each forest. Constraint (7) makes sure that the demand at power plant is satisfied by the total inbound biomass transported from preprocessing facilities at each period. Constraint (8) ensures that harvesting teams can only harvest forest that are available at current period. Constraint (9) makes sure that harvesting team can move out of forest \( i \) at current period if and only if it moved into forest \( i \) in the previous period. Constraint (10) ensures that each harvesting team can only move once at each period. Constraint (11) ensures that each forest can only be harvested by one harvesting team at most in one period.

6. Solution Approach

Because of the complexity of the model, we decompose the problem into two sub-problems: the first one determines the harvesting locations and material flows in each period; and the second one finds the best route for each harvesting team based on the harvesting locations selected in the first step. By decomposing the original problem into two sub-problems, the number of binary variables and potential solutions decrease in each sub-problem, which reduces the computational complexity significantly.

We developed two different models: a location and allocation model that solves the first sub-problem; and a routing model that solves the second sub-problem. The location and allocation model with emphasis on where the harvesting team would be in each period does not consider the actual routes of harvesting teams. The goal of the location and allocation model is to determine the optimal harvesting locations and material flows in each period so that the total logistics cost, including harvesting, transporting, storing, and preprocessing cost of woody biomass is minimized. With harvesting locations selected in the location and allocation model, the routes of harvesting team can be easily determined in the routing model. The goal of the routing model is to find the optimal route for each harvesting team so that the total reallocation cost of harvesting teams is minimized.

6.1 Location and Allocation Model

In order to determine the harvesting locations in each period, we introduce a new binary variable \( z'_i \) to denote whether forest \( i \) is harvested in period \( t \). Specifically,

\[
z'_i = \begin{cases} 
1, & \text{if forest } i \text{ is harvested in period } t; \\
0, & \text{otherwise}. 
\end{cases}
\]
Other decision variables such as material flows $U$ and $V$ and parameters are defined the same as in the model above. The location and allocation model can be formulated as follows:

$$
\min_{(U,V,Z)} \sum_{t=1}^{T} \left( \sum_{i=1}^{I} c_i^t x_i^t + \sum_{j=1}^{J} c_j^t y_j^t + \sum_{i=1}^{I} \sum_{j=1}^{J} c_{ij} u_{ij}^t + \sum_{j=1}^{J} c_j^t v_j^t + \sum_{j=1}^{J} \beta c_j^t v_j^t \right)
$$

$$
+ \frac{1}{K} \sum_{t=1}^{T-1} \sum_{i=1}^{I} \sum_{j=1}^{J} d_{ij} c_i^{t+1} c_j^t
$$

s.t.\( \forall 1 \leq t \leq T \)

$$
\sum_{i=1}^{I} u_{ij}^t \leq U_i^t, \quad \forall 1 \leq i \leq I
$$

$$
\sum_{j=1}^{J} v_j^t \geq Z_t, \quad \forall 1 \leq t \leq T
$$

$$
\gamma_i = \begin{cases} 0, & \text{if } t = 1 \\ x_{i-1}^t + x_{i-1}^t - \sum_{t=3}^{t-1} x_{i-1}^t - \sum_{t=1}^{t-1} x_{i-1}^t, & \text{if } 3 \leq t \leq \tau + 2 \\ x_{i-1}^t - \sum_{t=1}^{t-1} x_{i-1}^t, & \text{if } t > \tau + 2 \\ \end{cases}
$$

$$
\gamma_j = \begin{cases} 0, & \text{if } t = 1 \\ \sum_{i=1}^{I} c_i^t u_{ij}^t - v_j^t, & \text{if } 2 \leq t \leq T \\ \end{cases}
$$

$$
0 \leq y_j^t \leq B_j, \quad \forall 1 \leq j \leq J
$$

$$
\frac{\sum_{j=1}^{J} u_{ij}^t}{M} \leq 1 - \frac{z_i^t}{Z}, \quad \forall 1 \leq i \leq I, \ M \text{ is a large number}
$$

$$
\sum_{i=1}^{I} c_i^t = K.
$$

The objective function (13) consists of two types of costs: logistics cost, including harvesting cost, transportation cost of woody biomass, and storage cost; and an estimation of the transportation cost of harvesting teams. Specifically in period $t$, $\sum_{i=1}^{I} c_i^t x_i^t$ denotes the total harvesting cost, $\sum_{j=1}^{J} c_j^t y_j^t$ denotes the total storage cost, $\sum_{i=1}^{I} \sum_{j=1}^{J} c_{ij} u_{ij}^t$ denotes the transportation cost of moving woody biomass from forests to pretreatment facilities, $\sum_{j=1}^{J} c_j^t v_j^t$ denotes the preprocessing cost in all pretreatment facilities, $\sum_{j=1}^{J} \beta c_j^t v_j^t$ denotes the cost of transporting pretreated woody biomass from pretreatment facilities to the power plant. The last term in objective function estimates the reallocation cost of harvesting teams without finding the actual route for each harvesting team. $\sum_{j=1}^{J} \sum_{t=1}^{T} d_{ij} c_i^{t+1} c_j^t$ denotes the total reallocation cost of all potential routes between harvesting locations in period $t$ and harvesting locations in period $t + 1$. Since the number of harvesting locations is exactly the same as the number of harvesting teams $K$, each harvesting team can move to $K$ different harvesting locations at the end of each period. Therefore, $\frac{1}{T} \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} d_{ij} c_i^{t+1} c_j^t$ can be viewed as the “average” reallocation cost of all harvesting teams between periods.

Since the reallocation cost of harvesting teams varies depending on several different factors such as equipment type (self propelled or not; oversized or overweighted or not), gas price, transport truck MPG (miles per gallon), transportation distance, highway permit fee, flag/pilot vehicle cost and labor cost, the cost of reallocating harvesting teams may account for a large or small fraction of the total cost of the logistics system. If the reallocation cost of harvesting teams is relatively high, harvesting teams would prefer to move to closer forests even though other logistics cost such as transportation cost could be higher. On the contrary, if the reallocation cost of harvesting teams is relatively low, harvesting teams might prefer to move to forests that incur lower logistics cost regardless of the distance of the reallocation.
The result of the routing model, the original model (2), is determined, i.e., the harvesting locations are selected in each period, the next step is to assign each selected location to a harvesting team in each period. Connecting all the locations assigned to the same harvesting team in chronological order completes the route of that team. The routing model can be formulated as follows:

\[ \min_W \sum_{i=1}^{T-1} \sum_{k=1}^{K} \sum_{j=1}^{I} \sum_{l=1}^{L} w_{ij}^k d_{lj} w_{ij}^k \]  
\[ \text{s.t.} \forall 1 \leq t \leq T-1 \]
\[ w_{ij}^k = z_{i,j}^{k+1} \]
\[ \sum_{j=1}^{I} w_{ij}^k = \sum_{j'=1}^{I} w_{ij'}^k \quad \forall 1 \leq k \leq K, 1 \leq i \leq I \]
\[ \sum_{i=1}^{I} \sum_{j=1}^{I} w_{ij}^k = 1 \quad \forall 1 \leq k \leq K \]
\[ \sum_{k=1}^{K} \sum_{l=1}^{L} w_{ij}^k = z_{i}^j \quad \forall 1 \leq i \leq I, \]

where \( w_{ij}^k \) is defined the same as (1).

The objective function (21) minimizes the total reallocation cost of harvesting teams. Constraint (22) ensures that harvesting teams can only move between consecutively selected harvesting locations. Constraint (23) is the flow conservation equation that makes sure harvesting team \( k \) can move out of forest \( i \) at period \( t \) if and only if it moved into forest \( i \) in the previous period. Constraint (24) confirms that each harvesting team can only move to one forest at the end of each period. Constraint (25) guarantees that each selected location can only be harvested by one harvesting team.

The result of the routing model, \( W \), as well as the result of the location and allocation model, \( U \) and \( V \), solve the original model (2).
7. Case Study
A case study is presented in this section to demonstrate the types of analysis our operational model will support. We consider the same case in Boone County where a new biomass boiler was installed at the University of Missouri power plant. The new woody biomass boiler needs up to 100,000 tons of wood chips per year and 10% of these will come from the forest residues of logged trees and thinning projects. The total amount of available woody biomass in Boone County is estimated to be 17,508 dry tons per year by using the estimation method in Woody Biomass Technology Demonstration Project [10] and the data from the Forest Inventory and Analysis National Program, USDA Forest Service. The locations of the two pretreatment facilities are assumed to be fixed and known. The fixed cost of transporting logging residues is $6.96 per ton, and the incremental cost is $0.14 per ton-mile given by [11]. In our case where the supply radius is 50 miles, the transportation cost including fixed and variable cost is estimated as $0.42 per ton-mile.

The amount of available biomass at each 1-mile² pixel ranges from 100 to 200 dry tons. Because a small harvesting team with a three-person crew can harvest approximately 200 dry tons of woody biomass per week [12]-[14], we assume that a 1-mile² pixel can be harvested within one week. Therefore, the duration of a planning period is set to be one week and the planning horizon is set to 40 weeks so that the 10,000-ton yearly demand at MU power plant can be met.

The capacity of the pretreatment facility is assumed to be 200 tons per week. All preprocessing facilities have the same processing cost and storage cost. The storage cost at each preprocessing facility is estimated as $6.75/ton per month.

The loss of dry matter is an important concern during the storage of woody biomass. The rate of deterioration depends on several factors, such as particle size of woody biomass, moisture content, air flow, compaction, and storage time. The total dry matter loss in bark or bark piles is approximately 20~26% in 6 months [15], while nearly 19% of dry matter in whole tree chips is lost in 6 months [16]. In this case study, since wood chips are the product of preprocessing, we use [16]'s result and set the degradation ratio as 99.2%, i.e., 0.8% of dry matter is lost during storage each week, so that \( (0.992)^{26} = 0.81 \).

The cutting cycle varies depending on the type of trees in the forest. Several types of trees have a flexible cutting cycle. For example, silver maple, black locust, cottonwood, and honey locust can have a 1-year, 2-year or 5-year cutting cycle [17]. Shorter cutting cycles could lead to higher tree growth rate but may increase the possibility for degrading stand quality through stem damage, root damage, and soil compaction, while longer cutting cycle could increase tree quality and reduce such damages [18]. In our case, the cutting cycle is assumed to be one year or 52 weeks. Since the planning horizon is one year, the cutting cycle only prevents the reentry of harvesting teams in this study. However, the cutting cycle could affect the harvesting decisions significantly in the long run.

7.1 Seasonality in Demand at Power Plant
We consider the seasonal change in the demand of woody biomass. The seasonal demand of woody biomass is estimated upon the data of electricity generation at the power plant. We assume that the monthly demand of woody biomass needed is proportional to the amount of electricity generated each month at the MU power plant. We also assume that the weekly demand of woody biomass does not vary within the same month.

7.2 Scenario Analysis of Different Harvesting Teams
The productivity of harvesting teams varies from 150 green tons per week to 2000 green tons per week, depending on the type of harvesting equipment and the number of personnel. Based on operational guidelines provided by [12], a team that includes a five-person crew with one feller-buncher, one grapple skidder, one loader and two trucks is estimated to harvest 75 dry tons per day. A smaller harvesting team that has a three-person crew including one chainsaw operator, one grapple skidder and one loader may produce 50 dry tons per day. The labor cost of a chainsaw operator is about $50 per day, while the cost increases to $125 per day for a feller-buncher operator.

Two scenarios are created to evaluate the performance of different harvesting teams with different harvesting systems. The first scenario considers two low-cost low-productivity teams, while the other considers one high-cost high-productivity team. In the first scenario, each team has a three-person crew and is equipped with a chainsaw harvesting system. The productivity is assumed to be 250 tons/week, which means the harvesting team can harvest one pixel each week. In the second scenario, the harvesting team has a three-person crew and is equipped with a feller-buncher harvesting system. The productivity is assumed to be 400 tons/week. The high-productivity team is assumed to be
Harvesting team

Harvesting Cost
Reallocation Cost
250 tons/week $3,775/week $7/mile + permit
400 tons/week $6,075/week $10.5/mile + permit

251,454 $203,560 $4,497
Harvesting team

250 tons/week $3,775/week $7/mile + permit
400 tons/week $6,075/week $10.5/mile + permit

125 and $3,775

Table 2: Differences in harvesting and reallocation cost

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Harvesting team</th>
<th>Total Cost</th>
<th>Harvesting Cost</th>
<th>Reallocation Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 persons with chainsaw</td>
<td>$577,778</td>
<td>$252,470</td>
<td>$3,457</td>
</tr>
<tr>
<td>2</td>
<td>3 persons with feller-buncher</td>
<td>$521,454</td>
<td>$203,560</td>
<td>$4,497</td>
</tr>
</tbody>
</table>

Table 2 shows that the harvesting cost of the chainsaw harvesting system is approximately 25% higher than the feller-buncher harvesting system, while the harvesting cost of feller-buncher harvesting system is approximately 33% higher than the chainsaw harvesting system. The feller-buncher harvesting system incurs relatively less harvesting cost, because its unit harvesting cost is $6,075 per week or nearly $3,038 per pixel, compared to $3,775 per pixel of the chainsaw harvesting system. However, since the harvesting cost accounts for almost half of the total cost in both systems, the total cost of the feller-buncher harvesting system is less than the chainsaw harvesting system.

7.3 Results and Analysis

Since most of the forests harvested in both scenarios are the same there is no significant difference in transportation cost, pretreatment cost or storage cost between these two harvesting systems. Table 2 compares the major differences in total harvesting cost and total reallocation cost between these two harvesting systems.

<table>
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<tr>
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8. Conclusions

In this paper, we consider the multi-period operational decision making problem of the woody biomass-based energy logistics system, where seasonality in supply and demand, cutting cycle, and biomass deterioration are considered. With components in the woody biomass-based energy logistics network determined in a previous strategic model, the objective of the operational model is to find the optimal assignment plan of harvesting teams and the optimal allocation of material flows between levels so that the total operational cost of harvesting, transportation, preprocessing, storage, and conversion over a finite planning horizon is minimized. A mixed integer linear programming model is developed for the problem. This is of course difficult to solve optimally in a reasonable amount of time, because the size of the potential solutions grows exponentially. In order to deal with this we decomposed the model into two interrelated sub-models, each of which makes partial decisions of the whole problem. The first location-allocation model determines the material flows between levels as well as the locations of harvesting sites. The second routing model determines the reallocation of harvesting teams between periods based on the harvesting locations selected in the location-allocation model. The decomposition process decreases the size of the potential solutions, thereby makes the problem solvable.

Two case studies with different harvesting systems are conducted to illustrate the performance of the solution approach. The structure of the logistics network is based on the result of previous analysis in Boone County, Missouri. The results show that high-productivity harvesting system could be more cost efficient than low-productivity system in small areas where reallocation cost does not weigh much in the total cost. In addition, the results also indicate that factors

Yu, Klein, Jang
such as geographical distribution of forests, measures of distance, and structure of transportation network affect the reallocation of harvesting teams. GIS was implemented to improve the accuracy of the case study. A real transportation network was created so that road-network distance can be calculated. GIS also provides explicit routes on the real road network with detailed directions.

References


