An approach to the scheduling of wood harvesting machines

A Shabaev¹, A Sokolov², A Urban¹, D Pyatin¹

¹ Engineering Center, Petrozavodsk State University, 33 Lenin Avenue, Petrozavodsk 185910, Russian Federation
² Institute of Forestry Mining and Construction Sciences, Petrozavodsk State University, 33 Lenin Avenue, Petrozavodsk 185910, Russian Federation

*Corresponding email: a_sokolov@petrsu.ru

Abstract: An approach to the scheduling of wood harvesting machines is described in the paper. A multicriteria mathematical model with a large number of technical and technological constraints is presented. It is shown that the original problem of wood harvesting machines scheduling is reduced to a generalized traveling salesman problem. An algorithm for solving the problem based on a meta-heuristic algorithm of simulated annealing has been developed. The algorithm was used in decision support system for wood harvesting planning and management “Opti-Wood”, developed by Opti-Soft company. The algorithm was numerically tested on several dozens of harvesting plans for a given road network in southern Karelia. A comparative analysis showed that the version with territorial clustering is more preferable, and can be used as a qualitative approximation for obtaining the initial state in this and other metaheuristic methods.

1. Introduction

The active use of computerized production planning systems based on mathematical modeling and operations research, along with geographical information systems (GIS) [1, 2], is considered the most effective way to improve the efficiency of production and equipment use in the forest complex. The use of such systems can reduce production costs by optimizing production schedules [3, 4].

This article presents a solution of the problem of wood harvesting machines scheduling with a large number of technical and technological constraints. A mathematical model of the problem is developed. The initial problem is reduced to a generalized traveling salesman problem and the solution method based on meta-heuristic simulated annealing algorithm is proposed.

The planning of wood harvesting operations includes several subtasks: selection of harvesting sites for use in the planning period, allocation of wood harvesting machines over the sites and sequencing of the sites harvesting within the planning period, and setting the harvesting dates for each of them.

This article describes only the tasks of wood harvesting machines allocation and sequencing the harvesting sites. It is assumed that the initial list of sites for harvesting within the planned period is known, and volumes of all types of products at each site are assigned to specific customer orders. This task belongs to the job-shop class [5].

The task is to determine such a minimum number of wood harvesting machinery set such allocation of machinery sets over the harvesting sites and such sequence of sites for each machinery set, the implementation of which provides:
Minimal overall costs, including:
- machinery set relocating costs, depending on the total distance between harvesting sites;
- costs of logging and transporting operations according to current tariffs;
- additional transportation costs (transportation of staff, fuel, spare parts, etc.), depending on the distance between the current harvesting site and the garage.

The following requirements:
- all defined harvesting sites must be harvested;
- only one machinery set can be assigned to a harvesting site;
- each harvesting operation is among permitted operations for the machinery set;
- obligatory sites for the machinery set (if available) should be included in its work plan;
- sites are harvested sequentially: the starting date for the next site follows the ending date on the previous one, taking into account machinery set relocation;
- the maximum allowable harvested volume for each type of harvesting operation, specified for each machinery set, is not exceeded;
- harvesting on a site is carried out only during specified availability periods and not earlier than allowable starting date on the condition of minimum logging cycle duration;
- the harvesting start date on the site cannot be earlier than the end date of the corresponding road clearing preparation plus the required road construction period;
- the required volume for each consumer’s order must be harvested before the end of the required delivery period for this order.

2. Methods and Materials
The solution of the problem is based on the developed mathematical model. The following notation will be used in this model:

Index sets:
- $D$ – set of harvesting sites, $d \in D$;
- $G \subseteq D$ – set of road clearings;
- $A(g) \subseteq D$ – set of harvesting sites, adjacent to the road clearing $g \in G$;
- $H$ – set of harvesting machinery sets, $h \in H$;
- $F$ – set of harvesting operations, $f \in F$;
- $S$ – set of supply orders $s \in S$;
- $F_s \subseteq F$ – set of permitted harvesting operations for the machinery set $h \in H$;
- $D_h \subseteq D$ – set of harvesting sites with the harvesting operation $f, f \in F$;
- $D_h \subseteq D$ – set of obligatory harvesting sites for the machinery set $h \in H$;
- $T = [t^1, t^2]$ – discrete planning period by dates, where $t^1$ – planning start date, $t^2$ – planning end date.

Harvesting machinery set parameters:
- $r_h$ – rating of the machinery set $h \in H$;
- $p_h$ – average productivity of the machinery set $h$ (cub. m./h.), $h \in H$;
- $t_h^r$ – average relocation time for machinery set $h \in H$ (days);
- $t_h^s$ – work starting date for the machinery set $h \in H$ within the planning period, provided that the machinery set is operating in the current site. If the current site is not specified, then the work starting date for machinery set is the planning start date;
- $V_{hs}$ – the maximum allowable harvesting volume for machinery set $h \in H$ for the type of harvesting operation $f, f \in F$;
- $c_h$ – shift change penalty for the machinery set $h \in H$.

Harvesting site parameters:
- $v_d$ – total harvesting volume for the site $d \in D$;
- $f_d$ – type of harvesting operation for the site $d \in D, f_d \in F$.
\[ t_d^D \] – the earliest possible date of the harvesting start on the condition of minimum logging cycle duration for the site \( d \in D \);  
\[ t_s^g \] – time period for the road construction \( g \in G \) (days);  
\( I_d \) – periods of operation interruption for the site \( d \in D \);  
\( k_d \) – productivity adjustment factor for the site \( d \in D \);  
\( c_d \) – costs of logging and transporting operations according to current tariffs for the site \( d \in D \) (rub/cub. m.).

**Consumer’s order parameter:**
Allowable delivery period for the order \( s \in S \):

\[
T_s = [t_s^1, t_s^2]
\]  

(1)

**Calculated parameters and functions:**

\( t_{h,d} \) – duration of harvesting operation on the site \( d \in D \) taking into account the working hours of the machinery set \( h \in H \) and taking into account the productivity adjustment factor,

\[
t_{h,d} = \frac{v_{d,s}}{p_h \cdot k_d}
\]  

(2)

where, \( t_{d,g}(t_1, t_2) \) – the minimum relocation time between sites \( d \) and \( g \) within the time period \([t_1, t_2]\) taking into account the road network restrictions, \( d, g \in D \); \( t_{h,d}(t_1, t_2) \) – the minimum driving time of the machinery set \( h \in H \) from the garage to site \( d \in D \) within the time period \([t_1, t_2]\) taking into account the road network restrictions; \( v_{d,s} \) – the timber volume to be delivered from site \( d \in D \) to the consumer according to order \( s \in S \); \( t_{h,d}(i) \) – calculated date of production completion according to the order \( s \in S \) to provide the volume \( v_{d,s} \) on the site \( d \in D \), if the harvesting on the site is started at the time \( i \) taking into account the given number of working days per week and working hours per day for machinery set \( h \in H \).

**Unknown factors:**

\( U \subset H \) – subset of machinery sets to be used;

\( n_h \) – number of harvesting sites associated with the machinery set \( h \in U \);

\( S_h \) – ordered set of triples:

\[
S_h = [s_{h,i}] = [(d_{h_{1,i}}, t_{h_{1,i}}^1, t_{h_{1,i}}^2), \ldots, (d_{h_{n_h,i}}, t_{h_{n_h,i}}^1, t_{h_{n_h,i}}^2)] \quad i \in [1..n_h] \quad h \in U
\]  

(3)

where, \( d_{h,i} \in D \); \( t_{h,i}^1 \) – operation start date for the machinery set \( h \) at the site \( d_{h,i} \); \( t_{h,i}^2 \) – operation end date for the machinery set \( h \) at the site \( d_{h,i} \).

The order of elements in \( S_h \) is determined by the harvesting sites sequence in the harvesting plan of the machinery set \( h \), so the whole set \( S_h \) defines the schedule for the machinery set \( h \in U \).

Optimization model is determined by expressions (4-18):

\[
|U| \rightarrow \min
\]  

(4)

– minimizing of the number of used machinery sets. \( U \) must be chosen in such a way that harvesting operations are assigned primarily to machine sets with higher ratings.

Sort the machinery sets by rating and introduce an auxiliary mapping:

\[
R : r_i \rightarrow 2^i
\]  

(5)

This mapping allows to determine the following objective function for searching the most highly-rated set of machines:
\[ \sum_{i \in \mathcal{D}} R(r_i) \rightarrow \max, \]  

where, the following condition is true for the mapping:

\[ \sum_{i < j} R(r_i) < R(r_j), \quad i, j \in U \]  

- taking into account the most highly-rated machinery sets.

\[ \sum_{d \in \mathcal{D}_d, i \in \mathcal{N}_i} f_{d,i} \left( t_{h,i}^2, t_{h,i+1}^2 \right) + \sum_{d \in \mathcal{D}_d, i \in \mathcal{N}_i} c_{f,h,i} \left( t_{h,i}^1, t_{h,i+1}^1 \right) + \sum_{d \in \mathcal{D}_d, i \in \mathcal{N}_i} c_{v,d} v_d \rightarrow \min \]  

- minimizing the costs of logging and transporting operations according to current tariffs, machinery set relocating costs and additional transportation costs. For the specified optimization criteria, the “priority criteria” scheme is used. [7].

Assuming \( \mathcal{X}_h = \{d_{h,i}\}, i \in [1..n_h] \), be a set of harvesting sites from the schedule \( S_h \) of the machinery set \( h \in U \), we can write the problem constraints as follows:

\[ \bigcup_{h \in \mathcal{D}_h} \mathcal{X}_h = \mathcal{D} \]  

- all defined harvesting sites must be harvested within the planning period.

\[ \bigcap_{h \in \mathcal{D}_h} \mathcal{X}_h = \emptyset \]  

- only one machinery set can be assigned to a harvesting site.

\[ f_d \in \mathcal{F}_h, \quad d = d_{h,i}, \quad i \in [1..n_h], \quad h \in U \]  

- the specific harvesting operation performed on the site should be permitted for the machinery set.

\[ \sum_{d \in \mathcal{X}_h \cap \mathcal{D}_f} v_d \leq V_{h,f}, \quad \forall f \in \mathcal{F}_h, \forall h \in U \]  

- the maximum allowable harvested volume for each type of harvesting operation specified for machinery set should not be exceeded.

\[ \mathcal{D}_h \subset \mathcal{X}_h, \forall h \in U \]  

- obligatory sites for the machinery set should be included in its work plan.

\[ t_{h,1}^1 = \max \left( t_{h,1}^2 + t_{h,1}^\alpha, t_h^0 \right) \]

\[ t_{h,1}^1 = \max \left( t_{h,1-1}^2 + t_h^\alpha, t_h^0 \right) \]

\[ d = d_{h,i}, \quad i \in [1..n_h], \quad h \in U \]  

- constraints on the harvesting operations start date for the ordinary site.

\[ t_{h,1}^1 = \max \left( t_{h,1}^2 + t_h^\alpha, t_{h,j}^2, t_{h,j+1}^2 + t_j^0 \right) \]

\[ t_{h,1}^1 = \max \left( t_{h,1-1}^2 + t_h^\alpha, t_{h,j}^2, t_{h,j+1}^2 + t_j^0 \right) \]

\[ d = A(g), \quad g = d_{h,i}, \quad d = d_{h,i}, \quad i \in [1..n_h], j \in [1..n_h], \quad g, h \in U \]  

- constraints on the harvesting operations start date for the site, adjacent to the road clearing.
\[ t^2_{h,i} = t^1_{h,i} + t_{h,d}, d = d_{h,i}, i \in [1..n_h], h \in U \]  

– constraint on the harvesting operations end date.

\[ [t^1_{h,i}, t^2_{h,i}] \cap I_d = \emptyset, d = d_{h,i}, i \in [1..n_h], h \in U \]  

– prohibition of harvesting during the operation interruption periods for the sites.

\[ t_{h,d,s}, t^2_{h,d} \leq t^1_{s}, d = d_{h,i}, i \in [1..n_h], d_{h,i} \in D, s \in S, h \in U \]  

– constraints on the allowable delivery periods for the orders.

The mathematical model (4-18) is a version of the generalized Multiple Traveling Salesman Problem (mTSP), which defines the vertex-non-intersecting set of Hamiltonian path. The problem is significantly complicated by multi-criteria objective function, a large number of constraints and large-dimension of input data.

Under the conditions of a real production process, the number of harvesting sites can reach 1000, and the number of forest machinery sets can be up to 20. Thus, the total number of variants for the machinery sets allocation is 20^{1000}, which prohibits the use of brute-force search.

This generalization of the traveling salesman problem is reduced to the well-known ordinary traveling salesman problem and, accordingly, belongs to the NP-hard class. Therefore, there are no exact effective polynomial algorithms for solving it.

One of the most common ways to solve the mTSP are heuristic and metaheuristic methods, including well-proven in practice algorithm of simulated annealing and genetic algorithms (GA) [8-10].

2.1. Algorithms

Investigating the possibilities of these metaheuristic methods for solving the described problem, the authors found that in practice the genetic algorithm works slightly worse than the simulated annealing algorithm, mainly because the gene structure does not allow a good enough implementation of the crossing operation – the basis of a successful state change in the genetic algorithm. Therefore, the simulated annealing algorithm was chosen for the numerical solution of the problem.

The algorithm was first introduced in article [11] and is currently used to solve a wide range of practical problems in various fields [12, 13]. In general, the algorithm of simulated annealing is characterized by the initial state, the operation of getting a new state, the transition function between states and the function of changing the “temperature” parameter, affecting the solution search area [14].

The authors developed an algorithm for solving the described problem. The scheduling process in the proposed algorithm is divided into 2 stages – getting a state and generating a schedule by state. At the first stage, constraints (9-13) related to the solution structure are taken into account. The second stage takes into account constraints (13-18) associated with time. The algorithm includes the following steps:

**Step 1.** Sort the machinery sets by rating.

**Step 2.** Initial state generation \( S' \).

For the described task, the state \( S \) is a set of machinery sets \( U_s \subset U \) with sets of harvesting sites vectors \( X' \subset X \). Let \( m = \left| X' \right|, i \in X' \), then:
\[
S(x^*) = \begin{cases} 
X_i = (d_{i,1}, ..., d_{i,n}) \\
... \\
X_{n} = (d_{n,1}, ..., d_{n,n}) 
\end{cases} 
\]

(19)

Using "greedy" algorithm, the sites are distributed over territorial clusters, taking into account the harvesting costs and the machinery sets relocating costs.

**Step 3.** Scheduling on the state \( S^* \) and calculating its estimation \( E^* \), which is the current value of the objective function.

**Step 4.** Search the state space while \( T_i > T_{\text{min}} \) (i.e. until the minimum "temperature" is reached):

**Step 4.1.** Getting the new state \( S' \) using the following operations:

- transposition of intervals \([l_1, r_1]\) and \([l_2, r_2]\) in the harvesting sites vectors \( X_1 \) and \( X_2 \), \( l_1 \leq r_1, l_2 \leq r_2, l_1, r_1 \in [1, ..., n_1], l_2, r_2 \in [1, ..., n_2] \);

- transposition of the sites \( j_1 \) and \( j_2 \), in the vector of specific machinery set harvesting sites \( i \in U_s, j_1, j_2 \in [1, ..., n_s] \);

- inversion of the sites sequence in vector \( X_i \), between positions \( l \) and \( r \) for the machinery set \( i \), \( i \in U_s, l \leq r, l, r \in [1, ..., n_s] \).

**Step 4.2.** Scheduling on the state \( S' \) and calculation of \( E' \);

**Step 4.3.** Transition from \( S^* \) to \( S' \) using the Boltzmann function \( \phi(E^*, E', T_i) \) with the probability:

\[
p(E^*, E', T_i) = \exp\left(-\frac{|E^*-E'|}{T_i}\right) 
\]

(20)

**Step 4.4.** Decrease of the “temperature” parameter \( T_i = \frac{T_{\text{max}}}{i} \) and start of the next iteration \( i = i + 1 \).

**Step 5.** Getting the required schedule on the final state.

3. **Conclusion**

An approach to scheduling of wood harvesting machines operation is described in the paper, a multicriterial mathematical model is developed. It is shown that the original problem is reduced to a generalized traveling salesman problem. An algorithm for solving the problem based on a meta-heuristic algorithm of simulated annealing has been developed. The algorithm was used in decision support system for wood harvesting planning and management “Opti-Wood”, developed by Opti-Soft company.

The algorithm was numerically tested on several dozens of harvesting plans for a given road network in southern Karelia. A comparative analysis showed that the version with territorial clustering is more preferable, and can be used as a qualitative approximation for the getting of initial state in this and other metaheuristic methods.

The disadvantage of the proposed algorithm may be in somewhat limited set of possible states, which may complicate the search of the optimal solution. This is a consequence of applying state change operations to sites sequence of only one specified forest machinery set. Therefore, one of potential directions of further research is developing another algorithm using transposition of sites among different machinery sets.
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