International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Mathematical Modelling of Engineering Problems
Vol. 9, No. 2, April, 2022, pp. 425-430
Journal homepage: http://iieta.org/journals/mmep

Mobile Chipper Scheduling in the Production of Fuel Chips

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https://doi.org/10.18280/mmep.090217

Received: 6 October 2021
Accepted: 16 March 2022

Keywords:
mobile chipping machine, movement optimization model, movement schedule, Simplex algorithm, wood chip

ABSTRACT

Due to economic and environmental factors, boiler houses are forced to switch to wood fuel, which is very popular in the modern world. The most practical way to supply them with wood fuel is to mobilize mobile chippers that can move between different boiler houses and save money on additional chipping equipment. This paper seeks to build a mathematical model to optimize the movement of a mobile chipper between multiple boiler houses and its operation during the heating season. The model was designed for long-term planning, and it relies on a simplex algorithm. It considers three crucial parameters: machine capacity, feedstock amount, and traveled distance, and is suitable for schedule modeling purposes in the presence of fewer than 12 nodes. The number of nodes can be higher after a heuristic rule is applied. The proposal can be help schedule the biomass feedstock development at the regional level and switch to the local types of fuel. In addition, it will reduce the cost of thermal energy and increase the volume of wood waste chipped.

1. INTRODUCTION

The increased interest in woody biomass resources over the past thirty years suggests that biofuels with their favorable carbon balance have more environmental advantages when compared to extractable resources [1]. Wood fuels belong to a group of environmentally friendly renewable energy sources, the burning of which reduces carbon emissions and wildfires. Waste from timber processing operations can exceed 50% of the total round wood volume to be treated, an amount that can pollute vast areas of forestland.

Many developed countries undertake a range of measures to increase the share of renewables, from policy adoption at the state and local levels to provision of subsidies, contributions or tax benefits for the population and enterprises [2]. Over the past half century, more than half of the world's forestry products have been sold as wood fuel [3]. At present, the wood fuel sector exhibits great potential for expansion and is constantly growing, which is not the case for other forestry products. The production of woody biomass facilitates the growth of agricultural and forestry sectors, opening up new prospects for farmers and forest owners, but it also comes with certain challenges. The primary one is a price competitive sale of woody biomass resources [4]. In Russia, biofuel production quickly became a profitable business, as evidenced by many initiatives that have emerged in recent years [5]. When pressed to form a briquette or a pellet, woody resources acquire high energy density, become environmentally friendly and convenient for transportation, and suit domestic and industrial purposes [6]. The use of waste wood as fuel substantially enhances the efficiency of energy supply at enterprises and reduces the amount of air emissions. According to the study [7], Russia has more than 270 wood pellet manufacturing facilities that generate up to 3.5 million tons of wood pellets per year. Those large and medium-sized forestry enterprises either produce wood pellets as byproducts or utilize them as fuel in boilers. However, this type of fuel is still in little demand on the Russian domestic market, such that around

98% of wood pellets produced in Russia are exported to other countries [8].

Energy conservation and transition to environmentally friendly fuels require the use of new equipment and proper training in this field. Some regions in Russia with a developed forestry industry may see switching from coal and oil to ecological fuels (such as wood chips) as the potential need. Low-quality wood, felling residues, and sawmill waste, which can be processed into fuel chips which can heat the building of the logging enterprise itself, lumber warehouses and nearby lumber camps [9].

Wood chips are the preferred fuel for timber terminals. They can be the main product derived from energy plantations [10]. Unlike technological chips, fuel chips have practically no quality requirements [11]. The problem of high chip transport stability can be overcome by generating it on-site. However, it would be excessive to purchase individual chippers for each small boiler house, as it will stay idle for most of the time. Therefore, a more reasonable solution is to create one mobile chipper that can move freely between boiler houses and create piles of fuel chips wherever needed [12, 13].

A chipper that moves between boiler houses needs to follow a specific planned route and know the exact volumes of fuel chips to create to maintain fuel supply until the next arrival. Mobile chipper routing and scheduling should receive adequate attention because without them, the chipper may fail to visit all locations at the right time in the winter season [14]. Mobile crusher schedule disruptions can result in staff being required to work seven days a week that may negatively affect the health of personnel and lead to equipment wear and tear [15]. Not to mention the likelihood of freezing in the absence of necessary fuel.

When drawing up a schedule, it is necessary to consider the state of the road network and chipper's energy demand. The amount of wood waiting to be turned into chips and fuel demand thus are crucial for designing logging roads [16]. When determining the amount of to-be-chipped wood, one should consider the volume of wood that will come from the planned forest thinning operations.

The choice of the optimal chipper routing sequence and travel schedule depends on the capacity of the vehicle. This paper aims to build a mathematical model for mobile chipper's travel missions to optimize its operation during the heating season and supply each boiler house with as much fuel as necessary. For this, it is necessary to minimize the driving time between boiler houses while taking the chipper's capacity and the planning horizon into account. The proposed method can help plan routes and design projects to supply distant boiler houses with wood fuel.

2. MATERIALS AND METHODS

2.1 Mathematical model for a mobile device's travel

A mathematical model describes the motion of a single mobile chipper traveling between boiler houses while considering the following parameters: chipper's capacity, fuel demand at the boiler houses, and travel distance between locations. The planning horizon spans one heating season or an interval between planning and the complete satisfaction of fuel demand). It includes the minimum number of travel cycles of the mobile chipper required. A travel cycle is a schedule of chipper's travel or a sequence of locations that a machine has to visit. The number of travel cycles is unknown.

The following notations will be used in building the mathematical model:

$m-$ the number of boiler houses. Then, $M = \{1, \cdots, m\}$ would be the index set of boiler houses. The *input data* include:

R – the capacity of the mobile chipper (i.e., the number of solid cubic meters of fuel chips produced per wording day, that is, within 8 hours).

$V_i^{/}$ – the boiler house's daily demand for fuel chips (i.e., the number of solid cubic meters), with $i \in M$. It can be defined as an average quantity of fuel chips that one boiler house i requires per day to operate. The daily demand for fuels chips is the ratio of the total seasonal demand to the total number of days of the heating season.

$V_i^{//}$ – the boiler house's total demand for fuel chips (producing more chips would be inefficient), with $i \in M$.

W_i – the boiler house's initial biomass feedstock on the day of planning, with $i \in M$.

T – the maximum planning horizon (number of days). This variable helps to limit the planning horizon. For example, there are several days until the heating season ends. In this case, the planning horizon should be limited to the number of days left until the end of the heating season. In another scenario, preventive maintenance is to be carried out. Here, it is also advisable to limit the planning horizon.

$A_{i,k}$ – time required to drive from one boiler house i to another k (number of hours), with $i \in M$ and $k \in M$.

The variables parameters include:

n – the number of travel cycles. Then, $N = \{1, \cdots, n\}$ would be the index set of travel cycles.

$X_{i,\, j}$ – the duration a mobile chipper takes to generate fuel chips at the boiler house i during the cycle j (number of days), with $i = 1, \dots, m+1$ and $j = 1, \dots, n$.

An additional fake destination (m + 1) was introduced to determine the idle time, which can be used for preventive maintenance and granting employees who serve the chipper personal time off, vacation days, and sick leave.

In the movement scheduling problem, the permutation of boiler houses is the unknown parameter denoted as $P[l]$, where $P[l] \in M$ is a boiler house in some permutation sequence, with $l \in \{1, \dots, m\}$ and $P[m+1] = m+1$.

2.2 Boundary conditions

The fuel demand of each boiler house in each travel cycle must be lower than the amount of available fuel (initial biomass feedstock + produced fuel chips). The formula would be:

$$V_{P[l]}^{-} \cdot \left(\sum_{j=1}^{r-1} \sum_{i=1}^{m+1} X_{P[i].\, j} + \sum_{i=1}^{l-1} X_{P[i].\, r} \right) \le R \cdot \sum_{j=1}^{r-1} X_{P[l].\, j} + W_l \,, \forall l \in \{1, \dots, m\}, \forall r \in N \tag{1}$$

The produced amount of fuel and its initial biomass feedstock should be enough to satisfy the total demand for fuel chips when a chipper is not present at the boiler house. The total volume of fuel chips produced for each boiler house during the heating season must be the same as the total volume of chips required to operate until the end of the heating season minus the volume of its initial feedstock. The formula for chipper capacity would be:

$$R \cdot \sum_{j \in N} X_{P[l],\, j} = V^{//}_{P[l]} - W_{P[l]}, \forall l \in \{1, \dots, m\} \tag{2}$$

The planning horizon is limited to a specified value, as shown below:

$$\sum_{j \in N} \sum_{i \in \{1, \dots, m+1\}} X_{P[i],\, j} \leq T \tag{3}$$

The duration a mobile chipper takes to generate fuel chips at each boiler house during each cycle takes on a positive value, as shown below:

$$X_{i,\, j} \geq 0, i = 1, \dots, (m+1), j = 1, \dots, n \tag{4}$$

An objective function would be:

$$\sum_{i=1}^{m-1} A_{P[i],P[i+1]} \to \min \tag{5}$$

The objective function seeks to minimize the time a mobile chipper will need to travel between boiler houses. The said parameter was chosen to determine the sequence of locations. With the knowledge of the required movement time, it is possible to minimize movement costs.

The main advantage of this model is its simplicity. In general, it is a non-linear model because it defines the permutation of boiler houses. At the same time, it becomes linear for each permutation and a given number of cycles. Therefore, each permutation receives a different method to solve the movement scheduling problem. The proposed model can be easily adapted to other optimality criteria.

2.3 Algorithm for optimizing the movement schedule of a mobile chipper

The problem-solving method seeks to find feasible solutions to the system of linear constraints by gradually increasing the number of travel cycles of the mobile chipper, starting with one cycle. At the same time, it is vital to determine location permutations in accordance with the objective function (5). The increase in the travel cycles continues until the system of constraints (1) - (4) receives at least one feasible solution, that is until all boiler houses have enough fuel. For each number of cycles set, several iterations were calculated with respect to the number of possible permutations. Each iteration consists of three stages:

Stage 1: Destination permutation. Boiler houses undergo rearrangement according to some conditions (the presence of roads between locations). Permutation shows the new sequence of locations a mobile chipper has to visit. After each permutation, the driving time between locations is calculated. The less it takes to approach the destination, the better.

Stage 2: Solving constraint system. When rearranging boiler houses and setting a particular number of travel cycles, it is crucial to solve the system of linear constraints (1) - (4) to determine the operating time of the chipper at each boiler house and idle time. For this, bringing the constraint system to the canonical form is in order. This process involves adding additional variables to inequalities (1) and (3) where the inequality symbol is 'less than' and artificial variables to constraint (2) having an equal sign. The next step is to establish the operating time of the chipper at each boiler house using the simplex method [17] while taking the restrictions on the volume of chips that can be produced and the initial feedstock into account. In this case, the minimum value of the sum of the artificial variables acts as the objective function (6) and shows the extent to which the solution satisfies the model constraints. If the value of the objective function is large, then the constraint system is incompatible, and a shift to another permutation is required. If incompatibility remains with all permutations, then the number of travel cycles should be higher. A successful solution is associated with the objective-function value being equal to zero. At this solution, the minimum number of travel cycles required to satisfy the fuel needs completely becomes apparent.

Overall, the problem being solved at stage 2 can be described as follows. The constraint (1) will take the following form after transformation:

$$\begin{gathered} V^{-}_{P[l]} \cdot \left(\sum_{j=1}^{r-1} \sum_{i=1}^{m+1} X_{P[i],\, j} + \sum_{i=1}^{l-1} X_{P[i],\, r} \right) + \\ Z_k = R \cdot \sum_{j=1}^{r-1} X_{P[l],\, j} + W_l, \forall l \in \{1, \dots, m\}, \\ \forall r \in N \end{gathered} \tag{6}$$

where: Z_k – additional variable, $k = 1, \dots, m \cdot n$.

The constraint (2) will take the following form after transformation:

$$R \cdot \sum_{j \in N} X_{i,\, j} + Y_i = V^{//}_i - W_i, \forall i \in M \tag{7}$$

where: Y_i – artificial variable.

Finally, the constraint (3) will be transformed into:

$$\sum_{j \in N} \sum_{i \in \{1, \dots, m+1\}} X_{P[i],\, j} + Z_{m \cdot n+1} = T \tag{8}$$

where: $Z_{m \cdot n+1}$ – additional variable.

The non-negativity condition for all variables would be:

$$\begin{gathered} X_{i,\, j} \geq 0, i = 1, \dots, (m+1), j = 1, \dots, n, \\ Z_k \geq 0, k = 1, \dots, (m \cdot n + 1), \\ Y_i \geq 0, i = 1, \dots, m). \end{gathered}$$

The objective function of the problem is simply the minimum value of the sum of artificial variables, as shown below:

$$\sum_{i \in M} Y_i \to \min \tag{9}$$

Stage 3: Comparing solutions. This stage involves admissible solutions to the constraint system. An admissible solution is a solution with the minimum number of travel cycles and efficient permutations (i.e., the sequence of locations that enables the fastest routes). The obtained solution is compared with other alternatives by looking at the minimum time required to travel between locations (5). Solutions with the most efficient permutations are deemed the best. In general, there will be just a few of them to choose from.

2.4 Input data

To test the model, five boiler houses were selected. The heating season spans 273 days. It begins September 1 and concludes May 31. The average capacity of the chipper is 240 m^3 per day. Assume that one working day has 12 hours, and the machine operates seven days a week. The driving time between boiler houses is shown in Table 1.

Table 1. Driving time between boiler houses, hours

Boiler house	1	2	3	4	5
1	0	17	8	20	14
2	17	0	9	3	4
3	8	9	0	12	6
4	20	3	12	0	6
5	14	4	6	6	0

The fuel demands and initial biomass feedstock of each boiler house are depicted in Table 2. For simplicity, assume that the chipper generates zero cubic meters of chips on the day when it moves to another boiler house.

Table 2. Fuel demands and initial biomass feedstock of each boiler house

Boiler house	Average daily fuel demand, ,^{3}	Total fuel demand, m^3	Initial feedstock, m^3
1	13	3500	30
2	10	2700	300
3	9	2500	450
4	11	3100	200
5	8	2100	350

3. RESULTS

The optimal movement schedule for the mobile chipper obtained using a mathematical model is depicted in Figure 1.

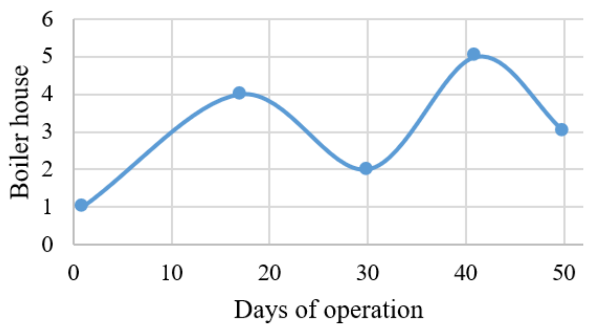

Figure 1. Movement schedule of the mobile chipper showing which boiler houses to visit and when

As can be seen from the Figure 1 above, locations are arranged in the following order: 1, 4, 2, 5, 3. The starting point is the boiler house 1, which had the smallest reserve of chips at the beginning of the examined period and the highest consumption rate of fuel (Table 2). The stopping point is the boiler house 3, which had the largest reserve and the minimum rate of fuel consumption. That is, the movement was based on the initial amount of chips on the boiler house. The time-optimal routes take 33 hours to drive. From the resulting schedule, it follows that the proposed model considers not just the time of driving. It considers the initial volume and consumption rate of fuel chips. Hence, it allows optimizing the biomass preparation process without shutting down the boilers.

After that, an analysis was made of the operating time of the chipper and the amount of chips produced.

Figures 2 and 3 show the number of productive days (the period when the machine produces chips on-site) and volumes of chips for each boiler house.

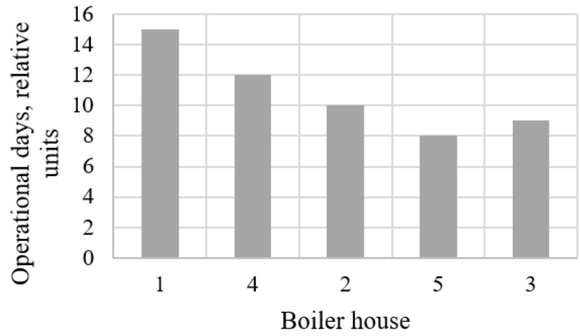

Figure 2. The number of productive days and the total yield of fuel chips per boiler house obtained during the heating season

Figure 2 shows that the mobile chipper spent more time at the boiler house 1 (15 operational days) because it had the greatest fuel demand. It took the least amount of time (8 operational days) to supply the boiler house 5, as its total fuel demand was the lowest among the examined locations (Table 2). It follows that the required number of operational days depends on the initial fuel supply. This conclusion is in good agreement with data in Figure 3.

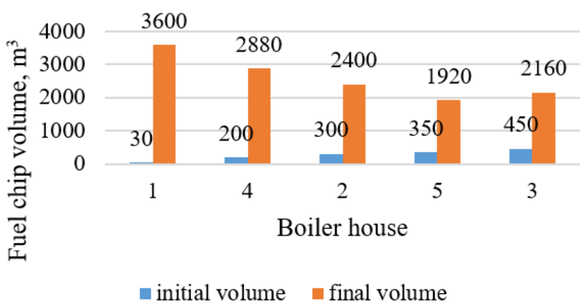

Figure 3. The volume of fuel chips before the scheduled arrival of the mobile chipper and after its scheduled departure

In general, there were 60 working days, of which 54 were productive, and the machine produced 12.960 cubic meters of chips. The given volume satisfied the needs of five boiler houses located at a sufficiently far apart from each other.

The proposed mathematical model considers factors that are vital for practical implementation and affect the machine scheduling process. The model is simple to use and the resulting movement schedule can be effectively employed in reality. Another advantage of the proposed model is that it enables a wood treatment organization to satisfy its fuel needs with the minimum number of travel cycles. It also takes into account all previous cycles. The total length of all cycles can be set individually, and the movement schedule is adjustable.

The factor domain, however, is complex, as many crucial factors are hard to incorporate into the model, ranging from weather conditions and job shifts to the presence of raw materials to chip on-site. Given this above limitation, the present paper offers a long-term movement schedule covering the entire heating season. Long-term planning does not require absolute precision — the longer the planning period, the more challenging the accurate scheduling.

4. DISCUSSION

Even though the proposed scheduling algorithm can generate multiple movement schedules using different input sets (e.g., data on fuel reserves), it is not a one-size-fits-all solution. There are input data values that do not lead to a feasible solution. For instance, if the initial feedstock amount is zero or close to zero, the mobile chipper must visit all boiler houses at once, but it would be impossible. To avoid this situation, one needs to adjust the mathematical model – to add new controllable factors and new constraints connecting them. In this way, the model will be able to consider the following two scenario: (1) fuel chips are transported to boiler houses where they are stored before the heating season begins; (2) boilers operate on auxiliary fuels (such as coal and oil) until the mobile chipper arrives.

The given solution may not be effective in the presence of a large number of boiler houses, say more than 12, because generating all the permutations possible will take too much time. If there are M locations, there are $M!$ permutations. In this case, one can optimize the generation of location sequences by reducing the number of possible permutations. For this, look at the most probable combinations. Another way toward optimization is to determine the time required to meets the fuel needs of each boiler house in the most efficient permutations, not all of them. By doing this, it is possible to significantly reduce the number of operations in the first and second stages of the algorithm and thus cut down the total running time of the algorithm. In the worst-case, the simplex method actually takes time exponential in the size of the input. In reality, however, the number of iterations to solve the problem is somewhere around 3m (m denotes the problem constraints), and each iteration is proportional to m^3. Hence, the simplex method can be used in practically important tasks. The proposed algorithm relies on a modified simplex method with a recalculated inverse of the basis matrix.

Other studies have used mixed-integer nonlinear programming models to achieve economic and environmental goals of the supply chain management [18]. The Lagrangian relaxation method has been used to improve planning operations in the forestry industry. The results showed that that approach optimizes well the movement schedule of forestry equipment with the increasing working time of the machines. Building a mathematical model allows a more in-depth study of various schedule options to find the best variant for an efficient harvesting process with minimal environmental damage [19]. Another alternative is schedule simulation [20], which enables the synchronization between chippers and trucks in the field. Using this method, researchers explored two scenarios: (1) chippers operate within the territory of the enterprise; (2) chip production takes place at the felling site with the subsequent transportation by truck. The results show that the first scenario is more rational because it is easier to transport raw materials than finished products. These two scenarios were combined in Ref. [21]. Chipping at the terminal involves transporting woody biomass from felling sites on smaller trucks and transporting chips from terminals to processing facilities on larger trucks. Given the balance between chopping and transport efficiency, the overall goal is to minimize the traveled distance between the destinations [22]. Synchronizing the arrival of trucks with chipping schedules is not necessary when chipping occurs at terminals or processing facilities because chips can last for long time [23].

Due to the absence of intermediate stops during transportation (the biomass is loaded directly into trucks and unloaded at the boiler houses), the process of collecting waste from logging operations is usually not time-limited. In turn, chipper scheduling can simplify the preparation of a fuel biomass feedstock and significantly reduce transportation and machine replacement costs.

5. CONCLUSIONS

After analyzing the results obtained, the following conclusions can be drawn.

The paper creates an optimal movement schedule for a mobile chipper traveling between multiple boiler houses during the heating season.

A mathematical model relies on the simplex method and allows the long-term operation planning.

The findings show that the model takes into account the following parameters: machine capacity, feedstock amount, and traveled distance.

The developed algorithm is suitable for scenarios with less than 12 nodes (boiler houses). It is possible to increase the number of nodes to make it tens or hundreds if the algorithm is limited to generating the most promising permutations at step 1.

The use of the given model and algorithm will enable the regions to switch to local types of fuel and thus reduce the cost of thermal energy. In the long run, it will solve the woody waste problem.

The results of this article can be used to manage delivery chains: scheduling, time spent at one facility, etc. Work in this direction can be continued by studying more boilers or adding new variables to this methodology.

ACKNOWLEDGMENT

The work was carried out within the confines of the scientific school “Advances in lumber industry and forestry”. The underlying content of this paper was supported by the grant of the Russian Science Foundation № 22-26-00009, https://rscf.ru/project/22-26-00009.

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NOMENCLATURE

m	the number of boiler houses
R	the capacity of the mobile chipper
$V_i^{/}$	the boiler house's daily demand for fuel chips
$V_i^{//}$	the boiler house's total demand for fuel chips
W_i	the boiler house's initial biomass feedstock on the day of planning
T	the maximum planning horizon
$A_{i,k}$	time required to drive from one boiler house i to another k
n	the number of travel cycles
$X_{i,\,j}$	the duration a mobile chipper takes to generate fuel chips at the boiler house *i* during the cycle *j*