Finding an effective technological chain of logging operations

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Abstract. The choice of technological process’ parameters certainly affects the result of its implementation. When performing logging operations, there are many options for their sequence, the use of machines at different stages of performance and periods of the year. Choosing the technological chain, enterprise management is faced with various possible solutions. In most cases, they are taken speculatively - based on personal experience. The given study is a continuation of the group of authors work on the complex problem of algorithmization and optimization of logging operations, taking into account the analysis of various moving and processing operations of wood resources. In previous publications, the authors presented a graphic-analytical model for solving the task. This article presents a description of the algorithm developed on the basis of the presented mathematical and graphic-analytical models for finding an effective technological chain of transport, loading and unloading and processing operations of the logging process in dynamic natural production conditions. The algorithm was successfully tested on the example of data as close as possible to the conditions of the Krasnoyarsk territory.

1. Introduction

The scientific community has not yet formed a unified universal methodology that can be used to increase the availability of wood resources located in the forest territory. Such a task requires the use of two key types of tools:

1. Economic and mathematical apparatus used to assess the resource potential of a certain territory;
2. Geographic information system, which allows to solve a wide class of problems, with reference to the geographical location of the investigated objects and the use of cartographic material processed with the use of computer technology.

The necessary difference of such a technique should be in the study of processes and the development of appropriate solutions in a changing environment. The latter circumstance is often overlooked, but it is quite obvious that the economic conditions of industrial enterprises are dynamic, which is influenced primarily by the natural environment.

The development of such a methodology is designed to solve the applied problems of the forest, in particular, the logging industry. At the same time, its development is a fundamental task, the solution of which involves bringing the proper theoretical and methodological justification. This paper presents the separate results of the study of the author's team in this area.

Currently, the remoteness of the territories in which logging enterprises operate from processing facilities is rapidly increasing. At the same time, there is an increase in the cost price of harvested raw
materials, which reduces the economic efficiency of logging as such. This situation, as well as a number of technogenic and natural-climatic factors, leads to the fact that the cost of individual forest resources is higher than the sale price. Such wood is considered to be economically inaccessible. Alongside this, the use of the existing mathematical apparatus in conjunction with the economic justification allows to identify the most effective forest infrastructure. Its implementation in practice should address a key challenge beyond the economy - the organization of continuous and sustainable use of forests. At the same time, the problem of increasing the availability of wood resources is solved by determining the optimal routes of delivery and dispersal of loggers in the territories. The latter is understood not only economic but also transport, environmental, etc. [1].

The key task of researches in this direction is to solve a complex of engineering and economic problems. The first of them consists, first of all, in choosing not only effective, efficient, but also optimal technical solutions for the delivery of wood resources from the forest area to the consumer. The second - in the economic justification of the selected technologies, machines and equipment, as well as the product portfolio and the direct consumer of products.

There are studies devoted to the justification of through flows of harvesting, transportation and processing of wood based on mathematical models, performed by Shegelman I R [2, 3]. The use of graphic-analytical models providing the construction of relationships between operations, allows to perceive technological chain for certain types of work in a logical sequence, eliminates duplication of certain technological elements, provides an opportunity to assess the various systems of machines and the structure of production flows in various technological processes of forestry [4].

However, these studies do not provide for the possibility of their use for modeling the technological chain in dynamic conditions, characterized by the need to take into account the natural and production characteristics when transporting wood from the cutting area to the consumer.

The methods of substantiation of finding the shortest paths between the vertices of the graph are described in Moore's [5], Floyd's [6], Dijkstra's [7], Bellman's [8] and other researches. They allow to carry out the analysis of static elements of work of the enterprises and serve as a basis for realization of stationary-dynamic tasks of stream programming at rationalization of flows in transport systems [9-12]. The simplex method of linear programming can be used to solve such problems [13].

The above methods and algorithms can be used in the process of considering the operations of the technological process of logging operations in dynamics when presenting them in the form of time-stretched graphs. These researches demonstrate in detail the basic schemes and analysis capabilities of the operating network. However, they characterize the possibility of passing through the arcs of each time interval only one flow option and do not take into account the specifics of the logging industry, envisaging at justification of the schedule of the logging technological process the need for a comprehensive solution to the problems of developing several cutting areas within one-time range. In view of this, they cannot always be used in solving the issues of justification of the technological chain of work at timber enterprises.

In the conditions of the need to implement such a comprehensive analysis, it becomes obvious that the use of machines and mechanisms involved at performance of works on one of the analyzed sites of the logging enterprise reduces the resources of their possible application during the execution of the same operations in the territory of another site in the time interval accepted for analysis. The noted researches stipulating theoretical possibility of passing several flows on the same operations of the technological process of each analyzed period provide the researcher with the possibility of the analysis only the graphs with independent from each other throughput capacity of separate parallel arcs of analyzed time intervals.

The purpose of the study is to develop an algorithm for the technological chain of transport, loading and unloading and processing operations of the logging process in dynamic natural-production conditions using the developed graphic-analytical model.
2. Materials and methods
The object of the study is the process of wood transportation (delivery) from the cutting area to the consumer. Analysis was used as a key research method. Meanwhile, the developed algorithm was based on the results of the work of the author's team and using the Bellman-Ford algorithm. Approbation of the results was carried out on the example of logging enterprises of the Krasnoyarsk territory.

3. Results and Discussion
This study is a continuation of the work of the author’s team on the complex problem of algorithmization and optimization of logging operations, taking into account the analysis of various moving and processing operations of wood resources. In the paper Mokhirev A and Rukomojnikov K [14], the authors propose detailed graphical models of wood transportation from the cutting area to the consumer, loading and unloading and processing operations taking place at the intermediate and lower forest warehouse. In the study Rukomojnikov K P, Mokhirev A P [15], on the basis of a graphic-analytical model, a technique for solving this problem is proposed. Suggested mathematical dependencies allow to carry out search of the maximum flow of the minimum cost in dynamic structure of technological process of works’ performance at the enterprise. In addition to the dynamic component, the method differs by taking into account the income of the enterprise from the sale of marketable products.

The next stage of the researches is a description of the algorithm developed on the basis of the presented mathematical and graphic-analytical models for finding an effective technological chain of transport, loading, unloading and processing operations of the logging process in dynamic natural and production conditions.

The developed algorithm includes the following steps:
1. Take for calculation the vertices and arcs of the graph from the first period of the technological process \( \theta = 1 \), using a variant of the time-stretched graph \( G_p \), relating to a particular situation of the technological process of timber removal from logging sites.
2. Taking into account the values of the flow \( \xi(x_i, x_j, \theta, \theta + \tau_{ij}(\theta)) \) moving along arcs of a graph \( G_p \), build a residual network \( G_p^R = (X_p^R; A_p^R) \). At the same time, each arc of the new network connecting the «vertex-time» pair \((x_i, \theta)\) with the «vertex-time» pair \((x_j, \theta)\), along which a flow of any value is started up at the first stage of calculation, has an inverse arc connecting \((x_j, \theta)\) with \((x_i, \theta)\) with the residual throughput \( V^R(x_j, x_i, \theta, \theta) = \xi(x_i, x_j, \theta, \theta) \) and cost \( C^R(x_j, x_i, \theta, \theta) = -C(x_i, x_j, \theta, \theta) \).

If the value of the transported flow \( \xi(x_i, x_j, \theta, \theta) \) is equal to the throughput of the arc, so \( C^R(x_j, x_i, \theta, \theta) = \infty \). The movement of the reverse flow along any of the reverse arcs of the residual network leads to the possibility of increasing the throughput of any of the arcs characterizing the same operation of the technological process in the analyzed time interval by the value of:

\[
V^R_{N(i=b)j}(\theta) \leq \frac{\sum_{i=[1,b]} \sum_{j=[1,b]} \xi(x_i, x_j, \theta, \theta + \tau_{ij}(\theta))}{P^R_{N(i=b)j}(\theta)}
\]

Each arc connecting a «vertex-time» pair \((x_i, \theta)\) with a «vertex-time» pair \((x_j, \theta + \tau_{ij}(\theta))\) has a residual bandwidth \( V^R(x_i, x_j, \theta, \theta + \tau_{ij}(\theta)) = V(x_i, x_j, \theta, \theta + \tau_{ij}(\theta)) - \xi(x_i, x_j, \theta, \theta + \tau_{ij}(\theta)) = \infty \), and a reverse arc with a residual bandwidth \( V^R(x_j, x_i, \theta + \tau_{ij}(\theta), \theta) = V(x_j, x_i, \theta + \tau_{ij}(\theta), \theta) = \xi(x_j, x_i, \theta + \tau_{ij}(\theta), \theta) \) and cost \( Z^R(x_j, x_i, \theta + \tau_{ij}(\theta), \theta) = -Z(x_j, x_i, \theta + \tau_{ij}(\theta), \theta) \).

The residual network initially coincides with the original graph.

Determine the path \( P^R_{P(i=b)j} \) of the minimum cost in the constructed residual network using the Bellman-Ford algorithm.
If there is no such path and the analysis of all analyzed periods is performed, then it is possible to draw a conclusion about the correspondence of the previously found path variant to the optimal variant of the given flow movement and proceed to step 9.

If there is no such path only within the analyzed periods (at the moment of time \((\theta)\)) and it is possible to make a transition to the next period \((\theta + \tau_{ij}(\theta))\), then add the vertices and arcs of the next period to the graph. Since the throughput capacities of the arcs of each of the periods in the areas associated with the dummy source and dummy effluent depend on the flow started up along similar arcs of the previous periods, then carry out the calculation of the throughput capacities of its arcs connecting a «vertex-time» pair \((x_S, \theta + \tau_{ij}(\theta))\) with the «vertex-time» pair \((x^u_{1}, \theta + \tau_{ij}(\theta))\), and «vertex-time» pair \((x^l_{i}, \theta + \tau_{ij}(\theta))\) with the «vertex-time» pair \((x_T, \theta + \tau_{ij}(\theta))\), according to the formulas:

\[
V_{ln}(\theta + \tau_{ij}(\theta)) = V_N - \sum_{\theta=1}^{\theta=p} \xi_{ln}(\theta),
\]

\[
V^y(\theta + \tau_{ij}(\theta)) = Q^y_U - \sum_{\theta=1}^{\theta=p} \xi^y(\theta),
\]

If the path is found, then proceed to the next step.

3. Determine the maximum throughput of the identified minimum cost path in the residual dynamic network.
where $f_{h,h+1}$ - labor costs characterizing the analyzed saturated arc of a narrow production site as part of the selected path, directed at a time point $(\theta)$ to a dummy effluent, machine-shifts; $f_{h+1,h}$ - labor costs characterizing the response to the analyzed saturated arc of a narrow production area, the reverse arc at the time point $(\theta)$, machine-shifts;

4. Update the values of flows along the arcs of the graph $G_p$.

\[ f^* = \frac{f_{h,h+1}^*}{f_{h+1,h}} \]

\[ \delta^*_h = \min \left\{ \begin{array}{l}
\min \left( \begin{array}{l}
V^\mu_h(x_i, x_j^h) \\
\text{where } (x_i, x_j^h) \in E^\mu_{p(S-T)}
\end{array} \right) ; \\
\min \left( \begin{array}{l}
V^\mu_h(x_i, x_j^h, \theta, \theta) + \frac{1}{f^*} \cdot V^\mu_h(x_i, x_j^h, \theta, \theta) \\
\text{where } (x_i, x_j^h, \theta) \in E^\mu_{p(S-T)} \quad \text{and } \theta \in [0,p]
\end{array} \right) ; \\
\min \left( \begin{array}{l}
V^\mu_h(x_i^h, x_j^h, \theta, \theta + \tau_{ij}(\theta)) \\
\text{where } (x_i^h, x_j^h) \in E^\mu_{p(S-T)}
\end{array} \right) ; \\
\min \left( \begin{array}{l}
V^\mu_h(x_i^h, x_j^h, \theta, \theta + \tau_{ij}(\theta)) \\
\text{where } (x_i^h, x_j^h, \theta) \in E^\mu_{p(S-T)} \quad \text{and } \theta \in [0,p]
\end{array} \right) ; \\
\min \left( \begin{array}{l}
V^\mu_h(x_i^h, x_j^h, \theta, \theta) + \frac{1}{f^*} \cdot V^\mu_h(x_i^h, x_j^h, \theta, \theta) \\
\text{where } (x_i^h, x_j^h, \theta) \in E^\mu_{p(S-T)} \quad \text{and } \theta \in [0,p]
\end{array} \right) ; \\
\end{array} \right. \right\} \quad (4) \]

\[ \left( \begin{array}{l}
V^\mu_h(x_i^h, x_j^h, \theta, \theta) + \frac{1}{f^*} \cdot V^\mu_h(x_i^h, x_j^h, \theta, \theta) \\
\text{where } (x_i^h, x_j^h, \theta) \in E^\mu_{p(S-T)} \quad \text{and } \theta \in [0,p]
\end{array} \right) ; \\
\end{array} \right\} \right) ; \quad (5) \]

a) for arcs connecting the «vertex-time» pairs $(x_i^h, \theta + \tau_{ij}(\theta))$ with $(x_i^h, \theta)$ in the graph $G_p^\mu$ with cost $C(x_i, x_j, \theta, \theta + \tau_{ij}(\theta)) \leq 0$, replace the flow $\xi(x_j, x_i, \theta, \theta + \tau_{ij}(\theta))$ along similar arcs of the
graph $G_p$, directed from $(x_j, \theta)$ to $(x_i, \theta + \tau_{ij}(\theta))$, by the value from $\xi \left( x_j, x_i, \theta, \theta + \tau_{ij}(\theta) \right)$ to $\xi \left( x_j, x_i, \theta, \theta + \tau_{ij}(\theta) \right) - \delta_p^\mu$:

b) for arcs connecting the «vertex-time» pairs $(x_i^\mu, \theta)$ with $(x_j^\mu, \theta)$ in the graph $G_p^\mu$, with cost $C(x_i, x_j, \theta, \theta + \tau_{ij}(\theta)) \leq 0$, replace the flow $\xi \left( x_j, x_i, \theta, \theta + \tau_{ij}(\theta) \right)$ along similar arcs of the graph $G_p$, directed from $(x_j, \theta)$ to $(x_i, \theta)$, by the value from $\xi \left( x_j, x_i, \theta, \theta + \tau_{ij}(\theta) \right)$ to $\xi \left( x_j, x_i, \theta, \theta + \tau_{ij}(\theta) \right) - \delta_p^\mu$;

c) for arcs connecting the «vertex-time» pairs $(x_i^\mu, \theta)$ with $(x_j^\mu, \theta + \tau_{ij}(\theta))$ in the graph $G_p^\mu$, with cost $C(x_i, x_j, \theta, \theta + \tau_{ij}(\theta)) \geq 0$, replace the flow $\xi \left( x_j, x_i, \theta, \theta + \tau_{ij}(\theta) \right)$ along similar arcs of the graph $G_p$, directed from $(x_i, \theta)$ to $(x_j, \theta + \tau_{ij}(\theta))$, by the value from $\xi \left( x_j, x_i, \theta, \theta + \tau_{ij}(\theta) \right)$ to $\xi \left( x_j, x_i, \theta, \theta + \tau_{ij}(\theta) \right) + \delta_p^\mu$;

d) for arcs connecting the «vertex-time» pairs $(x_i^\mu, \theta)$ with $(x_j^\mu, \theta)$ in the graph $G_p^\mu$, with cost $C(x_i, x_j, \theta, \theta + \tau_{ij}(\theta)) \geq 0$, replace the flow $\xi \left( x_i, x_j, \theta + \tau_{ij}(\theta) \right)$ along similar arcs of the graph $G_p$, directed from $(x_i, \theta)$ to $(x_j, \theta)$, by the value from $\xi \left( x_i, x_j, \theta + \tau_{ij}(\theta) \right)$ to $\xi \left( x_i, x_j, \theta + \tau_{ij}(\theta) \right) + \delta_p^\mu$;

e) update the values of the flows along the arcs connecting:

- «vertex-time» pair $(x_i^\mu, \theta)$ with «vertex-time» pair $(x_k, \theta)$, by the value from $\xi \left( x_j, x_k, \theta, \theta \right)$ to $\xi \left( x_j, x_k, \theta, \theta \right) - \delta_p^\mu$;

- «vertex-time» pair $(x_T, \theta)$ with «vertex-time» pair $(x_i^\mu, \theta)$, by the value from $\xi \left( x_T, x_i, \theta, \theta \right)$ to $\xi \left( x_T, x_i, \theta, \theta \right) - \delta_p^\mu$;

5. Determine the cost of the accepted path

$$\sum \xi \left( x, x, \theta, \theta \right) = \sum \sum C \left( x_i, x_j \right) + \sum \sum C \left( x_j, x_i \right) + \sum \sum C \left( x_j, x_j \right) \cdot f^*, \quad (6)$$

where, $\sum \left( x_i, x_j \right) \in p_{p(s-t)}^\mu$ - a section of a path consisting of straight arcs going in the direction from a dummy source to a dummy effluent; $\sum \left( x_j, x_i \right) \in p_{p(t-r)}^\mu$ - a section of the path including forward and reverse arcs, directed from the dummy effluent and returning back, creating a cycle; $\sum \left( x_j, x_i \right) \in p_{p(s-t)}^\mu$ - total variable costs on the section of the path from a dummy source to a dummy effluent along straight arcs, m.u.;

$\sum \left( x_j, x_i \right) \in p_{p(t-r)}^\mu$ - total variable costs on a cyclic section of the path along the reverse arcs, m.u.;

$\sum \left( x_j, x_i \right) \in p_{p(t-r)}^\mu$ - total variable costs on a cyclic section of the path along the straight arcs, m.u.;

6. Calculate the time $m^*(\theta)$ remaining until the end of the period.

7. Replace the bandwidth and weight of the arcs connecting:

- «vertex-time» pair $(x_s, \theta)$ with «vertex-time» pair $(x_j^\mu, \theta)$, by the value from $V_{L_N} \left( x_s, x_j, \theta, \theta \right)$ to $V_{L_N} \left( x_s, x_j, \theta, \theta \right) - \delta_p^\mu$;

- «vertex-time» pair $(x_T, \theta)$ with «vertex-time» pair $(x_T, \theta)$, by the value from $V^N \left( x_i, x_T, \theta, \theta \right)$ to $V^N \left( x_i, x_T, \theta, \theta \right) - \delta_p^\mu$;

The weight characteristics of the reverse arcs obtained when the flow passes through the arcs of the graph are equal to $C_{\mu}^N = C_{\mu}^N$.

Carry out replacement of capacities on the arcs corresponding to the same technological operations:

$$\Pi_{ij}^\mu(\theta) = \frac{m^*(\theta)}{f_{ij}^\mu(\theta)}. \quad (7)$$
8. Build a residual network. Proceed to step 2.
9. When identifying the maximum flow \( v(p) \) of the minimum cost in the graph \( G_p \), move to the initial dynamic graph, discarding the dummy vertices \( S \) and \( T \).

To solve this problem, the algorithm was formed in Excel.

4. Results and Discussion
The implementation of any algorithm in practice is a matter of discussion. The operation of an industrial enterprise in difficult climatic and production conditions often diverges from theoretical developments. Nevertheless, it is the approbation that checks the adequacy and viability of algorithms related to the transportation of goods, in particular wood resources.

The initial data for the implementation of the numerical example were formed from real data of logging enterprises of the Krasnoyarsk territory of the Russian Federation.

The natural and climatic conditions of the logging area should be divided into 5 periods: winter (124 days), winter-spring (31 days), spring (72 days), summer (62 days), autumn (71 days). In each period the performance of machines on operations is different. Logging is carried out on two sites, from which it is possible to transport wood directly to the consumer or through the lower coastal warehouse. The roads are partly temporary logging roads or year-round roads. On two sites timber can be harvested in the form of whips or sortiments of up to 20000 m\(^3\) in the first area and up to 50000 m\(^3\) in the second area. It is possible to transport the wood by rafting along the river from the lower coastal warehouse, rafts can be formed for this purpose. Timber storage between periods is carried out in stacks in the lower warehouse, for this purpose a land area is rented and personnel are hired for security. The consumer is ready to accept wood in any period in the amount of 70000 m\(^3\). To solve the problem, the cost of performing technological operations \( C \), the productivity of \( II \) machines and equipment for their implementation, as well as labor costs \( f \) for performing operations are determined.

According to the proposed algorithm and data, a rational technological chain is found. To compare the indicators, an analysis of other variants of the technological chains of transport and moving works was carried out. In the Krasnoyarsk territory, under similar conditions, the most commonly used options are:

1) Transportation in the summer to the lower warehouse with further rafting of the maximum possible volume of wood, the rest of the volume during the harvesting period (winter) by road to the consumer. In this case, the volume of wood equal to 18600 m\(^3\) is transported from the second forest site in the summer to the lower warehouse with further water transport to the consumer. The rest of the volume of wood of the second forest area (31400 m\(^3\)) in winter by road to the consumer. The entire volume (20000 m\(^3\)) from the first forest area is transported in winter.

2) Transportation by motor transport of the maximum possible volume in the winter to the consumer, the remaining volume-by road in the summer to the consumer. In this case, the transportation of the entire volume (50000 m\(^3\)) from the second site will be delivered to the consumer in the winter, part of the volume (3770 m\(^3\)) from the first site is also transported in the winter, the rest of the volume (16230 m\(^3\)) of the first forest site in the summer.

Thus, as a result of using the proposed methodology in solving the problem:
- the rational sequence of development of forest areas is established;

| Characteristic          | Option     |
|-------------------------|------------|
| Volume of transportation, m\(^3\) | first 70 000 second 70 000 calculated 70 000 |
| Costs, RUB.             | 130 361 200 137 252 225 126 938 060 |
| Salesincom, RUB         | 252 000 000 252 000 000 252 000 000 |
| Profit, RUB.            | 121 638 800 114 747 775 125061940 |
- the rational volume of timber, which can be exported to the lower coastal warehouse for further transportation by water transport at the minimum cost of labor, has been established;
- the possibility of reducing the total costs for the implementation of the work plan for transport and relocation operations by 3% compared to other possible variants of technological chains was revealed. The economic effect reaches 49 rubles / m$^3$.

5. Conclusion
The proposed algorithm allows to carry out an analytical approach to justify the sequence of timber transportation from different forest areas, to substantiate the use of forest warehouses in the logging process, raids of application loading and unloading operations, the type of transport (water, land), the choice of the consumer and the type of final commercial product in a dynamic natural production environment.

A numerical example of solving the problem has shown the efficiency of the method of finding a rational technological chain of logging operations in dynamic natural-production conditions.

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