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# DEVELOPMENT OF METHODOLOGICAL FOUNDATIONS FOR THE DESIGN OF LOGGING INFRASTRUCTURE TAKING INTO ACCOUNT THE DYNAMICALLY CHANGING ENVIRONMENT

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*Development of forest resources is currently associated with significant difficulties, primarily due to unsatisfactory infrastructure in greater part of the forest area. It is necessary to create an effective, mathematically based forest infrastructure so that the forest industry will be developing actively. This will create the prerequisites for effective continuous and sustainable use of the forest. At the same time, the transport and economic availability of wood resources will increase significantly. There are many options for organizing the logging process by forestry enterprises. In most cases, they are selected by management based on personal experience. 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 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 developed algorithm can be considered as a methodological basis for logging infrastructure design, taking into account the dynamically changing environment.*

*Key words: algorithm, graph, forest infrastructure, logging process, graphic-analytical model*

## *INTRODUCTION*

Today, the Russian forest industry accounts for about 1% of the country's GDP. Industrial development of forest resources is associated with significant difficulties. This is primarily due to the extremely unsatisfactory infrastructure in most of the forest territory. The main part of the forests is developed in winter, so a seasonal forest infrastructure is created, which can only be used during certain periods of time. It is often created without taking into account the infrastructure of neighboring forest areas. In addition, the presence of an insufficiently developed logging infrastructure (transport, logging, timber-handling) is a serious economic problem for the majority of timber enterprises. This leads to low developing of the estimated cutting area and hinders the development of effective continuous sustainable forest exploitation. Therefore, in order for the forest industry to develop actively, it is necessary to create an effective forest infrastructure. For this purpose, it's required to have complete information about the territory under development, including data on the forest resource base, labor resources, the availability and elaboration of infrastructure (including the road network), terrain features, climate indicators, etc.

Forest infrastructure design was carried out by many domestic and foreign scientists. In paper [1] options for justification and design of a forest road network were proposed, providing for determining the economic availability of resources, taking into account the transport infrastructure. However, the proposed methodology of creating a transport network does not consider the dynamics of the forest fund.Modern scientists engaged in the problems of the forest complex are paying more and more attention to the issue of forest resources accessibility as a major factor in the development of logging infrastructure. Scientific works of the Omsk region former Minister of economy A. G. Tretyakov [2, 3] are aimed at a comprehensive study of this issue. The problem of transport accessibility of forest resources occupies a central place in A. G. Tretyakov's researches. Transport accessibility of forests as the main factor of the forest resources level of use was considered by M. A. Efremov [4]. This researcher described methodological approaches to the system of assessing the economic profitability of forest wood resources. The theoretical core of the presented

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research results is the pricing model for round timber by breed-quality-size groups. In the works of V. A. Sokolov, the economic accessibility of forest resources is considered as a consequence of their ecological accessibility [5, 6]. His researches reveal the topic of using calculated cutting areas in the context of prompt update of information about the protection of ecologically significant forests.

Thus, to date, the issue of designing forest infrastructure taking into account harvesting seasons and climatic features has been studied fragmentarily; the studies lack complexity, consistency, mathematical justification, and the relationship between various aspects of this issue. Its research requires a serious theoretical and methodological basis. In modern realities, the volume and quality characteristics of available wood resources are rapidly changing under the influence of the logging process and technogenic factors. The creation of a mathematically justified effective forest infrastructure will allow to disperse logging across the territories that are somewhat remote from the forest industry centers, thereby creating prerequisites for organizing effective continuous and sustainable use of the forest. At the same time, the transport and economic availability of wood resources will increase significantly.

When organizing the transportation of wood from the cutting area to the consumer, there are engineering tasks that involve many options for their solution: determining the sequence of wood removal from the cutting area; identifying the need to use warehouses; choosing the mode of transport; choosing the technological chain of transport, storage and processing operations; choosing the time of year to perform certain operations; choosing the consumer.

I. R. Shegelman's researches [7, 8] provide mathematical models justifying the flows of harvesting, transportation and processing of wood. Application of graphic-analytical models show the relationships between operations, allows to represent the technological chain of various types of logging operations in a logical sequence, and to evaluate the structure of production flows in various technological processes of forest operations [9, 10].

However, mentioned studies do not allow us to use them for modeling the technological chain, taking into account the dynamically changing environment.

The methods for finding the shortest paths in a graph are described in Moore's [11], Floyd’s [12], Dijkstra’s [13], Bellman’s [14] and other researches. They can be used to find rational flows in transport systems [15, 16].

The above methods and algorithms can be used to represent the technological operations of the logging process in dynamics in the form of a dynamic network. However, they assume passing through the arcs of each time period only one flow option and do not take into account the specifics of the logging industry, which consists in solving the problems of developing several cutting areas within a single time interval.

The need for simultaneous consideration of several cutting areas leads to the fact that the resources of machines and equipment involved in the performance of works on one of the logging sites will be reduced while performing the same operations on another site in the analyzed time interval. The noted researches allow us to analyze only the graphs with independent from each other throughput capacity of separate parallel arcs of analyzed time ranges. In this regard, they cannot always be used to find an effectivetechnological chain of works at timber enterprises.

Therefore, it is relevant to develop an algorithm for solving this problem using the developed graphic-analytical model, which is a methodological basis for designing logging infrastructure taking into account the dynamically changing environment.

## THEORY AND EXPERIMENTAL

In the paper Mokhirev A and Rukomojnikov K [17] the authors consider graphical models of the sequence of logging process operations. In the study of Rukomojnikov K.P., Mokhirev A.P. [18] on the basis of the graphic-analytical model, mathematical model and method for solving this problem are proposed. The considered mathematical dependencies allow us to find the maximum flow of the minimum cost in the dynamic structure of the technological process of logging operations. The methodology also takes into account the enterprise's income from the sale of commercial products. The purpose of this study is to develop an algorithm for finding an effective technological chain of logging operations in dynamic natural production conditions based on the presented mathematical and graphic-analytical models.

## RESULTS AND DISCUSSION

The algorithm consists of the following steps:

1. A part of the time-stretched graph $G_p$, related to a certain situation of the technological process of wood removal from logging sites, corresponding to the first period of the technological process θ=1, is considered.
2. Taking into account the values of the flow $\zeta(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))$ and $\zeta(x_i, x_j, \theta, \theta)$ moving along arcs of a graph $G_p$, a residual network $G^\mu{}_p=(X^\mu{}_p, A^\mu{}_p)$ is constructed. 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 is started up at the first stage of calculation, has an inverse arc connecting $(x_i, \theta)$ with $(x_j, \theta)$ with the residual throughput $V^\mu (x_i, x_j, \theta, \theta)= \zeta(x_i, x_j, \theta, \theta)$ and cost $C^\mu (x_i, x_j, \theta, \theta)=-C(x_i, x_j, \theta, \theta)$. If the value of the transported flow $\zeta(x_i, x_j, \theta, \theta)$ is equal to the throughput of the arc, so $C^\mu (x_i, x_j, \theta, \theta)=\infty$. 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 technologica

process in than alyzed time interval by the value of:

$$V^{N}_{N_h(i=b)j}(\theta) \le \frac{\sum\limits_{i\in[1;b)\cup[b;g)}\ \sum\limits_{x_j\in X} f^{N}_{ij}(\theta)\cdot\xi^{N}_{ij}(\theta)}{f^{N}_{(i=b)j}(\theta)} \qquad (1)$$

The residual throughput of arcs connecting the «vertex-time» pair ($x_i$, θ) with the «vertex-time» pair ($x_j$,$\theta+\tau_{ij}(\theta)$) equals to $V^{\mu}(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))=V^{\mu}(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))-\zeta(x_i, x_j,\theta,\theta+\tau_{ij}(\theta))=\infty$. Residual throughput of corresponding reverse arcs $V^{\mu}(x_i, x_j, \theta+\tau_{ij}(\theta),\theta)=\zeta(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))$ cost $Z^{\mu}(x_i, x_j,\theta+\tau_{ij}(\theta),\theta)=-Z^{\mu}(x_i,x_j,\theta,\theta+\tau_{ij}(\theta))$. The residual network initially coincides with the original graph. The path $P^{\mu}{}_{p}$ of the minimum cost in the constructed residual network is determined using the Ford-Bellman algorithm. If there is no such path and the analysis of all analyzed p periods is performed, then it is possible to draw a conclusion about the correspondence of the previously found path variant to the optimal one and proceed to step 9. If there is no such path only within the analyzed periods (at the time moment θ) and it is possible to make a transition to the next period ($\theta+\tau_{ij}(\theta)$), then add the vertices and arcs of this period to the graph. Since the throughput capacities of the arcs of each of the periods, connecting the vertices of the graph 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 arcs connecting a «vertex-time» pair ($x_S$,$\theta+\tau_{ij}(\theta)$) with the «vertex-time» pair ($x^{\mu}{}_j$,$\theta+\tau_{ij}(\theta)$), and «vertex-time» pair ($x^{\mu}{}_i$,$\theta+\tau_{ij}(\theta)$) with the «vertex-time» pair ($x_T$,$\theta+\tau_{ij}(\theta)$), according to (2), (3). If the path is found, then proceed to the next step.

$$V_{L_N}\left(\theta+\tau_{ij}(\theta)\right)=V_N-\sum_{\theta=1}^{\theta=p}\xi_{L_N}(\theta) \qquad (2)$$

$$V^{y}\left(\theta+\tau_{ij}(\theta)\right)=Q^{y}_{U}-\sum_{\theta=1}^{\theta=p}\xi^{y}(\theta) \qquad (3)$$

$$\delta^{\mu}_{p}=\min\left\{\begin{array}{c}
\left(\underset{\text{where }(x_S,x_j^h)\in P^{\mu}_{p\,(S\to T)}}{V^{\mu}(x_S,x_j^h)}\right); \\
\min\left(\underset{\substack{\text{where }(x_S,x_i^h)\in P^{\mu}_{p\,(S\to T)}\\ \theta\in[0,p]}}{V^{\mu}(x_S,x_i^h,\theta,\theta)}+\underset{\substack{\text{where }(x_i^h,x_S)\in P^{\mu}_{p\,(T\to T)}\\ \theta\in[0,p]}}{\frac{1}{f^*}\cdot V^{\mu}(x_i^h,x_S,\theta,\theta)}\right); \\
\min\left(\underset{\substack{\text{where }(x_i^h,x_j^h)\in P^{\mu}_{p\,(S\to T)}\\ \theta\in[0,p]}}{V^{\mu}\left(x_i^h,x_j^h,\theta,\theta+\tau_{ij}(\theta)\right)}\right); \\
\min\left(\underset{\substack{\text{where }(x_i^h,x_j^{h+1})\in P^{\mu}_{p\,(S\to T)}\\ \theta\in[0,p]}}{V^{\mu}(x_i^h,x_j^{h+1},\theta,\theta)}+\underset{\substack{\text{where }(x_j^{h+1},x_i^h)\in P^{\mu}_{p\,(T\to T)}\\ \theta\in[0,p]}}{\frac{1}{f^*}\cdot V^{\mu}(x_j^{h+1},x_i^h,\theta,\theta)}\right); \\
\min\left(\underset{\substack{\text{where }(x_i^h,x_j^{h+1})\in P^{\mu}_{p\,(T\to T)}\\ \theta\in[0,p]}}{\frac{1}{f^*}\cdot V^{\mu}\left(x_i^h,x_j^{h+1},\theta+\tau_{ij}(\theta),\theta+\tau_{ij}(\theta)\right)}\right); \\
\min\left(\underset{\substack{\text{where }(x_i^h,x_j^h)\in P^{\mu}_{p\,(T\to T)}\\ \theta\in[0,p]}}{\begin{array}{c}\frac{1}{f^*}\cdot V^{\mu}(x_j^h,x_i^h,\theta+\tau_{ij}(\theta),\theta); \\ \frac{1}{f^*}\cdot V^{\mu}\left(x_i^h,x_j^h,\theta,\theta+\tau_{ij}(\theta)\right)\end{array}}\right) \\
\left(\underset{\text{where }(x_i^h,x_T)\in P^{\mu}_{p\,(S\to T)}}{V^{\mu}(x_i^h,x_T)}\right); \\
\min\left(\underset{\substack{\text{where }(x_i^h,x_T)\in P^{\mu}_{p\,(S\to T)}\\ \theta\in[0,p]}}{V^{\mu}(x_i^h,x_T,\theta,\theta)}+\underset{\substack{\text{where }(x_T,x_i^h)\in P^{\mu}_{p\,(T\to T)}\\ \theta\in[0,p]}}{\frac{1}{f^*}\cdot V^{\mu}(x_T,x_i^h,\theta,\theta)}\right);
\end{array}\right\} \qquad (4)$$

$$f^* = \frac{f^*_{h,h+1}}{f^*_{h+1,h}} \qquad (5)$$

3. The maximum throughput of the identified pathis determined by (4). 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 θ to a dummy effluent, machine-shifts; $f_{h+1,h}$ - labor costs characterizing the response to the analyzedsaturated arc of a narrow production area, the reverse arc at the time point θ, machine-shifts.
4. The values of flows along the arcs of the graph $G_p$ are updated:

- forarcs, connecting the «vertex-time» pairs $(x^{\mu}_{i,}\theta+\tau_{ij}(\theta))$ with in the graph $G^{\mu}_{p}$ with cost $C(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))\le 0$, the flow $\zeta\,(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))$ along similar arcs of the graph $G_p$, directed from $(x_j, \theta)$ to $(x_i,\theta+\tau_{ij}(\theta)$ is replacedby the value $\zeta\,(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))-\delta^{\mu}_{p}$;
- for arcs connecting the «vertex-time» pairs $(x^{\mu}_{i,}\theta)$ with $(x^{\mu}_{ij,}\theta)$ in the graph $G^{\mu}_{p}$, with cost $C(x_i, x_j, \theta, \theta)\le 0$, the flow $\zeta\,(x_i, x_j, \theta, \theta)$ along similar arcs of the graph $G^{\mu}_{p}$, directed from $(x_j, \theta)$ to $(x_i, \theta)$, is replaced by the value $\zeta\,(x_i, x_j, \theta, \theta)-\delta^{\mu}_{p}$;
- for arcs connecting the «vertex-time» pairs $(x^{\mu}_{i,}\theta)$ with $(x^{\mu}_{j},\theta+\tau_{ij}(\theta))$ in the graph $G^{\mu}_{p}$, with cost $C(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))\ge 0$, the flow $\zeta\,(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))$ along similar arcs of the graph $G_p$, directed from $(x_{i,}\theta)$ to $(x_j,\theta+\tau_{ij}(\theta)$ is replaced by the value $\zeta\,(x_i, x_j, \theta, \theta+\tau_{ij}(\theta))+\delta^{\mu}_{p}$;
- for arcs connecting the «vertex-time» pairs $(x^{\mu}_{i,}\theta)$ with $(x^{\mu}_{j,}\theta)$ in the graph $G^{\mu}_{p}$, with cost $C(x_i, x_j, \theta, \theta)\ge 0$, the flow $\zeta\,(x_i, x_j, \theta, \theta)$ along similar arcs of the graph $G_p$, directed from $(x_{i,}\theta)$ to $(x_{j,}\theta)$ is replaced by the value $\zeta\,(x_i, x_j, \theta, \theta)+\delta^{\mu}_{p}$;
- the values of the flows are updated along the arcs connecting:

«vertex-time» pair $(x^{\mu}_{j,}\theta)$ with «vertex-time» pair $(x_{s,}\theta)$ by the value $\zeta\,(x_j, x_S, \theta, \theta)-\delta^{\mu}_{p}$;

«vertex-time» pair $(x_{T,}\theta)$ with «vertex-time» pair $(x^{\mu}_{i,}\theta)$, by the value to $\zeta\,(x_T, x_i, \theta, \theta)-\delta^{\mu}_{p}$.

5. The cost of the accepted path is determined:

$$\sum C = \sum_{(x_i,x_j)\in P^{\mu}_{p(S\to T)}} C_{(x_i,x_j)} + \left( \sum_{(x_j,x_i)\in P^{\mu}_{p(T\to T)}} C_{(x_j,x_i)} + \sum_{(x_i,x_j)\in P^{\mu}_{p(T\to T)}} C_{(x_i,x_j)} \right)\cdot f^* \qquad (6)$$

where $P^{\mu}_{p(S\to T)}$ - a section of a path consisting of straight arcs going in the direction from a dummy source to a dummy effluent; $P^{\mu}_{p(T\to T)}$ - a section of the path including forward and reverse arcs, directed from the dummy effluent and returning back, creating a cycle; $\sum_{(x_i,x_j)\in P^{\mu}_{p(S\to T)}} C_{(x_i,x_j)}$ - total variable costs on the section of the path from a dummy source to a dummy effluent along straight arcs, m.u.; $\sum_{(x_j,x_i)\in P^{\mu}_{p(T\to T)}} C_{(x_j,x_i)}$ - total variable costs on a cyclic section of the path along the reverse arcs, m.u.; $\sum_{(x_i,x_j)\in P^{\mu}_{p(T\to T)}} C_{(x_i,x_j)}$ - total variable costs on a cyclic section of the path along the straight arcs, m.u.

6. The time m(θ) remaining until the end of the period is calculated.
7. a) the bandwidth and weight of the arcs connecting«vertex-time» pair $(x_{s,}\theta)$ with «vertex-time» pair $(x^{\mu}_{j,}\theta)$ are replacedby the value $V_{LN}(x_s, x_j, \theta, \theta)-\delta^{\mu}_{p}$; b) the bandwidth and weight of the arcs connecting«vertex-time» pair $(x^{\mu}_{j,}\theta)$ with «vertex-time» pair $(x_{T,}\theta)$ are replaced by the value $V^{y}(x_s, x_j, \theta, \theta)-\delta^{\mu}_{p}$. The weight characteristics of the reverse arcs obtained when the flow passes through the arcs of the graph are equal to $C^{X}_{ji}=-C^{X}_{ij}$. Replacement of capacities on the arcs corresponding to the same technological operations is carried out:

$$D^{X}_{ij}(\theta) = \frac{m^*(\theta)}{f^{X}_{ij}(\theta)} \qquad (7)$$

8. A residual network is constructedand the transition to stage 2 is performed.
9. The transition to the initial dynamic graph is performed by dropping the dummy vertices S and T.

## *DISCUSSION*

According to the authors, as a result of using the proposed algorithm, it is possible to determine a rational sequence of development of forest areas, performing loading-unloading and processing operations, to justify the need of use forest warehouses, to determine the minimal total costs of the implementation of the work plan for transport and relocation operations and the profit received by selling products to the consumer.

For the wide implementation of the developed algorithm in production, it is advisable to develop software that will increase the degree of process automation of finding an effective sequence of technological operations performed during logging at timber enterprises of the Russian Federation.

## *CONCLUSION*

The proposed algorithm allows us to determine the effective technological chain of logging operations in dynamic natural production conditions.

Therefore, it can be considered as a methodological basis for the design of logging infrastructure, taking into account the dynamically changing environment.

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