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

Mathematical Modelling of Engineering Problems
Vol. 11, No. 4, April, 2024, pp. 1071-1078
Journal homepage: http://iieta.org/journals/mmep

A Comprehensive Assessment of Forest Transport Network Planning Taking into Account the Project's Technical, Economic, Environmental, and Social Aspects

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https://doi.org/10.18280/mmep.110425

Received: 6 October 2023
Revised: 17 January 2024
Accepted: 30 January 2024
Available online: 26 April 2024

Keywords:
forest categories, forest land, forest transportation network, integrated efficiency, mathematical model, resource potential, system approach

ABSTRACT

This research article examines the role of the transportation network in sustainable forest management and forest use within the forest reserve. The authors discovered a link between the efficiency of multipurpose forest management and the efficiency of the forest transportation network. The authors did draw attention to the fact that there needs to be a comprehensive methodology for assessing the efficiency of network planning for forest transportation. They also found that the efficiency of forest road network planning for reserve and protective forests needs to be evaluated. In this article, the authors define the fundamental parameters of forest transportation networks based on forest type and propose a method for obtaining a reliable assessment of the forest road network's efficiency. The estimation is based on the multipurpose nature of forest use and how forest land resource potential grows based on forest category. The authors suggest a comprehensive approach based on a mathematical model which includes elements of financial mathematics, combinatorics, and mathematical statistics to assess the efficiency of forest transportation network planning. By integrating diverse methodological tools into a unified forest transportation network planning tool, it becomes possible to precisely calculate the time required to recoup the costs associated with establishing and expanding a forest road network. The model takes into account the geographical arrangement of the network's individual elements and their dependence on the specific forest category in which it is designed. They also apply a systematic approach and economic and mathematical modelling, including linear and dynamic programming.

1. INTRODUCTION

Forest transport infrastructure is an essential factor in sustainable forest management and use. Without a sufficiently developed forest transportation network, it is technically, economically, environmentally, and socially impossible to realise the resource potential of forest land [1, 2]. Developing a forest transportation network is critical for long-term forest management and use. It is an essential component of forest infrastructure that ensures access to forest resources, harvesting, transportation, and further processing [3]. When adequate forest transport infrastructure is in place, harvesting and reforestation procedures can be optimised, access to inaccessible forest regions can be improved, the efficient use of forest resources can be ensured, and the productivity of the forest industry can be increased [4]. Forest management and forest transportation efficiency are interdependent. In its many facets, forest management serves many purposes and is intricate. Therefore, a comprehensive evaluation of the forest transportation network, which serves as a mechanism for achieving all forest benefits, is required [5, 6].

However, there is currently no systematic method for assessing the success of network planning for forest transport in the various forest categories. Researchers in this field mostly focus on basic forest management and commercial forests. Even though commercial forests are a vital part of the forest infrastructure, there are other types of forests where reforestation, forest conservation, and protection are carried out within the scope of permitted forest use [7-9]. In this context, the rational planning of the forest transportation network in reserve and protective forests is necessary.

The technical and economic, environmental, and social components are just a few of the different factors that go into determining how effectively a forest transport network is planned [10]. The technical and economic component relates to maximising the use of forest resources, lowering transportation expenses, and raising management productivity [11]. The environmental component considers the conservation of natural resources, biodiversity, and forest ecosystem services [12]. The social component entails satisfying the needs of forest users, ensuring the accessibility of forest resources for various population groups, and considering the local community's and public's interests [13].

The development of the forest transportation network and the rationality of forest management planning are currently the subject of a large number of scientific works, both in Russia and abroad [1-3, 10-15]. However, there is a lack of a unified and comprehensive approach to assessing the effectiveness of marked planning in this literature. The efficiency of the forest road network is frequently evaluated only in the context of basic forest management and commercial forests, ignoring other categories of forests and related management and conservation measures [16].

The current version of the Forest Code of the Russian Federation divides the country's forest fund into three categories: protective forests, commercial forests, and reserve forests. Each category has its own set of rules for managing and using the forest, and a network of forest roads is used to ensure that these rules are followed. The current state of the forest transportation network determines when finished products are removed from the forest when forestry work is scheduled, when planting materials, machinery, and workers are delivered on time to the work site, and when firefighting supplies arrive on time to prevent and fight forest fires [17-19]. The spatial configuration and element-by-element components of the forest road network differ depending on the type of forest in which it is located [20]. Table 1 shows the basic parameters of forest transportation networks based on forest category.

Table 1. Basic parameters of forest transportation networks by forest category [21, 22]

Elements of the Forest Transportation Network	**Period of Operation of Forest Roads**	**Rolling Stock in Use**	**Service Life**	**Average Annual Daily Traffic Intensity, Vehicles per Day**	**Annual Cargo Turnover, Million Tonnes (net)**	**Forest Road Category**
1	2	3	4	5	6	7
			Commercial forests			
Lumber and forestry vehicles, including firefighting vehicles	Continuous action	Lumber trailers, trucks and special vehicles with up to 8 t axle load	Unrestricted for permanent roads or limited to temporary forest roads	More than 200 100-200 50-100 Less than 50	0.35 to 0.7 0.14 to 0.35 Less than 0.14 Not set	I-LV II-LV III-LV IV-LV
	Summer operations	Lumber truck trains, trucks and		Less than 50 50-100	Not set Less than 0.14	IV-LV III-LV
	Winter operations	Special vehicles with an axle load of up to 8 t.		Less than 50		IV-LV
			Reserve and protective forests			
Forestry, including firefighting vehicles	Continuous action	Trucks and special vehicles with an axle load of up to 8 tonnes	Unlimited	50-100 Less than 50 in reserve forests	Up to 0.14	II-LH III-LH II-LH III-LH

According to Table 1, there are no forest roads in reserve and protective forests because these types of forests are not used for logging purposes. Given this situation, the forest transportation network in the designated forest categories consists of forest roads, including firefighting roads. Forest roads are highly important because they allow for the high-quality implementation of forest management activities like reforestation, forest protection, and conservation, despite the low traffic volume on these roads. In this situation, it is clear that the forest road network needs to be planned well, not just in commercial forests, to ensure that the forests are managed and used efficiently.

The aim of this project is to provide a dependable and flexible set of methods that can be used to evaluate the overall effectiveness of the forest transportation network across different types of forests. This method will encompass all facets of performance evaluation, encompassing the technical and economic, environmental, and social elements. This methodology will facilitate the optimisation of the forest transportation network, ensuring the efficient use of forest resources, preservation of the natural ecosystem, and fulfilment of diverse societal demands. Developing a thorough approach to assess the effectiveness of the forest transportation network is a pressing priority in contemporary forest management. Implementing this approach will provide a more precise assessment of the impact of forest transportation infrastructure on sustainable forest management, hence optimising the use of forest resources and enhancing the quality of life for individuals employed in or residing near forests. The utilisation of a robust and adaptable methodological framework in the design and development of the forest transport network will enable the attainment of sustainable development in forest regions and the conservation of the natural heritage for future generations. It should be noted that similar studies were carried out on the example of forests in the Brazilian Amazon [23] and Taojiang County (China) [24].

2. MATERIALS AND METHODS

The discussed circumstance necessitates the development of a scientific justification for forest transportation network planning in the various forest categories. This allows for evaluating the process's efficiency applying to all influencing factors. One such justification could be assessing the efficiency of the planned forest road network. However, the question of how to arrive at this assessment arises.

Currently, due to their high capital intensity, forest roads in commercial forests are the focus of most cases when the efficiency of forest road planning is assessed [25]. Reserve and protective forests are completely disregarded when the efficiency of forest road planning is assessed, and instead, rely solely on environmental or economic indicators solely for logging purposes. Such an approach is insufficient because it overlooks the multifaceted importance of forests and the multipurpose use of forest benefits, which occurs not only in commercial but also reserve and protective forests.

To determine the most accurate assessment of how well the forest road network works, it is important to note that forest land resources are one of the most important ways to measure how well the forest transportation network works [26]. This indicator encompasses a multilateral evaluation of the forest land resources to be used from any potential economic activity areas within the boundaries of commercial, reserve, or protective forests. Accordingly, it is inherently integral (Table 2).

Table 2. Forest land resources depending on the forest category

Type of Economic Activity	**Forest Category**		
	Commercial	**Reserve**	**Protective**
Use of forest resources from the perspective of the basic forest management			
Forest use (clear-cutting conditions)	Basic forest management cuttings, as well as sanitary cutting if the entire stand has lost its stability and target function (also after a fire)	Sanitary cutting if the entire stand has lost its stability and target function (also after a fire).*	
Forest use (thinning conditions)	Thinning (lighting, thinning, weeding, clear-cutting) and sanitary cutting of diseased, damaged and dying trees*		
Use of forest resources from the perspective of permitted forest use			
Direct forest management	Harvesting of oleoresin, harvesting and gathering of non-timber forest resources, hunting, fishing, recreation, research and religious activities and other economic activities specified in the Forestry Code of the Russian Federation, depending on forest categories.**		
Indirect forest management	The use of the forest's ecological and soil-protective functions (primarily in protective forests, but special protective areas can be designated in commercial and reserve forests). All forest areas not subject to basic logging are referred to as having carbon-sequestering functions of forests.		
Deferred alternative to using the forest area resources	When looking at the value of forest land resources from the standpoint of fundamental forest use, reserve forests and other forest areas where any kind of forest use is impossible due to a lack of a forest transportation network are more heavily affected. Inaccessible forest areas intended to be reclaimed should be considered a deferred alternative to forest use (future income).		
The forest as an object of existence	Use of wilderness' ethical and aesthetic factors based on the willingness to pay theory (recreational value)***		

Note: *Logging is permitted in reserve forests for citizens harvesting timber for their own needs and for the geological study of subsoils [Forest Code of the Russian Federation];

** The types of forest use permitted for implementation in protective forests located on forest fund lands are governed by forestry regulations [Forest Code of the Russian Federation].

***The willingness to pay theory assumes that the travel expenses travellers (vacationers) incur when visiting a natural site reflect, in part, the recreational value of a forest area.

Based on the information in Table 2, it is simple to conclude that due to the complexity of forest land resources, it is not possible to evaluate their use solely through the lens of technical and economic or environmental-economic indicators in order to prevent incompleteness and, consequently, the unreliability of such an assessment.

There is a strong correlation between the effective management of forest land resources and the efficiency of the forest transportation network. Access to inaccessible forest areas is made possible by well-developed forest transport infrastructure, which helps with resource harvesting and transportation and promotes reforestation and fire safety. Therefore, the relationship between the use of forest land resources and the state of the transport infrastructure should be considered when evaluating how effective forest transport network planning is.

A systematic approach is required to assess the efficiency of forest transportation network planning. Forest transportation network planning includes various road and transportation components that interact with one another and other forest infrastructure elements. Therefore, the evaluation model should include all of these components and their interactions to determine the system's overall efficiency.

Additionally, it should be noted that the various assessment methods should work in concert when seeking to determine the effectiveness of the forest transportation network. The interdependence and interaction of various parameters and efficiency indicators can significantly impact the overall efficiency of forest transport network planning. Therefore, the evaluation model must be able to account for these synergies and provide an exhaustive evaluation of efficiency. Given the foregoing, assessing how efficient forest transport network planning is should be comprehensive and systematic. Indeed, forest transportation network planning includes road and transport components, which are actually systems composed of elements defined by the assessment focus. The synergy between the assessment tools must also be considered (Figure 1).

It can be concluded that there is a significant need to develop a reliable method for assessing the efficiency of forest transportation network planning. This is based on the need for a scientific justification for rational planning of the forest transportation network for various forest categories. This method should be adaptable enough to be used for planning forest transportation networks for various forest types, and it should include an assessment of both the road and transportation components of the forest road network planning project. Developing a methodological set that satisfies the outlined criteria enables the implementation of such an assessment method.

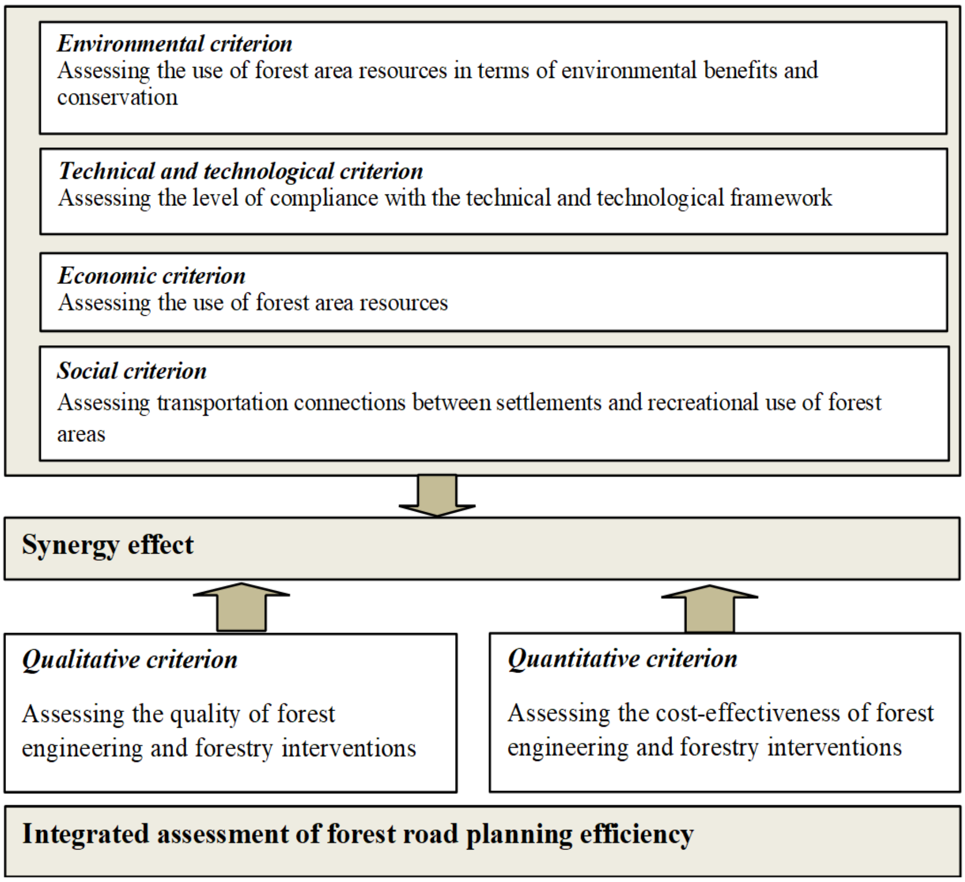

Figure 1. Systematic approach to the integrated assessment of forest transportation planning efficiency

3. RESULTS AND DISCUSSION

The following correlation can be derived from the systematic approach in determining the integrated forest transportation network efficiency planning (E_p) for various forest categories in terms of the road planning component:

$$E_p = \{E_{rp} = \frac{(P^{rm}+P^{ec})^2 \cdot (t+1)^2}{{C_{tot}}^2 \cdot t^2} \times 100\% \; E_{rf} = \frac{(P^{rm}+P^{ec})^2 \cdot (t+1)^2}{(\sum_l^L C_s + \sum_d^D C_s)^2 \cdot t^2} \times 100\% \; E_{ff} = \frac{{C_{de}}^2 (t+1)^2}{{C_{tot}}^2 \cdot t^2} \times 100\% \quad (3)$$

where, E_{rp} is the efficiency of use of forest land resources depending on the forest category and considering the current state of the forest transportation network during the period from t to (t+1), rub./rub.; E_{rf} is the efficiency of reforestation measures implemented with respect to the current state of a forest transportation network during the period from t to (t+1) by forest categories, rub./rub.; E_{ff} is the efficiency of fire prevention measures implemented with respect to the current state of a forest transportation network during the period from t to (t+1) for each forest category, rub./rub.; C_s is the normative costs required to reproduce the *l-th* species, $l \ni [0, \dots, L]$(*d-th* resource) $d \ni [0, \dots, D]$ while ensuring their regeneration (both after clear-cuts in commercial forests and after sanitary cutting, as well as after forest fires by forest category), growing to maturity, protection and conservation during the period from t to (t+1), rub./ha; C_{tot} is the total costs for creating and developing (including reconstruction and repair) a forest transportation network by forest category, and this index includes costs related to the necessity of creating an extra road network during the period from t to (t+1), rub./ha; C_{de} is the value of the ecological-economic damage to forest ecosystems caused by forest fires and prevented due to timely fire prevention measures during the period of (t+1), rub./ha. This indicator is found according to the methodological set outlined by Abuzov et al. [27]. The expression P^{rm}+P^{ec} is the total gross profit from multipurpose forest use during the period of (t+1), rub./ha. Here, the indicator P^{rm} is the profit from selling raw wood material (mostly from commercial forests). Concerning the indicator P^{ec}, it should be noted that it is an integral value which includes both profit from ecological services the forest receives and profit from the permitted (secondary) forest use depending on the forest category and how forest land resources are used in the social aspect (tourism; hunting; fishing; collecting medicinal herbs, berries; research activities) according to the Forest Code of Russia.

The following correlation in terms of determining the overall efficiency of forest transportation network planning for various forest categories is determined using a systematic approach as part of the transportation component of the planning project discussed above:

$$E_{rs}^t = \{E_{rs}^{tw} = \frac{{P_t^{tw}}^2 \cdot (t+1)^2}{{C_t^{tw}}^2 \cdot t^2} \times 100\% \; E_{rs}^{ts} = \frac{{P_t^{ts}}^2 \cdot (t+1)^2}{{C_t^{ts}}^2 \cdot t^2} \times 100\% \; E_{rs}^{tg} = \frac{L_t^{tg}(t+1)}{L_{t+1}^{tg}(t)} \times 100\% \; E_{rs}^{ff} \frac{t_f(t)}{t_s(t)} \times 100\% \quad (2)$$

where, E_{rs}^{t} is the efficiency of rolling stock used for timber transportation, depending on the current state of the transportation network within the forest fund area. This indicator mostly relates to finding the overall efficiency of the forest transportation network in commercial forests. However, it also partly concerns thinning or harvesting operations required when this network is erected and developed in reserve and protective forests during the period from *t* to (*t*+1), rub./rub.; E_{rs}^{ts} is the efficiency of the rolling stock used for transporting non-timber forest products and forest products by forest category depending on the current state of the transportation network within the forest fund during the period from *t* to (*t*+1) rub./rub.; E_{rs}^{tg} is the efficiency of intersettlement freight exchange depending on the current state of the transportation networks laid within the forest fund area by forest category during the period from *t* to (*t*+1), rub./rub.; E_{rs}^{ff} is the efficiency of the delivery of firefighting brigades and vehicles depending on the current state of the transportation network laid within the forest fund area by forest category during the period from *t* to (*t*+1), rub./rub.; P_{t}^{tw} is the total productivity of timber trucks in terms of transportation costs per vehicle shift during the period of (*t*+1), rub. C_{t}^{tw} is the total cost of a vehicle shift for timber hauling during the period from *t* to (*t*+1), rub.; P_{t}^{ts} is the total cost-based productivity of rolling stock used to move secondary forest resources and deliver forestry cargo per vehicle shift by forest category during the period of (*t*+1), rub.; C_{t}^{ts} is the total cost of a vehicle shift in secondary forest resources transportation and cargo delivery by forest category during the period of *t* to (*t*+1), rub.; L_{t}^{tg} is the distance of cargo delivery between settlements during the period *t*, km; L_{t+1}^{tg} is the distance of cargo delivery between settlements depending on the current level of the transportation networks laid within the forest fund area during the period of (*t*+1), km; t_f is the actual time of delivery of firefighting vehicles and fire brigades to the fire seat during the period from *t* to (*t*+1), *h*. This indicator is found as a ratio of normative time to estimated time required for transporting firefighting vehicles and fire brigades to the fire seat using separate elements of the forest transportation network by forest category (including cross-country distances). Here, the inevitable slowing of forest trucks' average technical speeds is also considered. t_s is the normative time for transporting people and firefighting equipment that shall not exceed 1 hour for forest areas of the first flammability category, 2 hours for the second, and 3 hours for the third, fourth, and fifth flammability category.

The overall integrated efficiency of forest transport network planning for different forest categories is an integral value generator in and of itself for the transportation and road components of the planning project. Hence, it is reasonable to combine the systems denoted by Eqs. (1)-(2) into a single methodological set because

The authors have added a restriction to the growth of the integrated efficiency in terms of the cost-effectiveness of the forest transport network planning project by forest category. This restriction is how the integration above is made using the formula for calculating the geometric mean. This restriction is caused by the inherent inability of the function that determines the overall effect to target an infinite increase in the final indicator.

Thus, the Eqs. (1)-(2) are integrated as follows:

$$E_{tot} = \sqrt[7]{E_{rp}\, E_{rf} \cdot E_{ff} \cdot E_{rs}^{tw} \cdot E_{rs}^{ts} \cdot E_{rs}^{tg} \cdot E_{rs}^{ff}} \qquad (3)$$

It should also be noted that the methodological set presented has the following limitations:

1. The payback of a forest transportation network planning project by forest category:

$$\frac{P^{rm} + P^{ec}}{(1+e)^{t}} \cdot \left(1 + \frac{1}{(1+e)^{(t+1)}}\right) > C_{tot} \qquad (4)$$

where, *e* is the discount factor. This indicator was added to the model due to the possibility of changes in the price parameters of production processes during the period from *t* to (*t*+1).

2. Financial sustainability of a company investing in the forest transportation network planning project:

$$\frac{C_{tot}}{(1+e)^{t}} \cdot \left(1 + \frac{1}{(1+e)^{(t+1)}}\right) \le C_{max} \qquad (5)$$

where, C_{max} is the company's financial capacity during the period from *t* to (*t*+1), rub.

3. Cost recovery of reforestation costs:

$$\frac{\sum_{l}^{L} C_s + \sum_{d}^{D} C_s}{(1+e)^{t}} \cdot \left(1 + \frac{1}{(1+e)^{(t+1)}}\right) \le P^{rm} + P^{ec} \qquad (6)$$

4. Transport accessibility of forest plots and wildfire-affected areas, as well as natural road-building material sites:

According to Abuzov et al. [27], the effective distance of delivery of construction brigades, equipment, and road construction materials to the *i-th* forest plot from the *j-th* point of departure should not exceed the economically available delivery distance:

$$L_{ij} \le L_e \qquad (7)$$

where, L_{ij} is the distance between the *i-th* forest plot and the *j-th* raw material depot (departure point of construction brigades and equipment, and the location of natural building materials), km; L_e is the economically feasible delivery distance, km.

5. Actual assessment of forest area resources surviving after fires:

$$C_{de} \le \mathrm{C}_{tot}^{rf} \qquad (8)$$

where, C_{tot}^{rf} is the total economic value of the forest resources during the period of *t*, rub./ha.

This restriction will prevent the duplication of estimates when calculating the total economic value of forest resources surviving the negative effects of fires in the same forest plot to avoid exceeding the amounts of surviving forest resources over those actually available for the period of (*t*+1).

The restrictions of the target features in the above mathematical model also include natural non-negativity of freight flows; the requirement for continuous, sustainable forest management; compliance of the speeds of light and heavy trucks with regulatory requirements; the naturally occurring reduction in the average technical speeds of forest trucks; and compliance of the actual arrival time of firefighting vehicles and fire brigades to a fire seat with that accepted in the regulations.

Additionally, it should be noted that the developed methodological set is adaptable enough to permit its use in various natural production settings.

Forest roads play a crucial role in managing forests and providing access for many activities, including leisure, rescue operations, firefighting, and interventions to maintain forest health. The process of constructing new forest roads and redesigning old ones can be intricate due to the inclusion of elements such as location, design, construction, and maintenance in the decision-making process. Hence, the task of achieving the most efficient road network planning, road alignment, and road design continues to be a difficult endeavour. Hence, the use of cutting-edge analysis techniques and the growing accessibility of high-resolution data, in conjunction with conventional survey methods, may greatly enhance the effectiveness of forest road planning, design, and management. The models that we developed are combined with the works of other authors in this area of research [28, 29], which provides evidence for their validation. When compared to alternative models [23, 24, 28, 29], the developed model offers a thorough evaluation of the planning of forest transport networks, considering the technical, economic, environmental, and social dimensions of the project. The model adapts continuously to all tangible and intangible forest management benefits. In addition, it facilitates the assessment of the quality of forestry measures implemented, the determination of the optimal rolling stock operation schedule, and the evaluation of the condition of forest roads and transportation connections connecting settlements.

According to data reported by Gerasimov et al. [30], the average density of forest roads in Russia is less than 1.5 m/ha, which is one tenth of the road density in the Nordic countries. As stated by Smirnov et al. [31], the absence of an adequate number of roads that operate continuously results in the annual isolation of approximately 15 million residents of forest settlements during the autumn and spring seasons, disrupts the rhythm of the timber-hauling process, and raises the cost of forest products. Using the developed model in practice will significantly reduce these problems.

Furthermore, it is not advisable to promote the establishment of "greenfield" initiatives in undeveloped forest regions that are presently devoid of any form of infrastructure. Regions characterised by productive southern taiga, mixed and deciduous forests, well-established wood-processing infrastructure, and dense forest roadways may be the key to facilitating the transition towards resilient forestry in a financially advantageous manner. All this will help reduce the negative environmental load on forests in Russia [32].

4. CONCLUSIONS

A model for assessing the efficiency of forest transport network planning has been developed in this paper to calculate the project's cumulative effect. The model is built using various methodological tools, including the system approach, mathematical statistics, financial mathematics, probability theory, combinatorics, and dynamic and economic-mathematical modelling.

The developed model provides a comprehensive assessment of forest transport network planning while taking into account the project's technical, economic, environmental, and social (tourism, hunting, fishing, collecting medicinal herbs, berries, research activities) aspects. The model continuously adapts to all tangible and intangible benefits from forest management. Furthermore, it aids in determining the quality of forestry measures delivered, selecting the most efficient rolling stock operation schedule, and determining the current state of forest roads and transportation connections between settlements.

Incorporating various methodological tools into a single forest transportation network planning tool allows for accurately determining the cost-recovery period for creating and developing a forest road network. The model considers the network's element-by-element spatial configuration and its reliance on the forest category in which it is planned.

Therefore, the developed model provides a tool for making optimal engineering decisions when planning the forest transportation network. It helps to make better use of forest resources, improve forest management activities, build transportation infrastructure, and improve connectivity between settlements.

Future research will focus on further improving and testing the applicability of the model in various contexts in the Russian Federation and other countries.

ACKNOWLEDGMENT

The study was carried out within the confines of the Scientific School Advances in Lumber Industry and Forestry.

Part of the research materials were obtained through the Russian Science Foundation (Grant No.: 23-16-00092), found at https://rscf.ru/project/23-16-00092/.

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