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# Mathematical model of transport network planning on the territory of the forest fund

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**Abstract.** The main purpose of the paper is to develop a mathematical model for planning the transport network in the territory of the forest fund based on the criteria of ecological and economic efficiency. Setting the goal is caused by the fact that, despite the urgency of the problem of ensuring effective ecological, social and economic development of forest fund and the existing scientific achievements in this field, both in Russia and abroad, the scientific base has accumulated a small amount of research that considers forest transport systems as one of the main factors that contributes to achieving the goal of sustainable development of forest territories in modern conditions of management. The complex analysis of the ecological and economic efficiency of transport network planning in the forest fund territory is only indirectly present in the scientific literature and is local in nature. The paper presents an approach according to which a qualitative criterion is formed for evaluating the effectiveness of the transport network functioning on the territory of the forest fund as achieving the maximum of all potential revenues from the use of various types of forest resources and the ecological potential of the territory on the basis of the planned network.

## 1. Introduction

The transport system which operating on the territory of the forest fund of the country's regions (TSFF) in general can be considered as a complex transfer, dynamically developing, system of roads, vehicles, loading, reloading, unloading machines that connect a set of cargo-forming forest blocks and allotments with the transit route of transport of forest products to consumers. There are technological, technical and economic, organizational and managerial links between the elements of the TSFF, which together determine its structure in 2 aspects - static (stable relations) and dynamic (the way of the elements function and interact) [1].

A distinctive feature of the development of the transport network of forest territories in the region is the use of territorial and sectoral approaches that take into account both the interests of cargo carriers – users of forest roads, and the needs of progressive social and economic development of forest territories. Within the framework of the territorial approach, such elements as public roads of forest territories, specialized transport and logistics centers, roadside organizations of repair and service that affect the social and economic development of forest territories are identified. The industry approach identifies a system of special logging roads that affect the functioning of the regional logging complex [2].

In general, TSFF planning is a multi-criteria task, since the cost of its construction and operation, ecological, social and technical efficiency are contradictory. Based on the criteria that contradict each



other, it is necessary to consider the planned TSFF and the territory of the forest fund intended for development as a single system that is existed in synergetic relationships with each other. Since the World community and Russia have declared the transition to the principles of sustainable development, we propose to evaluate the effectiveness of the planned TSFF, taking into account the ecological and economic indicators of the project.

## 2. Methods of the research

Historically, our forest roads were built only for the development of woodlands with mature stands, without regard to the optimal situation in the context of the territory of the forest fund of the region as a whole. With the transition to a market economy, the construction of forest roads in Russia has almost stopped.

Today, the Federal level has decided to finance the construction of forest roads from budgets of various levels, since the State, represented by its subjects, according to the current Forest Code of the Russian Federation, is the owner of forest land. To effectively address this extremely resource-intensive problem, it is necessary to develop strategic principles for planning the TSFF, taking into account the current realities of the market economy and the transition of the World community and Russia to the principles of sustainable development, declared for the first time at the international level by the UN Conference on sustainable development (Rio-92 [1]) and, to the extent possible, promoted by the World community (Johannesburg-2002 [2]; the UN Economic Commission for Europe, 2012 [2]; Fücks, 2014 [3] Duwe, 2015 [4]; G.I. Broman and K.-H. Robert, 2017 [5] etc.).

It is obvious that the rational inclusion of individual roads in the overall system of the TSFF is a complex, but very important task for society. TSFF as a system exists in a production environment that is subject to constant changes – the parameters of the forest fund change in accordance with the biological patterns of growth of stands, there is a transfer of part of the forest territory from one category to another, changes in forest and ecological legislation, requirements for the technologies used, etc. This is why it is effective if its parameters meet the requirements of the external environment at any given time. The process of such appliance is an adaptation, so now it is relevant to consider the TSFF not only as a formed system in the form of a materialized unity of interconnected technical objects, but also as a complex open system characterized by functioning, development and adaptation in relation to the external environment. This consideration reflects not only the needs of production, but also the current level of research of transport systems, which is consistently developing with the transition from the study of individual elements with static characteristics to spatial, dynamic, adaptive systems. In addition, the task of planning TSFF is not only constructive and functional, but also compromising in nature due to the fact that its cost, ecological compatibility and technical efficiency are contradictory, and these compromises are interrelated and determine new contradictions. It is obvious that the parameters of the TSFF system can be established only after choosing a rational forest management option for the natural and industrial conditions of a particular region, both at the moment and in the future. This can be done on the basis of a regional system of forest management measures, differentiated depending on the purpose of forests, the characteristics of the natural and economic conditions of the region and the level of intensification of forest management, the forest properties of forest-forming tree species, and within them – economic groups of forest types. This choice determines, ultimately, the amount of workload on the TSFF system in the dynamics of its development.

The task of forming a new TSFF in general and its road network in particular requires significant financial and material resources and therefore must be scientifically justified and planned. Taking into account the ecological orientation of modern forest management, it is important to justify the cost effectiveness of creating and developing a forest road network (FRN), taking into account the overall ecological, social and economic impact of the state project realization. It is obvious that the forest industry cannot increase the level of development of the existing TSFF in a short time and develop it to optimal parameters due to the huge capital intensity of the task. In these conditions of forest management, there is an urgent need to form a unified scientific and technical strategy for its development, in

which it is necessary to consider not a narrow issue, but the development of forest transport infrastructure as a whole on the basis of the principles of sustainable development of territories. TSFF is an important and capital-intensive component of the modern forest ecosystem, without it, it is impossible to obtain any real economic income from the use of forest resources and the implementation of the ecological potential of forest territories, not to mention achieving the maximum of their ecological, social and economic productivity. The formation of synergetic relations between the TSFF and the forest ecosystem is possible on the basis of a complex ecological, social and economic criterion as the basic one in its planning. The indicator of the best project solution in this case is the achievement of maximum productivity of the TSFF and the forest ecosystem from their joint existence over the entire planning period.

It is obvious that the payback of the TSFF planning project is directly dependent on the total economic cost of the resource potential of the forest territories that are supposed to be developed. In the scientific literature [6], the indicator of this cost is an integral sum of direct and indirect forest use, the cost of forest existence and the deferred alternative of their use. In the context of calculating the value of the indicated indicator, it should be noted that various methodological developments [7-11] for determining the indicated value are based on different approaches to calculating the indicated value and do not give precise instructions for calculating the last two components of the noted indicator. Moreover, the presence and level of development of the transport network in the assessed territories is not subject to accounting in these methods, although, as noted above, without the presence of TSFF, any civilizational forest management becomes impossible.

Based on the analysis of the scientific literature on this issue, it becomes obvious that, despite the variety of scientific works [3-11], there are no studies in the field of evaluating the effectiveness of the creation and development of a transport network on the territory of the forest fund through the interconnection of ecological and economic indicators of this project. This circumstance determines the relevance of developing a mathematical apparatus for solving the optimization problem, taking into account the ecological and economic evaluation criteria.

The development of the designated apparatus for solving the optimization problem requires an unambiguous description of all the dependencies included in the mathematical model TSFF, in the target function and the system of constraints.

### 3. Results of the research

Ecological and economic efficiency of planning of the transport network on the territory of the forest fund ( $E^{TR}$ ) is the ratio of the total economic cost of forest resources to capital expenditures on the creation and development of TSFF with discounting of these flows on the development stages of the forest fund territories. This ratio allows us to determine the return on investment (return on capital), i.e. it shows the amount of possible profit from investments made in a public project by time periods (stages of development) from  $t_i$  to  $t_n$ , and is defined by the expression (1):

$$\left\{ \begin{array}{l} E^{TR} = C_{\text{economy}}^{\text{total}}(T) / C_{\text{return}}(T) \rightarrow \max \\ C_{\text{economy}}^{\text{total}}(T) = \sum_{t=0}^T \frac{C_{\text{economy}}^{\text{total}}(t_i)}{(1+e)^{t_i}} \cdot \left(1 + \frac{1}{(1+e)^T}\right) \\ C_{\text{return}}(T) = \sum_{t=0}^T \frac{C_{\text{return}}(t_i)}{(1+e)^{t_i}} \cdot \left(1 + \frac{1}{(1+e)^T}\right) \\ C_{\text{return}}(t_i) = C_{\text{create}}(t_i) \cdot \prod_{k=1}^V k_v(t_i) + C_{\text{operation}}(t_i) \cdot \prod_{k=1}^G k_g(t_i) \rightarrow \min \\ T = \sum_0^T t_i \end{array} \right. \quad (1)$$

where  $C_{\text{economy}}^{\text{total}}$  – the total economic cost of forest resources included in the zone of gravity of the planned TSFF, rubles/ha;

$e$  – discount rate;

$T$  – period of development of the territory of the forest fund, years;

$t_i$  – time from the moment of economic evaluation to the moment of resource procurement,  $t_i \in \{0, \dots, T\}$ , years;

$C_{\text{return}}$  – the cost of creating and operating TSFF, rubles/ha, at time  $t_i$ ; to determine the rate of return on invested capital TSFF costs of development and operation, it is advisable to not count within the rubles/km, but via rubles/ha, this calculation approach is based on the need to reduce data to a single denominator.

$C_{\text{create}}$  – the cost of creating TSFF in the time period  $t_i$ , rubles/ha.;

These cost items include: the cost of road construction materials, semi-finished products, structures and products; transport costs for the delivery of materials and workers; costs for the purchase and operation of construction machinery and equipment; basic and additional wages of workers.

$C_{\text{operation}}$  – the cost of operating the TSFF during the time period  $t_i$ , rubles /ha.;

These cost items include: the cost of construction of temporary branches and mustaches; workers' wages; depreciation charges for permanent tracks; costs for maintenance and current repairs of the transport network, etc.

$k_v$  – the coefficients that adjust the total value of construction costs of TSFF in the time period  $t_i$  depending on the influence of natural-geographical factors, such as the influence of the type of soil on the width of the work on felling trees, uprooting stumps, removing vegetation, backfilling pits, the leveling and compaction of soil; influence of soil on the scope of work for the construction of the subgrade, depending on the width of the subgrade, the working level and the type of soil; the influence of remoteness of the construction of a road from the industrial centers and communication lines, etc.;

$k_g$ - coefficients that adjust the total amount of operating costs during the time period  $t_i$ .

With regard to determining the total economic cost of forest resources, the following should be noted. According to sources [7-11], this indicator should take into account all material and non-material benefits that are not associated with traditional methods of using wood for wood processing or with maintaining forests for agriculture. As indicated above, this cost integrates four components: direct cost of use, indirect cost of use, cost of deferred alternative, and cost of existence. It is quite easy to calculate the direct cost of forest use, which is not the case for the other components of the total economic cost, such as the calculation of the indicator of increased productivity of workers from recreation in the forest within the indirect cost of use.

The complexity of calculating the total economic cost of forest resources to be developed by the planned TSFF is characterized not only by the difficulty of determining the value of the indirect cost of forest resources, but also by the difficulty of assigning them to one or another category of terms of the designated indicator. For example, the cost of existence can also be considered from different positions, depending on the category of forests (ecological inaccessibility for the main forest use), depending on the goals of forest conservation (if the territory is used for recreational purposes, it is logical to calculate the cost of existence in the context of the direct cost of use, etc.), etc.

Taking into account the above, we propose to divide the total economic cost of forest resources into two main components: the cost of use (logging) and the cost of conservation of forest resources (accounting for secondary forest use, ecological and social functions of the forest) at time  $t_i$ . This approach ensures the rational choice of the forest management system by dividing the direct cost of forest resources by the method of their use.

In the cost of forest conservation, we propose to include indicators of indirect cost that can be calculated, as well as take into account the indicators of deferred alternative of forest use and the cost of forest existence in the context of the indicator of non-development of the territory of the forest fund. Since the company investing in the project of creation and development of TSFF, on the one hand, loses income from the sale of l-rock reserves due to the lack of a forest road network at this stage of development. On the other hand, with the loss of this income, the company pays to some extent for the conservation of the forest area in order to use it at future stages of the transport network creation. It should be noted that in the field of practical activity of an economic entity, the  $i$ -th territory of the forest fund may not be fully subject to the main forest use (conditions for continuous logging), or selective logging may be carried out on the  $i$ -th territory of the forest fund. Therefore, part of this forest section will be preserved

and can be used for other purposes. Based on the fact that the purposes of using preserved forest land are different, either a single purpose of use or a combination of the specified purposes will be individual for each forest area. Taking into account the above, we propose to determine this indicator according to the expression (2):

$$C_{\text{economy}}^{\text{total}}(t_i) = C_{\text{economy}}^{\text{use}}(t_i) + \sum_{b=0}^B C_{\text{economy}_b}^{\text{save}}(t_i) \rightarrow \max \quad (2)$$

where  $C_{\text{economy}}^{\text{use}}(t_i)$  – cost of use (logging, the forest is cut down completely (conditions clear-cutting) on the  $i$ -th lesouchastok and this forest area is not subject to use for other purposes), rubles/ha, at time  $t_i$ ;

$C_{\text{economy}_b}^{\text{save}}(t_i)$  – the cost of preserving forest resources, rubles/ha, at time  $t_i$ ;

$b$  – the purpose of using the  $i$ -th territory of the forest fund while preserving forests at the time  $t_i$ ,  $b \in \{0, \dots, B\}$ .

Under the sum  $\sum_{b=0}^B C_{\text{economy}_b}^{\text{save}}(t_i)$  – the total cost of saving forest resources is taken, based on the intended use of the forest area, at the time  $t_i$ . If  $b = 0$ , the  $i$ -th territory of the forest fund is fully subject to use (conditions for continuous logging).

The cost of using forest resources is determined by the expression (3):

$$C_{\text{economy}}^{\text{use}}(t_i) = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^K \sum_{l=1}^L \left[ C_{il}^p(t_i) + (C_{ijkl}^{\text{TR}}(t_i) + C_{ijl}^{\text{Tech}}(t_i)) \cdot \prod_{k=1}^H k_h(t_i) \right] \cdot (Q_{il}^r(t_i) + Q_{il}^r(t_i-1) \cdot K_r) - \sum_{l=1}^L C_{fr}(t_i) - C_d(t_i) - P_{ij}^l \cdot \Delta t(t_i) \quad (3)$$

where " $C_{il}^p(t_i)$ " – the cost of  $l$ -breed wood on the  $i$ -th hectare on the root, rubles/ha, at the time  $t_i$ ;

$C_{ijkl}^{\text{TR}}(t_i)$  – transport costs for export when harvesting the volume of  $l$ -breed stock from the  $i$ -th hectare,  $i \in \{1, \dots, m\}$ , to the  $j$ -th warehouse (rail section, to the consumer),  $j \in \{1, \dots, n\}$ ,  $k$ -th type of transport  $k \in \{1, \dots, K\}$ , rubles/ha, at the time  $t_i$ ;

$C_{ijl}^{\text{Tech}}(t_i)$  – technological costs for harvesting the volume of  $l$ -breed stock, rubles/ha, at the time  $t_i$ ;

$Q_{il}^r(t_i)$  – the amount of wood reserve at the root of the  $l$ -breed, at the time  $t_i$ ;

$K_r$  – age coefficient for converting of wood reserve of age  $t_i-1$  to reserve of ripe wood of age  $t_i$ ;

$k_h(t_i)$  – coefficients that adjust the amount of transport and technological costs during the time period  $t_i$ , depending on the influence of factors such as: the distance of removal; natural and climatic conditions, the volume of the whip (the larger the volume of the whip, the less transport and technological costs), etc.;

$C_{fr}(t_i)$  – standard costs for reproduction of the  $l$ -th breed, which guarantee its restoration in clearings, cultivation to the age of maturity, protection and security, rubles/ha, at the time  $t_i$ ;

$\sum_{l=1}^L C_{fr}(t_i)$  – this indicator will include the costs associated with forest reforestation both before logging, if the restored forest was to be used, and after using the resource;

$C_d(t_i)$  – damage from environmental pollution not accounted for in economic activity, rubles/ha, at the time  $t_i$ ;

$P_{ij}^l(t_i)$  – deadening of the forestry asset (not realizing the  $l$ -breed reserve) from non-development of the forest fund territory due to the absence of the forest road network at the time  $t_i$ , rubles/ha;

$\Delta t$  – period of non-development of the forest Fund territory.

The sum of  $C_{il}^p(t_i) + C_{ijkl}^{\text{TR}}(t_i) + C_{ijl}^{\text{Tech}}(t_i)$  is considered as the cost of  $l$ -breed wood prepared and delivered to the  $j$ -th warehouse (rail section, to the consumer), rubles/m<sup>3</sup>.

It should be noted that wood on the root for medium-aged, ripening, mature and over-mature stands is estimated as wood at the current rates of forest taxes at the time of assessment. In the same way, the assessment of wood on the root, on the burning, clearings, whiskers, dead plantings, etc. is made taking into account the real consumer cost of this wood.

$P_{ij}''(t_i)$  - considered as a cost that includes potential revenue lost due to the postponement of revenue from forest management, plus the cost of removing revenue from future production cycles for a period of time  $\Delta t$ .

The cost of saving of forest resources is determined by the expression (4):

$$\left\{ \begin{array}{l} C_{\text{economy}_b}^{\text{save}}(t_i) = C_g(t_i) + C_{\text{cut}}(t_i) + C_{\text{sec}}(t_i) + C_{\text{pf}}(t_i) + C_h(t_i) - (C_m(t_i) - C_d(t_i)) \\ C_g(t_i) = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^K \sum_{d=1}^D [C_{id}^p(t_i) + C_{ijkd}^{\text{TR}}(t_i) + C_{ijd}^{\text{Tech}}(t_i)] \cdot Q_{id}^r(t_i) - \sum_d C_{fr}(t_i) - P_{ij}'' \cdot \Delta t(t_i) \\ C_{\text{cut}}(t_i) = C^{\text{year}} \cdot K_f^{\text{turn}} \\ C_{\text{sec}}(t_i) = 100 C_t^{\text{year}} \\ C_{\text{pf}}(t_i) = (Q_{i1}^r(t_i) \cdot K_1^{\text{abs}}(t_i)) \cdot C^t \end{array} \right. \quad (4)$$

where  $C_{il}^p(t_i)$  – the cost of the  $d$ -th secondary forest resource on the  $i$ -th hectare, rubles/ha, at the time  $t_i$ ;

$C_{ijkl}^{\text{TR}}(t_i)$  - transport costs for export when harvesting the volume of secondary forest resource stock from the  $i$ -th hectare to the  $j$ -th warehouse (rail section, to the consumer),  $k$  - th type of transport, rubles/ha, at the time  $t_i$ ;

$C_{ijl}^{\text{Tech}}(t_i)$  - technological costs for harvesting the volume of the reserve of the  $d$ -th forest resource, rubles/ha, at the time  $t_i$ ;

$Q_{id}^r(t_i)$  – the volume of the reserve of the  $d$ -th forest resource, at the time  $t_i$ ;

$C_{fr}(t_i)$  – standard costs for reproduction of the  $d$ -th forest resource, guaranteeing its restoration, rubles/ha, at the time  $t_i$ ;

$C_d(t_i)$  - damage from environmental pollution not accounted for in economic activity, rubles/ha, at the time  $t_i$ ;

$C_g(t_i)$  – the cost of selling  $d$ -th forest resources on 1 ha of forest land, rubles/ha, at the time  $t_i$ ;

$C_h(t_i)$  – the cost of useful (including environmental and soil protection) functions of the forest not included in the indicator  $C_{pf}(t_i)$  rubles/ha, at the time  $t_i$ ;

$C_m(t_i)$  - the cost of maintaining the social infrastructure created in connection with forest management, rubles/ha, at the time  $t_i$ ;

$C_{\text{cut}}(t_i)$  - the cost of cutting on 1 ha of forest, rubles/ha, at the time  $t_i$ ;

$C_{\text{sec}}(t_i)$  - the cost of secondary forest use: tourism, hunting, sports, and other purposes is assumed to be equal to one hundred times the annual amount of forest taxes levied for the corresponding type of forest use on the estimated area of forest land, rubles/ha, at the time  $t_i$ ;

$C_{\text{pf}}(t_i)$  - the cost of producing the carbon-depositing function of forests per 1 ha of forest, rubles/ha, at the time  $t_i$ ;

$C^{\text{year}}$  – the annual rate of forest taxes charged for cutting 1 ha of plantings;

$K_f^{\text{turn}}$  – the turnover coefficient of the felling, changes from 16.39 to 4.59 with the turnover of the felling from 50 to 120 years, respectively;

$C_t^{\text{year}}$  – the annual amount of forest taxes charged for the corresponding type of forest use;

$K_1^{\text{abs}}(t_i)$  – coefficient of  $\text{CO}_2$  absorption by forests of 1-breed of the  $i$ -th hectare at the time  $t_i$ ;

$C^t$  – specific estimated cost of the  $\text{CO}_2$  absorption function at time  $t_i$ , rubles/ha;

$P_{ij}''(t_i)$  – deadening of the forest asset (not realizing the reserve of the  $d$ -th forest resource) from not developing the territory of the forest fund due to the absence of a forest road network, at the time of  $t_i$ , rubles/ha;

$\Delta t$  – period of non-development of the forest fund territory.

Consideration of the indicator  $Q_{i1}^r(t_i)$  is twofold: on the one hand, this indicator represents an unrealized stock of 1 – breed, on the other hand, it is considered as the volume of the resource that produces the carbon-depositing function of forests at different cost indicators for the options for consideration.

It should also be noted that the calculation of indicators of the indirect cost of using forest resources and the so-called “weightless” forest benefits is discussed in detail in the sources [7-8, 10-11].

When implementing the proposed mathematical model of ecological and economic efficiency of planning the creation and development of a transport network on the territory of the forest fund, the following restrictions should be taken into account:

1. Payback of the TSFF planning project:

$$C_{\text{economy}}^{\text{total}}(T) > C_{\text{return}}(T) \quad (5)$$

2. Financial stability of an enterprise investing in a TSFF planning project:

$$C_{\text{return}}(T) \leq E_{\text{max}} \quad (6)$$

where  $E_{\text{max}}$  – financial capacity of the enterprise, rubles.

3. Transport accessibility of forest sections: The effective leverage for transporting a forest resource from the  $i$ -th forest plot to the  $j$ -th raw material warehouse should not exceed the economically available delivery distance.

$$L_{ij} \leq L_{\text{del}} \quad (7)$$

where  $L_{ij}$  - is the distance between the  $i$ -th forest plot and the  $j$ -th raw material warehouse, km.

4. Natural non-negativity of cargo flows:

$$Q_{ijkl}(t_i) \geq 0, \quad Q_{id}^3(t_i) \geq 0, \quad i=1, \dots, m; \quad j=1, \dots, n; \quad t_i=0, \dots, T; \quad k=1, \dots, K \quad (8)$$

5. The requirement for continuous, sustainable forest management: - for wood resources:

$$\sum_{t=0}^T \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^K \sum_{l=1}^L ((Q_{ijk}(t_i+1)l \cdot [C_i^p + C_{ijk}^{TR} + C_{ij}^{Tech}](t_i+1)l - C_{\text{return}}(t_i+1)l - C_{fr}(t_i+1)l - C_d(t_i+1)l - P_{ij}^{\cdot} \cdot \Delta t(t_i+1)l) - \sum_{t=0}^T \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^K \sum_{l=1}^L ((Q_{ijk}(t_i)l \cdot [C_i^p + C_{ijk}^{TR} + C_{ij}^{Tech}](t_i)l - C_{\text{return}}(t_i)l - C_{fr}(t_i)l - C_d(t_i)l - P_{ij}^{\cdot} \cdot \Delta t(t_i)l) \geq 0, \quad l=1, \dots, L \quad (9)$$

- for non-wood resources:

$$\sum_{t=0}^T \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^K \sum_{d=1}^D ((Q_i^r(t_i+1)d \cdot [C_i^p + C_{ijk}^{TR} + C_{ij}^{Tech}](t_i+1)d - C_{\text{return}}(t_i+1)d - C_{fr}(t_i+1)d - C_d(t_i+1)d - C_m(t_i+1)d - P_{ij}^{\cdot} \cdot \Delta t(t_i+1)d) - \sum_{t=0}^T \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^K \sum_{d=1}^D ((Q_i^r(t_i)d \cdot [C_i^p + C_{ijk}^{TR} + C_{ij}^{Tech}](t_i)d - C_{\text{return}}(t_i)d - C_{fr}(t_i)d - C_d(t_i)d - C_m(t_i)d - P_{ij}^{\cdot} \cdot \Delta t(t_i)d) \geq 0, \quad d=1, \dots, D \quad (10)$$

The proposed mathematical model in a dynamic formulation provides a correct calculation of the overall ecological and economic effect of the implementation of the project for planning the creation and development of a transport network on the territory of the forest fund.

#### 4. Results discussion

The developed mathematical model of ecological and economic assessment of TSFF efficiency reflects the profitability of its operation (including costs at all stages of its life cycle) for the entire planned period of interaction with the forest ecosystem, i.e. the payback for the design, construction and operation of the TSFF due to the development of the forest fund territory.

The scientific novelty of the methodology for developing a mathematical model of TSFF planning is as follows:

- in considering the planned TSFF and the territory of the proposed development of forest fund as a single system that is in synergy with each other;



- formulation of the qualitative criterion of TSFF effectiveness as achieving the maximum of all potential revenues from the use of various types of forest resources and the ecological potential of the territory based on the planned TSFF;
- development of a quantitative ecological and economic criterion for the effectiveness of the TSFF, taking into account: the costs associated with restoration of forest, protection of forests from fires and pests, the missed opportunity to obtain potential income due to the postponement of income from forest use, plus the costs of removing income from future production cycles.

Summing up, we can say that this mathematical model is necessary for evaluating the payback of the project of creating and developing a transport network on the territory of the forest fund by assessing the ecological and economic potential of forest sites and their social significance. The indicated model should have a complex integrated character by which the calculation of the total economic cost indicator provides a combined account of all the main useful functions of the forest in the dynamics. This model allows us to more objectively determine the value of the overall ecological, social and economic effect of the implementation of the state project for the development of the road network in the territory of the forest fund.

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