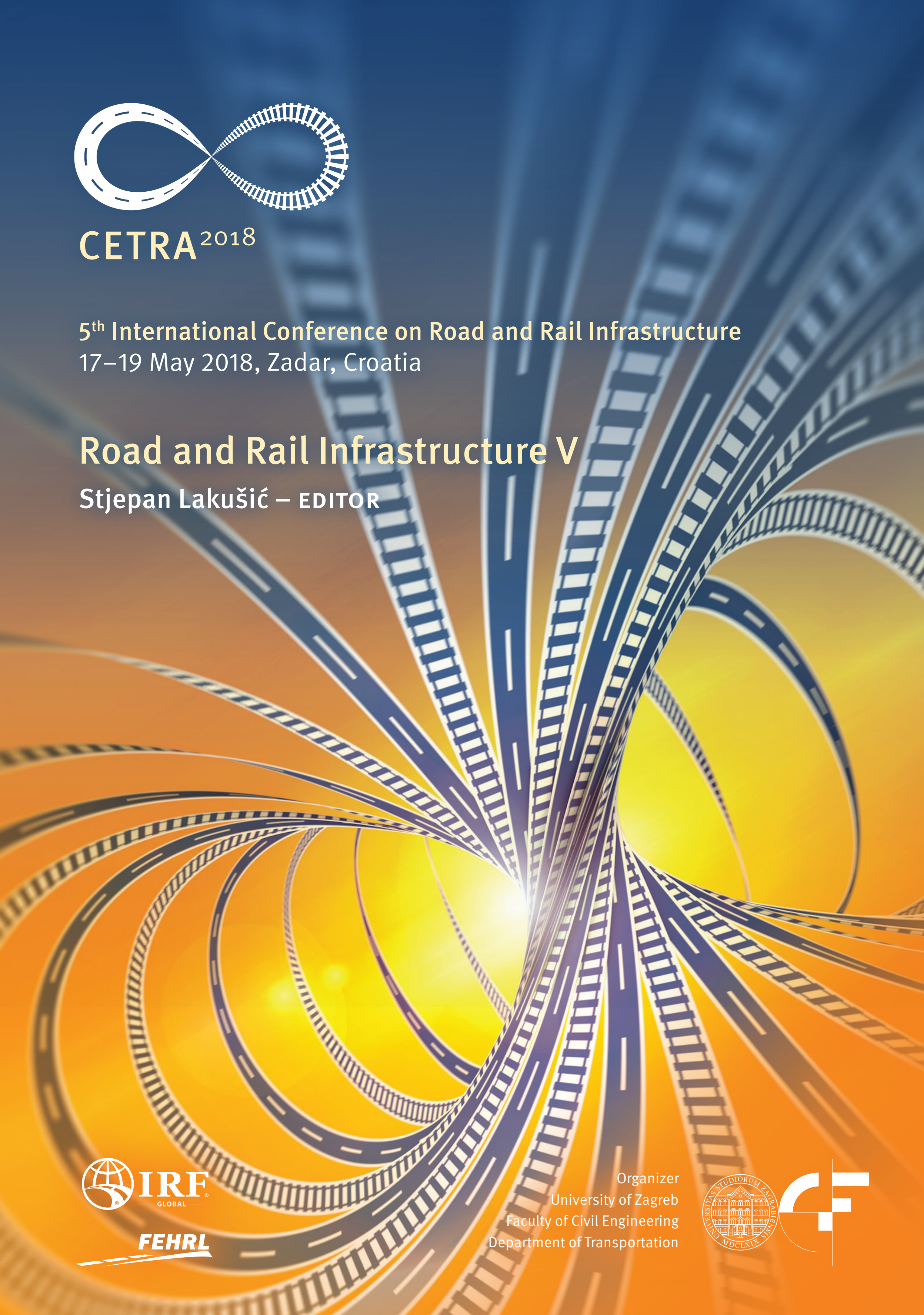

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17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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DIVIDING INVESTMENTS INTO SUSTAINABLE DEVELOPMENT OF RAILWAY TRANSPORT SYSTEM AS LINEAR PROGRAMMING PROBLEM

Vitalii Naumov[1], **Hanna Vasiutina**[2]
[1] *Cracow University of Technology, Department of Transport Systems, Poland*
[2] *Jagiellonian University, Faculty of Physics, Astronomy and Applied Computer Science, Poland*

Abstract

The problem of dividing the investments into development of railway transport systems is formulated as a linear programming problem. As the objective function for the optimization problem, we propose to use the sum of private performance indicators characterizing resource saving, the environmental component of functioning, the social component, and the quality of customer service. The vector of control variables in the proposed formulation is the set of investments shares for the considered directions of sustainable development, and the vector of the objective function coefficients contains functions of investments elasticity for the respective directions of the railway system sustainable development. As far as the objective coefficients depend on the number of productive resources (number of locomotives and handling mechanisms at the stations) and parameters of demand for transport services, computer simulations should be used for estimation of the objective function. The paper briefly describes the developed software for simulations of railway transport systems and solving the presented linear programming problem.

Keywords: railway transport system; sustainable development; linear programming; computer simulation

1 Introduction

Railway transport systems (RTS) are complex systems, which operation is considered at the technical, technological, social and economic levels. The main objective of their functioning is to meet the needs of trade and production enterprises in goods deliveries, as well as to provide transport services for population. The efficiency of the RTS operation is usually evaluated from the economic viewpoints – basing on the indicators of total operating costs, profitability of technological processes, and quality of service indicators. However, this approach does not correspond to the modern paradigm of managing complex technological and socio-economic systems – the concept of sustainable development, which implies a comprehensive solution to the problems of the efficiency increase, taking into account resource-saving, environmental and social indicators of their functioning.

The goal of this paper is to develop a tool for solving one of the crucial problems of transport management – optimal dividing of investments into development of railway transport systems considering its sustainability indices.

The paper has the following structure: in the second part, we provide a short review of recent publications in the field of the railway transport systems management; in the third section, the proposed mathematical model for dividing of investments into the RTS development is

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presented; the fourth part contains description of the developed software for simulations of railway transport systems; the fifth section presents a case study of solving the investments dividing problem with the use of the proposed mathematical model and the respective software; the last part contains conclusions and directions of future studies.

2 Literature review

The performed analysis of theoretical approaches in the field of improving the efficiency of the railway transport operation allows us to distinguish a number of characteristic works, which have the following features:

- in the majority of works [1-8], complex economic indicators are used as the efficiency criteria (objective functions), but there are also methods and approaches that consider the processes of increasing the efficiency of RTS on the basis of technological indicators [9-11] or indicators of safety [12, 13], as well as indicators that take into account the ecological component of technological processes [14, 15];
- methods of linear programming and their derivatives are one of the most frequently used methods for determining optimal parameters for the RTS operation processes [3-5, 10, 16]; in this case, as a rule, the tools for solving the transport problem as a version of the linear programming problem are used;
- existing theoretical approaches are generally not widely used in RTS management practice due to the lack of specialized software (among the analyzed works only in [2] special software packages are offered) that implements appropriate optimization and rationalization models, as well as due to lack of methodological guidelines for their use in practice.

In the theoretical works which use an economic indicator as the efficiency criterion, the total costs are the most common objective function: macroeconomic costs [5, 7], total transportation and storage costs [8], or costs of delay in the operations performance [10]. In addition, the profit or one of its derivatives [4, 17] is also commonly used as an economic performance indicator. This tendency could be explained by integral features of total costs – this indicator includes a number of technological performance indices.
Thus, in order to solve the problem of dividing investments into RTS development, we also propose to use the integral criterion defined as a sum of the efficiency indicators for the main directions of sustainable development – resource-saving, environmental efficiency, social parameters, and quality of clients' servicing.

3 Mathematical model of investments dividing problem

The task of ensuring sustainable development of RTS based on the proposed integral performance criterion E should be defined as maximization of the criterion value:

$$E = E_{res} + E_{ec} + E_{soc} + E_q \rightarrow \max \tag{1}$$

Where E_{res}, E_{ec}, E_{soc}, and E_q are private efficiency indicators characterizing resource-saving features of RTS, environmental component of the RTS operation, the social component of functioning, and the quality of customers service, respectively [€].

Among the activities of a technical nature aiming to increase the effectiveness of the RTS sustainable development, the following measures should be named:

- modernization of the railroads network within the RTS in the direction of their electrification (this measure provides an increase in the component E_{ec} due to the elimination of harmful emissions in electrified areas, as well as the increase in the component E_{res} due to the lower energy costs for electrified sections);

- modernization of the running gear and coupling devices of locomotives and wagons, as well as of sorting devices at stations in order to reduce the level of noise effects during movement operations and operations of the trains forming and disbanding (this measure provides an increase in the component E_{ec}).

The implementation of measures to improve the RTS operation, determining the values of the components E_{res}, E_{ec}, E_q, and social contributions E_{soc}, are carried out at the expense of the RTS profit for the previous period. On the grounds of the share δ_{sd} of funds allocated to ensure the sustainable development of the RTS, the amount of development funds is determined by the formula:

$$C_{sd}^{t} = PP_{RTS}^{(t-1)} \cdot \delta_{sd} \tag{2}$$

Where C_{sd}^{t} are financial resources allocated for sustainable development of RTS for the period t, [€]; $PP_{RTS}^{(t-1)}$ is pure profit for the period (t – 1), [€].

An amount of C_{sd}^{t} includes the financial resources allocated for the respective directions of the RTS sustainable development – development of resource-saving technologies (Δ_{res}), reducing the impact on the environment (Δ_{ec}), the social component of operation (Δ_{soc}) and improving the quality of customer service (Δ_q). In this case, each of the directions is characterized by a different elasticity of investment – the ratio of the relevant component of the efficiency criterion E to an amount of allocated funds. The efficiency criterion, taking into account the distribution of allocated funds among the directions of sustainable development, can be presented in the following form:

$$E = \Delta_{res} \cdot \varepsilon_{res} + \Delta_{ec} \cdot \varepsilon_{ec} + \Delta_{soc} \cdot \varepsilon_{soc} + \Delta_q \cdot \varepsilon_q \rightarrow \max \tag{3}$$

Where ε_{res}, ε_{ec}, ε_{soc}, and ε_q are functions of investment elasticity for the directions of resource-saving technologies development, reduction of harmful impact on the environment, ensuring the social component of the RTS operation, and improving the quality of customer service respectively.

An obvious restriction in solving the problem (3) is the full use of the amount of money allocated for sustainable development of a railway system. The presence of other restrictions is due to the fact that in the set of investment elasticity functions ε_{res}, ε_{ec} and ε_q, there are pairs of functions which values are determined by common parameters characterizing the technological processes of the RTS operation. Let's define the function of investments elasticity ε_i for the i-th direction of sustainable development, as the ratio of the effect E_i, obtained from the activities, for which the funds K_i are allocated:

$$\varepsilon_i = \frac{E_i}{K_i} \tag{4}$$

For the direction of ensuring the social component of the RTS operation, the effect would be measured directly by the allocated amount of financial resources, therefore the respective elasticity function would be constant: ε_{res} = 1. Directions for implementing resource-saving technologies and improving the quality of customer service are realized through optimization activities of technological character: optimizing the fleet of shunting and train locomotives, optimizing the number of handling mechanisms and other means of technological processes mechanization, and optimizing the routes for the delivery of goods within the RTS transport network. Possible capital investments for the implementation of these activities are required in order to purchase an additional number of shunting locomotives, loading and unloading mechanisms and other means of mechanization of technological processes.

Production resources of freight stations, which provide processing of a material flow, are shunting locomotives, handling mechanisms, and devices of mechanization and automation of sorting operations. The number of devices for mechanization and automation of sorting operations is determined on the basis of quantitative characteristics of the secondary demand for the services of freight stations – the needs that arose in the process of servicing the incoming railcar flows at the stations. At the same time, the satisfaction of primary demand is ensured by the movement of wagons along the territory of the station and their servicing on freight fronts. Thus, it can be argued that the number of devices for mechanization and automation of sorting operations at stations is functionally dependent on the number of wagons submitted for processing, and hence on the number of shunting locomotives and handling mechanisms. The described dependencies allow us to assert that numerical characteristics of the RTS resources are the arguments of the elasticity functions ε_{res}, ε_{ec}, and ε_q:

$$\begin{cases} \varepsilon_{res} = f(N_l, N_g), \\ \varepsilon_{ec} = f(N_l, N_g), \\ \varepsilon_q = f(N_l, N_g), \end{cases} \tag{5}$$

Where N_1 and N_g are the vectors of the number of shunting locomotives and handling mechanisms respectively at the freight stations of RTS.

Optimization of the objective function (3) with respect to variables δ_{res}, δ_{ec}, δ_{soc}, and δ_q should be carried out taking into account the set of restrictions on the lower nonzero boundary of variables:

$$\begin{cases} \delta_{res} + \delta_{ec} + \delta_{soc} + \delta_q = 1, \\ \delta_{res} \geq \delta_{res}^{min}, \\ \delta_{ec} \geq \delta_{ec}^{min}, \\ \delta_{soc} \geq \delta_{soc}^{min}, \\ \delta_q \geq \delta_q^{min}, \end{cases} \tag{6}$$

Where δ_i^{min} is the established lower boundary of the share of cash flows to ensure the i-th direction of the RTS sustainable development.

In this formulation, the problem (3) with constraints (6) could be attributed to the class of linear programming problems. In general, the linear programming problem is defined as the maximization of the objective function considering constraints determined by the system of inequalities:

$$F = c^T \cdot x \to \max : A \cdot x \leq b, \ \forall x \geq 0 \tag{7}$$

Where c is the vector of target elements; x is the vector of control variables; A is the constraint matrix; b is the constraint vector.

The vector of target elements in the problem of optimal allocation of financial resources for the RTS sustainable development is a set of numerical values of investment elasticity functions ε_{res}, ε_{ec}, ε_{soc}, and ε_q determined for known values of vectors N_1 and N_g:

$$c = \begin{vmatrix} \varepsilon_{res} & \varepsilon_{ec} & 1 & \varepsilon_q \end{vmatrix} \tag{8}$$

As control variables, the values of the shares of funds for the directions of sustainable development should be considered: $x = \begin{vmatrix} \delta_{res} & \delta_{ec} & \delta_{soc} & \delta_q \end{vmatrix}$.

In the form $A \cdot x \leq b$, the constraint system (6) could be represented as follows:

$$\begin{cases} \delta_{res} + \delta_{ec} + \delta_{soc} + \delta_q \leq 1, \\ -\delta_{res} - \delta_{ec} - \delta_{soc} - \delta_q \leq -1, \\ -\delta_{res} \leq -\delta_{res}^{min}, \\ -\delta_{ec} \leq -\delta_{ec}^{min}, \\ -\delta_{soc} \leq -\delta_{soc}^{min}, \\ -\delta_q \leq -\delta_q^{min}. \end{cases} \tag{9}$$

Thus, the constraint matrix A and the vector b for the problem under consideration take the following form:

$$A = \begin{vmatrix} 1 & 1 & 1 & 1 \\ -1 & -1 & -1 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{vmatrix}, b = \begin{vmatrix} 1 \\ -1 \\ -\delta_{res}^{min} \\ -\delta_{ec}^{min} \\ -\delta_{soc}^{min} \\ -\delta_q^{min} \end{vmatrix} \tag{10}$$

The solution of the problem of optimal allocation of financial resources to ensure sustainable development of RTS in the above formulation could be determined on the grounds of the simplex method.

4 Software implementation

The basis of the model of the RTS macro logistics system operation is the graph-based model. To develop the graph model, the Microsoft Visual Studio toolkit was used, while C# was chosen as the programming language. As the base library for creating the RTS model, the developed class library Graph.dll was used, containing a software implementation of the main algorithms for graphs optimization. The developed software for simulations of railway systems could be forked at https://github.com/naumovvs/railway-transport-system, and the library containing graph optimization tools is available at https://github.com/naumovvs/graph-optimization-tools.

In accordance with the developed software model, the RTS model is an instance of the TSModel class, which inherits the Graph class of the Graph.dll library. The fields of the base class Graph are the collections of Nodes and Links, which contain lists of all the vertices of the graph and its links, respectively. The vertices of the graph correspond to the stations in the RTS, and the links – to the railroads connecting the stations. The Nodes collection contains the elements of Node type (graph vertices). Basic fields of the Node class from the Graph.dll library are:

- Code is the code of the graph node;
- X and Y are the node coordinates: in the proposed software implementation of the RTS model, the longitude and latitude of the stations are taken as coordinates, obtained with the help of the Google Maps functions;
- Name is the name of the graph node (the station name);
- OutLinks and InLinks are collections containing lists of respective outgoing and incoming links associated with the node;
- outFlows and inFlows are collections containing lists of respective outgoing and incoming flows associated with the node.

The collection Links contains elements of the Link type (the graph link). Basic fields of the Link class from the Graph.dll library are the following:
- OutNode and InNode are outgoing and incoming nodes of the link – the references for objects in the Nodes list;
- Weight is the link weight – a numeric characteristic of the link (length, travel time, costs, etc.), in the proposed software implementation of RTS, the length of the run is considered as the weight of the link;
- Capacity is a bandwidth of the network link;
- Load is the actual load of the network link.

The TSModel class contains the following own fields (not inherited from the Graph class of the Graph.dll library) that allow describing the main technical and operational characteristics of the RTS:
- dictionaries LocoNum and GearNum of the Dictionary ‹Node, Integer› type, containing number of shunting locomotives and handling mechanisms at stations;
- dictionary LinksLoad of the Dictionary‹Link, Double› type, containing the transport network links load;
- dictionaries EQ and ET of the Dictionary ‹Node, Double› type, containing the values of the coefficient representing the ratio of the quantitative characteristics of demand and the servicing system, and the coefficient representing the ratio of the time characteristic of the demand intensity of and the time characteristic of the system performance, respectively;
- dictionaries TotalTW, TotalTL, and TotalTG of the Dictionary‹Node, Double› type containing the total processing time of wagons at stations, the total operating time of station locomotives, and the total operating time of handling mechanisms, respectively;
- random variables sI and sQ of the Stochastic type, characterizing the parameters of freight flows – the intensity of the flow of trains in the transport network, and the size of trains, respectively.

A preliminary stage in the problem solution is the estimation of the coefficient vector for the objective function – the values of the investment elasticity functions ε_{res}, ε_{ec}, and ε_q. In the program model, the simplexCoeffs procedure is developed to calculate the coefficients of the objective function, which returns the corresponding array of values. The variables, used to determine the values of elasticity functions, are the total operating time of shunting locomotives and handling mechanisms at the stations, as well as the value of the total service time for the wagons.

5 Case Study

Let's consider the procedure for solving the problem (3) by the simplex method for given $\delta_{res}^{min} = \delta_{ec}^{min} = \delta_{soc}^{min} = \delta_q^{min} = 0{,}05$. In accordance with the presented problem statement, for the constraint matrix A and the constraint vector b, the initial vocabulary of the linear programming problem is unattainable:

$$\begin{cases} x_5 = 1 - x_1 - x_2 - x_3 - x_4, \\ x_6 = -1 + x_1 + x_2 + x_3 + x_4, \\ x_7 = -0{,}05 + x_1, \\ x_8 = -0{,}05 + x_2, \\ x_9 = -0{,}05 + x_3, \\ x_{10} = -0{,}05 - x_4, \end{cases} \qquad (11)$$

$$z = \varepsilon_{res} \cdot x_1 + \varepsilon_{ec} \cdot x_2 + x_3 + \varepsilon_q \cdot x_4,$$

Where $x_1, \ldots, x_4$ are independent variables (vector x); $x_5, \ldots, x_{10}$ are auxiliary variables; z is current value of the objective function.
Thus, the dictionary for determining the optimal ratio of capital investments in the directions of sustainable development by the simplex method has the following form:

$$\begin{cases} x_1 = 0{,}85 + x_6 - x_8 - x_9 - x_{10}, \\ x_2 = 0{,}05 + x_8, \\ x_3 = 0{,}05 + x_9, \\ x_4 = 0{,}05 + x_{10}, \\ x_5 = 0 - x_6, \\ x_7 = 0{,}8 + x_6 - x_8 - x_9 - x_{10}, \end{cases} \tag{12}$$

$$\begin{aligned} z = {} & \varepsilon_{res} \cdot x_1 + \varepsilon_{ec} \cdot x_2 + x_3 + \varepsilon_q \cdot x_4 = \\ & = \varepsilon_{res} \cdot (0{,}85 + x_6 - x_{10} - x_8 - x_9) + \\ & + \varepsilon_{ec} \cdot (0{,}05 + x_8) + 0{,}05 + x_9 + \varepsilon_q \cdot (0{,}05 + x_{10}) = \\ & = (0{,}85 \cdot \varepsilon_{res} + 0{,}05 \cdot \varepsilon_{ec} + 0{,}05 + 0{,}05 \cdot \varepsilon_q) + \\ & + \varepsilon_{res} \cdot x_6 + (\varepsilon_{ec} - \varepsilon_{res}) \cdot x_8 + (1 - \varepsilon_{res}) \cdot x_9 + (\varepsilon_q - \varepsilon_{res}) \cdot x_{10}. \end{aligned}$$

In the developed software implementation of the RTS model, the solution of the problem (12) is performed in the SimulateTS procedure using the base classes of the developed Simplex.dll library (the library code could be forked from https://github.com/naumovvs/simplex-method). The objective function is specified as an instance of the ObjectiveFunction class, constraints – as instances of the Constraint class, and the linear programming problem in general form – as the LPP object from the Simplex.dll library. The procedure of searching for a solution is performed by the Solve function of the LPP class. The result of the SimulateTS procedure is an array containing the vector x values. The result of solving the problem of optimal investments allocation is one of the vertices of a simplex that bounds the space of admissible solutions taking into account the adopted system of constraints. The values of the vector $\left| \delta_{res} \quad \delta_{ec} \quad \delta_{soc} \quad \delta_q \right|$ representing the solution of the problem (12), are the corresponding vertices of the simplex where the objective function (3) takes the maximum possible value. It's easy to verify that the largest value of the share of capital investments corresponds to the direction for which the value of the elasticity function is the biggest. Thus, the most priority direction i_{pr} of the RTS sustainable development is defined as the argument from the maximum value of the elasticity function:

$$i_{pr} = \arg\left[\max_{i=\{R,E,S,Q\}} \varepsilon_i(\mu_\zeta, \mu_\psi) \right] \tag{13}$$

Where i = {R, E, S, Q} is the set of sustainable development directions: R – development of resource-saving technologies, E – reduction of harmful impact on the environment, S – ensuring the social component, Q – improvement of the servicing quality.
Results of the elasticity functions ε_i evaluation obtained for the Pridneprovskaya Railway (Ukraine) show that the functions values depend on parameters of stochastic demand for the RTS services (the expected value of the trains intensity μ_ζ and the mean train size μ_ψ were considered). Dependences of the elasticity functions on the expected values of the trains intensity for the parameter μ_ψ = 40 wagons are presented in Fig. 1.

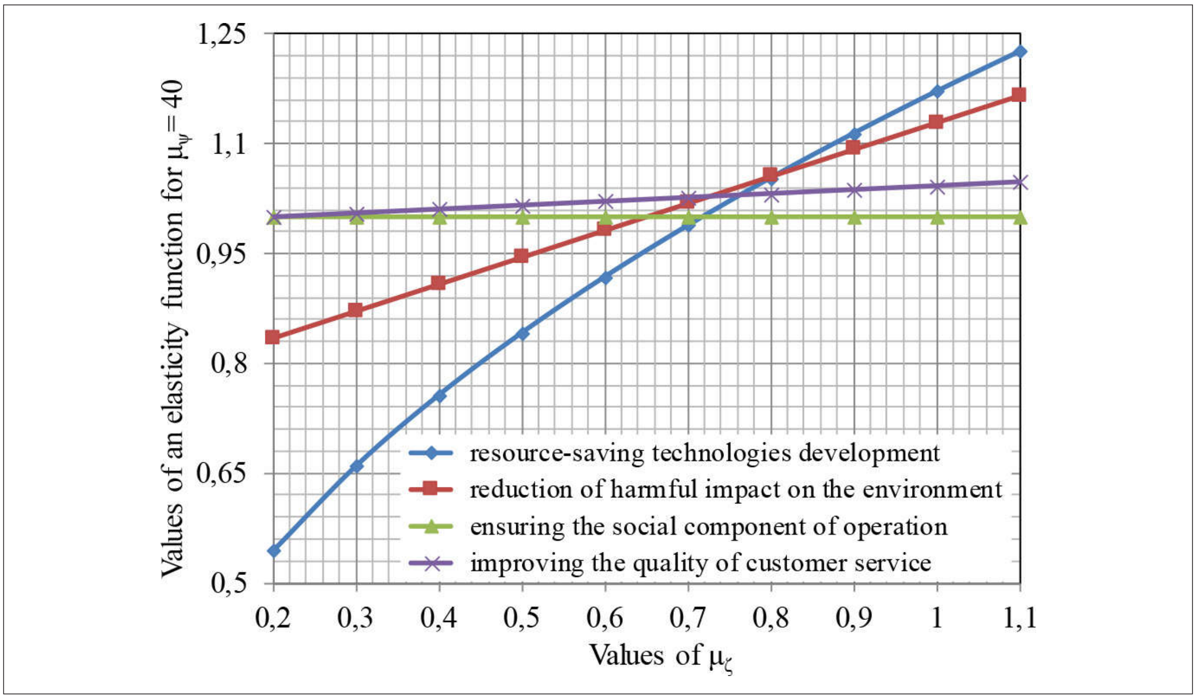

Figure 1 Dependencies of elasticity functions on the parameter μ_ζ

For the dependences of the elasticity functions on the parameter μ_ψ for the fixed μ_ζ = 0,75 trains/h (Fig. 2), such the ranges of μ_ψ values could be distinguished, for which one of the elasticity functions is maximal.

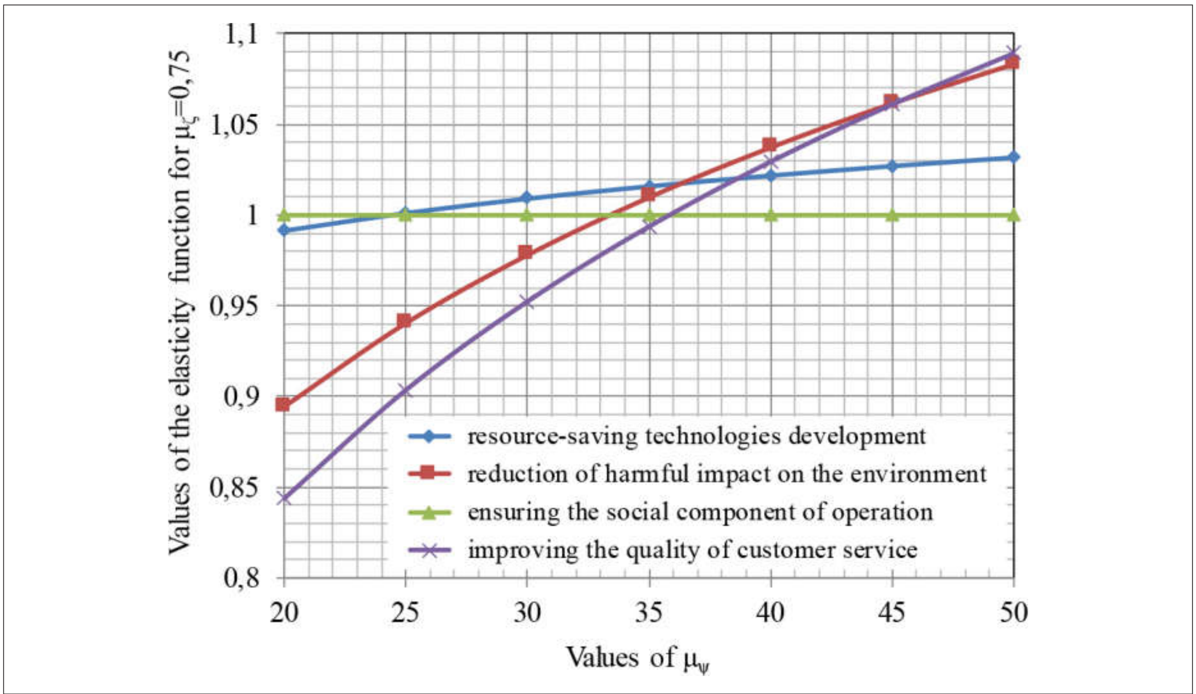

Figure 2 Dependencies of elasticity functions on the parameter μ_ψ

Examples in Fig. 2 and Fig. 3 show that in order to determine the priority directions of the RTS sustainable development, it is sufficient to establish which of the elasticity functions has the maximum value for the known μ_ζ and μ_ψ. For this, the boundaries of the ranges μ_ζ and μ_ψ should be determined, in which the corresponding elasticity functions are characterized by the largest values. Fig. 3 presents the priority areas of sustainable development of the Prid-neprovskaya Railway for the ranges of demand parameters μ_ζ and μ_ψ considered in this study.

Parameter values [train/h]	Parameter values [units]						
	20	25	30	35	40	45	50
0,2	S	S	S	S	S	Q	Q
0,3	S	S	S	S	Q	Q	Q
0,4	S	S	S	S	Q	Q	Q
0,5	S	S	S	S	Q	Q	Q
0,6	S	S	S	S	Q	Q	Q
0,7	S	S	S	S	Q	Q	Q
0,8	R	R	R	R	E	E	E
0,9	R	R	R	R	R	R	E
1,0	R	R	R	R	R	R	R
1,1	R	R	R	R	R	R	R

Figure 3 Priority areas of investments in the RTS sustainable development

Shown in Fig. 3 results could be used in practice to determine the priority direction of investments based on known numerical parameters of demand. For the chosen direction, the share of capital investments is determined as the biggest, the values of capital investments shares for other directions of the RTS sustainable development should be taken at the minimum admissible level.

6 Conclusions

In accordance with the contemporary paradigm of sustainable development, the operation of railway transport systems should be considered from the perspective of developing the resource-saving technologies, decreasing the harmful impact on the environment, ensuring the social component of operation, and providing the high quality of clients' servicing. The task of allocation of the financial resources for the mentioned directions of sustainable development is the optimization problem which is proposed to be solved as linear programming problem, where input parameters are represented as a vector containing shares of investments for the respective directions of the RTS development.

The developed software allows researchers to solve a wide range of problems related to railway systems operation. It considers technological parameters and demand characteristics as random variables, which ensures the elasticity of simulation procedures and the adequacy of the obtained results.

The simulations on the grounds of the proposed model for Pridneprovskaya Railway show that the largest value of the capital investments share corresponds to the direction of the RTS sustainable development which is characterized by the biggest value of the elasticity function. These results allow us to define the priority areas of the railway system development which should be defined for the known parameters of demand for the RTS services.

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