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Optimization of transport system operation using ranking method

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Abstract

The method of finding the maximum possible carload with the minimum duration of its processing in a transport system represented by fuzzy triangular numbers is described. The transport system means a complex consisting of a marshalling yard, freight port station and seaport, operating in a single coordinated mode for processing the carriage traffic on the railway network. The actuality of this task lies in the fact that the existing methods of solution do not take into account possible changes in the operating conditions of transport facilities that may affect the duration of processing of the carriage traffic processing. The applied method takes into account the fuzzy nature of the duration of the execution of technological operations in the transport system, which makes it possible to take decisions that are more adapted to real conditions. The peculiarity of solving this problem is the application in the objective function of fuzzy coefficients of the duration of the execution of technological operations. For the first time, the work of the transport system has been considered, including not only objects for the promotion of freight railway cars within the railway network, but also their processing beyond its borders.

Keywords: Transport system; Ranking method; Fuzzy conditions

1. Introduction

At present, statistical estimates of technical and technological performance indicators of railway facilities differ significantly from their nominal values: the actually used car fleet is found to be much less than the estimated one, while the average daily load of technical and freight stations, on the contrary, is significantly more than the

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estimated one. This phenomenon is caused by the general change in the situation in the railways in recent years [1]. The freight car fleet is now almost fully privatized and divided between the carriers operating their own car fleets. Trying to get the maximum profit from their cars, the operators are developing complicated freight transportation schemes for them, as the fee of the operator Ukrzaliznytsya PJSC for transportation of an empty car exceeds significantly that for transportation of a loaded car. This situation requires solving the problem of optimizing the car traffic handling in the rail network taking into account the accelerated transportation of cars between stations and the rational use of the technical capabilities of railway facilities.

Such a task is a transport problem. The method of reduction to the task of creating car traffic with a minimum duration of stay at the stations of the transport system is considered as a method of solving these problems. One of the main distinctive features of this approach is focusing on optimizing the time of car handling, rather than its cost, as is usually the case in problems of this type [2], which will not only reduce the cost of car handling at stations, but also optimize their operation technology in accordance with the current conditions and nature of freight transportation.

Movement and handling of cars in the railway network is planned using the complex multi-stage technology. In mathematical terms, the problem of movement and handling can be formulated as a mapping problem, in which each stream is associated with the car group sequences in the freight trains. Such mapping is based on a sequence of handling stages within the transport system, which should be understood as a complex consisting of a marshalling yard, a port freight station and a sea port, operating in a single coordinated mode in car handling in the railway network. The first stage of handling in the system is handling at the marshalling yard from the moment of arrival of the car routes until they depart in transfer trains to the port station. The second stage corresponds to car handling at the port station. The final stage is the distribution of groups of freight cars to freight areas and berths for freight handling operations.

2. Problem statement

In the study of the functioning process of the car handling transport system, it should be presented in the form of a directed graph G=(V, D) without loops and multiarches with source α and sink β, in which each of the arcs D will be associated with two connectivity components (see Fig. 1).

Fig. 1. Arc of the directed graph with two connectivity components.

The value of the first component is the traffic capacity of each element of the system (P_{ij}) which determines the maximum number of cars that can be passed through each arc. The value of the second component indicates the time of car handling in the elements of the system (t_{ij}) and corresponds to the time of the passage through the arc. In the flow theory, the most frequent graphs are those with arcs that are associated with the cost of passing, but since the Ukrainian railways has the approved rates for the use of cars, the cost of passage of cars in trains and shunting and other cost characteristics that can be used in the transport system during car traffic handling, have a definite character and do not change ad hoc under the influence of external factors, it is expedient to consider the time of car handling in the system, since on the load of the system at any given moment and the degree of utilization of the facilities of technical objects depend on this value.

The process of solving this task is finding the permissible car traffic, which will be handled in the system by the priority technology, the essence of which is described in [3], from source α to sink β for the minimum time of passing through the system, i.e., such a way of passing the car through the system for which the time of passing through the arcs is minimal for the maximum possible car traffic.

The mathematical problem statement has the form of an objective function with a system of constraints imposed on the basis of the values of the traffic capacity of each arc and the duration of passing each arc:

$$V = f(p_{ji}, i) = p_\alpha t_\alpha + \sum_{j=1}^{n_{i-1}} p_{ji} t_{ji} + p_\beta t_\beta \to V_{\min}, \tag{1}$$

$$\begin{cases} 1 \le i \le k; \\ 0 \le p_{ji} \le P_{ji}, \end{cases} \tag{2}$$

where:

- $p_\alpha t_\alpha$, $p_\beta t_\beta$ – number of cars which correspondingly arrive to the transport system for handling and leave it
- p_{ji} – number of cars which are processed by arcs of the graph of the transport system
- t_{ji} – duration of car handling in each arc of the graph
- k – number of possible routes of a car through technical facilities in the transport system during handling
- P_{ji} – train-handling capacity of the j-th connection in the i-th route

There are a few methods for finding a solution to the problem of this type, from serial search of ways of passing the arcs and vertices to the use of linear algorithms, network analysis and graph methods, which have been described in detail in the literature on the flow theory. The most common among them are: Busaker-Gowen's algorithm [4] which involves searching for ways of minimal cost until the moment when during passing the traffic the path ceases to be minimal; Klein's algorithm [5] according to which cycles of minimal average weight in the remaining network are cancelled because of their saturation by a unit of traffic until negative minimal average weights of the cycles disappear; Ford-Fulkerson's algorithm [6], which involves the successive saturation of arcs in the paths of a directed graph by their traffic capacity until passing the remaining unsaturated arcs from the source to the sink becomes impossible; and linear programming methods.

These methods are quite universal. The disadvantages of these methods include the necessity to specify the value of the traffic to be passed through the network, while the purpose of solving the problem is search for the optimal value of car traffic that can be handled in the system by the priority technology; cumbersomeness of methods and their poor visibility.

Most problems that reflect the work of physical objects and systems do not take into account their actual operative conditions, which have a significant impact on the accuracy and quality of the results of solving such problems. The information that is required for solving tasks is generally inaccurate, incomplete or absent at all. An accurate solution to problems with fuzzy information is inexpedient, since no optimization method will allow finding a solution that can be used to make a clear, substantiated management decision. Each obtained solution does not the mean optimal solution of the problem itself. In addition, in the literature on solving problems in the fuzzy conditions, methods for solving such problems are described most fully when the constraints of the objective function become of a fuzzy kind. In this case, we have a fuzzy objective function with a system of clear constraints. Therefore, solving this problem is relevant and has a scientific novelty among studies on the transport systems associated with uncertain conditions. Such important parameters of the operation of transport systems and networks, as the duration of operations in the cycle, the cost of passing through the arcs and others may change when the traffic passes the graphs under the influence of factors of known and unknown origin. Therefore, it is expedient to use such a method of setting parameters of the transport system, which would bring the representation of the directed graph to the real operative conditions of the system. The fuzzy form of the parameters may be one of such methods, in particular, the most commonly used in practice fuzzy triangular numbers [7, 8, 9], the essence of which is defining a parameter with three numbers – a clear value of the parameter and two degrees of fuzziness of its value.

For each fuzzy triangular number of kind A $<a_l, a, a_r>$ with significant points $a_l <= a <= a_r$ a membership function (level of confidence) is determined:

$$\mu_A(x) = \begin{cases} 0, x \le a_l; \\ \dfrac{x - a_l}{a - a_l}, a_l \le x \le a; \\ \dfrac{a_r - x}{a_r - a}, a \le x \le a_r; \\ 0, x \ge a_r. \end{cases} \tag{3}$$

A fuzzy graph is an adequate model for representing such tasks [10]. The fuzzy directed graph of representation of the transport system for car handling with the destination to sea ports which consists of (n+k+1) vertices, using triangular numbers, takes on the following general form (see Fig. 2):

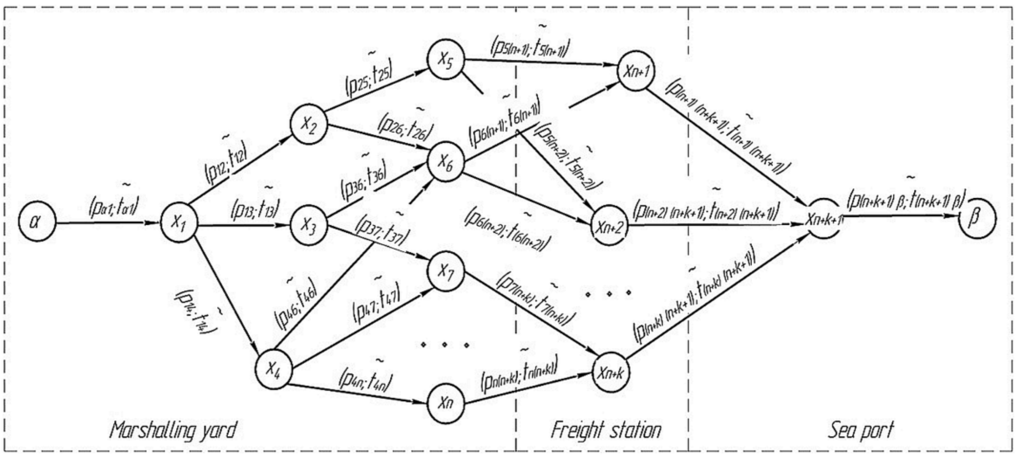

Fig. 2. Fuzzy directed graph of the general view of the transport system handling car traffic with the destination to sea ports.

In the figure, the vertices of the graph are technical facilities and devices that are involved in car traffic handling technology and play a crucial role in the model of presentation of the problem being considered: at the marshalling station – tracks of the receiving area, humping and detaching tracks, tracks of the marshalling and departure yard; at the port freight station – reception and departure tracks, turnout tracks and tracks of the district areas of the port; in the port –tracks of freight area, berths, dead-end tracks, as well as loading and unloading devices. The time of passing the traffic through each arc is matched to the duration of execution of technological handling operations in the transport system.

The conditions of integer variables and fuzzy duration of execution of technological operations, $\tilde{t}_{ij}$, and clear values of traffic capacity of the technical facilities of the system p_{ij} are imposed on solving the problem of finding the number of cars that can be handled in the transport system by the priority technology for a minimum amount of time. Problem (1), (2) acquires the form:

$$V = p_\alpha \tilde{t}_\alpha + \sum_{j=1}^{n_{i-1}} p_{ji} \tilde{t}_{ji} + p_\beta \tilde{t}_\beta \to V_{\min}, \tag{4}$$

$$\begin{cases} 1 \le i \le k; \\ 0 \le p_{ji} \le P_{ji}, \end{cases} \tag{5}$$

where $\widetilde{t}_{ji}$ – time of fulfillment of technological operations in the transport system in a fuzzy form, hours.

In this case, the fuzzy connectivity components along the arcs of the graph are given in the form of triangular numbers and are reflected in the objective function, not in the restrictions to it. Thus, the problem of finding the volume of cars to be handled in the system by the priority technology in the shortest time is formed as the problem of integer linear programming with a fuzzy objective function, which is reduced to the problem of parametric linear programming.

3. Method for finding the volume of cars to be handled in the system by the priority technology

Since the car traffic with the minimum possible duration of stay of cars in the transport system should not exceed some maximum permissible value in the directed graph, for solving this problem, the amount of the car traffic should be determined that can be handled in the system within the number of cars with regard to the traffic capacity values of technical facilities by the arcs of the graph n_{ij}. Ford-Fulkerson's algorithm was used for this purpose. Calculations were carried out by using the above directed graph in the transport system of the Odessa node in the Regional branch Odessa Railways of Ukrzaliznytsya PJSC, which consists of the Odessa-Sortuvalna and Odessa-Zastava I marshalling stations, Odessa-Port freight station and the Odessa International Trade Port. In this case, the limited use of such design and technological parameters as the number and specialization of tracks of the marshalling area of the marshalling station, the capacity of the tracks of the freight areas at the berths of the port, as well as the coefficients of the use of technical facilities of the berths due to the unevenness and different volumes of cars arriving to individual berths were taken into account.

Analysis of the results of calculations using the above method has proved that the car traffic that can be handled in the system using the traditional technology in any servicing variant is limited by the technical capacity of the shunting facilities of the port freight station for breaking up of transfer trains coming from the marshalling station, and is 760 cars/day. When the priority technology of car handling is used, the arc, to which the traffic capacity of the tracks of the receiving yard of the marshalling station is assigned, is limiting, and is 1,327 cars/day. It means that the technical capabilities of the system and the organization of its operation allow the use of the priority technology for the entire volume of cars arriving at the marshalling station with the destination to a sea port.

Below there is a general form of the objective function in accordance to Fig. 2:

$$\begin{aligned} \widetilde{f} &= \widetilde{t}_{\alpha 1} \cdot p_{\alpha 1} + \widetilde{t}_{12} \cdot p_{12} + \widetilde{t}_{13} \cdot p_{13} + \widetilde{t}_{14} \cdot p_{14} + \widetilde{t}_{25} \cdot p_{25} + \widetilde{t}_{26} \cdot p_{26} + \widetilde{t}_{36} \cdot p_{36} + \widetilde{t}_{37} \cdot p_{37} + \\ &+ \widetilde{t}_{46} \cdot p_{46} + \widetilde{t}_{47} \cdot p_{47} + \ldots + \widetilde{t}_{4n} \cdot p_{4n} + \widetilde{t}_{5(n+1)} \cdot p_{5(n+1)} + \widetilde{t}_{5(n+2)} \cdot p_{5(n+2)} + \widetilde{t}_{6(n+1)} \cdot p_{6(n+1)} + \\ &+ \widetilde{t}_{6(n+2)} \cdot p_{6(n+2)} + \ldots + \widetilde{t}_{7(n+k)} \cdot p_{7(n+k)} + \widetilde{t}_{n(n+k)} \cdot p_{n(n+k)} + \widetilde{t}_{(n+1)(n+k+1)} \cdot p_{(n+1)(n+k+1)} + \\ &+ \widetilde{t}_{(n+2)(n+k+1)} \cdot p_{(n+2)(n+k+1)} + \widetilde{t}_{(n+k)(n+k+1)} \cdot p_{(n+k)(n+k+1)} + \widetilde{t}_{(n+k+1)\beta} \cdot p_{(n+k+1)\beta} \rightarrow \min \end{aligned} \quad (6)$$

Let us consider the above objective function for the transport system, which is accepted as an investigated one. Table 1 contains values of car traffic handling time in a form of triangular numbers in accordance with the arcs of the directed graph.

There are a few approaches to solving similar tasks. One of them involves the use of solving methods without taking into account the fuzzy nature of the parameter setting imposing fuzzy restrictions on the results. Other approaches include application of fuzzy linear programming methods [6, 7], the first of which appeared in the second half of the 20th century and have now become very common in the mathematical, physical and computer sciences and CAD systems. One of the most convenient among these methods is a method based on the concept of comparing fuzzy numbers using ranking functions or qualitative ordering [8-10]. In such methods, the authors usually define a clear model which is equivalent to a fuzzy linear programming model, and then use the optimal solutions of this model as optimal solutions of fuzzy linear programming.

The literature describes a number of ranking methods proposed by different [11-16]. The main differences between these methods include the ways of ordering of values and the approaches to ranking. The disadvantage of these methods is the lack of universality in the estimation of fuzzy parameter values when solving practical problems. In addition, in some cases, the ranking method allows finding more than one optimal solution to the problem, which consequently requires searching for a criterion for choosing one among them. The result of the comparison of fuzzy numbers depends on the chosen method for determining the ranking index [17, 18]. In order to search for a solution to the problem of car traffic handling by the priority technology, the above-mentioned existing experience in solving similar problems both in transport and in other industries was taken into account in the study.

Table 1. Initial data to create an objection function.

Adjacent vertices of the arc	Significant points of duration of execution of an operation on the arcs		
	al	a	ar
α – 1	0.13	0.15	0.18
1 – 2	0.50	0.63	0.73
1 – 3	0.58	0.70	0.77
1 – 4	0.50	0.70	0.87
2 – 5	5.09	7.12	8.30
2 – 6	3.75	4.33	4.67
3 – 6	4.13	5.00	6.33
3 – 7	5.13	5.50	6.07
4 – 6	4.03	4.83	5.47
4 – 7	4.67	5.67	6.13
4 – 8	3.63	4.33	4.87
5 – 9	16.42	18.63	20.13
5 – 10	16.36	17.33	19.55
6 – 9	14.37	15.00	15.73
6 – 10	15.80	19.16	21.16
7 – 11	19.06	19.79	21.13
8 – 11	16.40	17.33	18.16
9 – 12	29.77	32.75	35.55
10 – 12	30.40	31.88	36.42
11 – 12	30.91	34.62	35.40
12 – β	9.73	11.62	13.46

In [19], a method was proposed which involves the sequence of actions to compare fuzzy coefficients with clear ones using the distribution density functions, solving problems in clear conditions, the use of mathematical expectation in the ranking function for further finding a solution to the problem of fuzzy linear programming. When more than one optimal solution are obtained, the best one is chosen by comparing dispersions, and the optimal solution is the one with the lowest value of the degree of dispersion in accordance with [20]. This method is sufficiently completely and accurately reflects the results of the search for optimal solutions to similar problems, since there is a probabilistic approach in the estimation of fuzzy numbers to identify the correct optimal solution to the problems of linear programming of fuzzy numbers. In order to solve the problem with a fuzzy form of the objective function, let us use the method of comparing fuzzy triangular numbers with the help of the ranking function. As a result, each fuzzy coefficient is replaced by a clear one, which forms a clear problem statement and gives the opportunity to get the optimal solution. Let us define the ranking indexes I (A) using in a method based on calculating the mathematical expectation of a random variable, the probability distribution of which is calculated using the function of membership of fuzzy numbers μ_A [17]:

$$I(A) = \frac{\int_{S_A} x \mu_A(x) dx}{\int_{S_A} \mu_A(x) dx} \tag{7}$$

where S_A – fuzzy number carrier A. Applying the ranking function for each fuzzy coefficient, we obtain the following clear problem statement:

$$f = 0.153 p_{\alpha 1} + 0.62 p_{12} + 0.683 p_{13} + 0.69 p_{14} + 6.83 p_{25} + 4.25 p_{26} + \\ + 5.15 p_{36} + 5.57 p_{37} + 4.78 p_{46} + 5.49 p_{47} + 4.28 p_{48} + 18.39 p_{59} + \\ + 17.75 p_{5\,10} + 15.03 p_{69} + 18.70 p_{6\,10} + 19.99 p_{7\,11} + 17.30 p_{8\,11} + \\ + 32.69 p_{9\,12} + 32.90 p_{10\,12} + 33.64 p_{11\,12} + 11.60 p_{12\,\beta} \rightarrow \min$$

under the following conditions, formulated taking into account the physical nature of the objects being investigated:

$$p_{12} + p_{13} + p_{14} - p_{\alpha 1} = 0;\ p_{12} - p_{25} - p_{26} = 0;\ p_{13} - p_{36} - p_{37} = 0;$$
$$p_{14} - p_{46} - p_{47} - p_{48} = 0;\ p_{25} - p_{59} - p_{510} = 0;\ p_{26} + p_{36} + p_{46} - p_{69} - p_{610} = 0;$$
$$p_{37} + p_{47} - p_{711} = 0;\ p_{48} - p_{811} = 0;\ p_{59} + p_{69} - p_{912} = 0;\ p_{510} + p_{610} - p_{1012} = 0;$$
$$p_{711} + p_{811} - p_{1112} = 0;\ p_{912} + p_{1012} + p_{1112} - p_{12\beta} = 0;\ p_{12\beta} - p_{\alpha 1} = 0;$$
$$0 \le p_{\alpha 1} \le 1327;\ 0 \le p_{12} \le 1280;\ 0 \le p_{13} \le 1180;\ 0 \le p_{14} \le 1150;\ 0 \le p_{25} \le 1220;$$
$$0 \le p_{26} \le 1140;\ 0 \le p_{36} \le 1240;\ 0 \le p_{37} \le 1018;\ 0 \le p_{46} \le 1086;\ 0 \le p_{47} \le 1191;$$
$$0 \le p_{48} \le 1212;\ 0 \le p_{59} \le 588;\ 0 \le p_{510} \le 588;\ 0 \le p_{69} \le 524;\ 0 \le p_{610} \le 604;$$
$$0 \le p_{711} \le 682;\ 0 \le p_{811} \le 650;\ 0 \le p_{912} \le 702;\ 0 \le p_{1012} \le 695;\ 0 \le p_{1112} \le 809;$$
$$0 \le p_{12\beta} \le 1320.$$

To solve the problem, we apply the method of a generalized lowering gradient, the essence of which is reduction of the dimension of the problem by excluding dependent variables and the use of the reduced gradient method to determine the direction of descent and as a criterion for determining the optimality. The obtained optimal solution of the problem is $\tilde{f} = (44989.80; 50012.52; 54061.52)$ and is shown graphically in Fig. 3. Thus, it can be stated that the length of time of the priority stay of the car in the transport system will be at least 44,989.8 car/hour, but not more than 54061.52 car/year. Most likely, this value will be 50012.52 car/h.

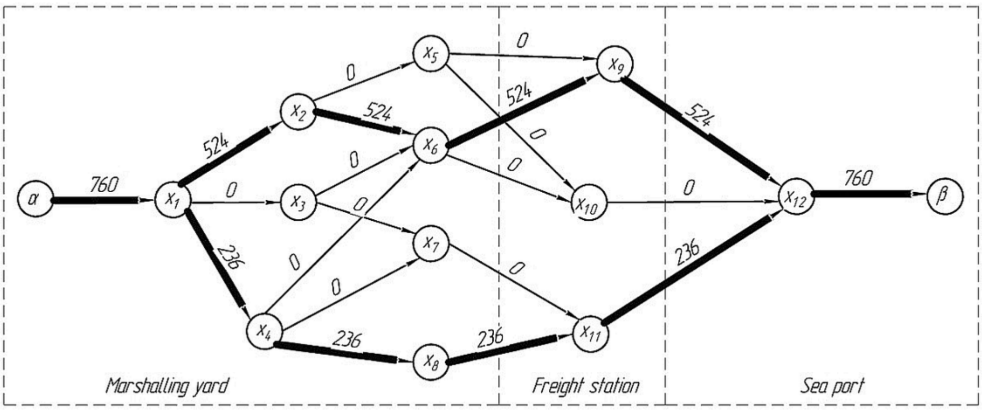

Fig. 3. Graphic interpretation of the optimal solution of the problem.

4. Conclusion

So, it can be noted that the approach used in this article allows finding a solution to the problem of determining the volume of cars with the destination to a seaport with a minimum duration of technological handling operations in the transport system with fuzzy assignment using ranking methods. The advantage of the approach is avoiding the use of cumbersome methods for solving this problem as a multi-criteria problem of parametric linear programming. The use of triangular fuzzy numbers when solving problems allows using a standard apparatus for linear programming methods. Solutions to fuzzy problems in the form of an objective function are more accurate and qualitative than those to a clearly defined task, due to the flexibility of the used representation of output data and the practicality of the approach to the problem of search and interpretation of a solution.

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