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Strategic approach to sustainable development of railway transport and optimizing the use of empty cars in organizing transportation of dangerous goods

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Abstract. Under present-day conditions in the development of the transport market, organizing the transportation of dangerous goods by rail is an urgent task, considering the specific properties of the impact of dangerous goods on technical devices, human health, and the environment. The number of parameters influencing the safety of the transportation process is quite large, therefore, programs for the safe and sustainable development of railway transport must involve protection from all possible sources of danger. The strategy for sustainable development of railway transport should be based on improving regulatory and technical documentation, developing safe technology for eliminating the consequences of emergencies, developing network computer technologies, and improving vehicles and transportation technology. Since the transportation of dangerous goods represents a significant share of the total transportation of goods, including railway transport, the research outlined in the presented work is aimed at solving some aspects of this strategy, which as a result forms a strategic approach to the sustainable development of railway transport when organizing the transportation of dangerous goods. In this paper, considering modern conditions for the development of railway transport, it is proposed to comprehensively implement the assigned task with a new approach by introducing a system of operational control during the transportation and temporary storage of dangerous goods and applying the developed method for the optimal distribution of empty cars among cargo checkpoints in the organization of the transportation process.

1. Introduction

Transportation of dangerous goods is an activity associated with the movement of dangerous goods from the place of their production or storage to their destination, with the preparation of freight, containers, vehicles, and crew, acceptance of freight, freight operations, and short-term storage of goods at all stages of movement [1–3].

Transportation of dangerous goods, including railway transport, is a necessary task in the context of sustainable development of transport, since ensuring the sustainable organization of such transportation will maintain the health of personnel and the population, exclude negative impacts on the environment, and take all necessary actions to prevent the occurrence of an emergency [4–6]. On the one hand, this direction corresponds to Sustainable Development Goal No. 9 “Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovations”, and on the other hand, it satisfies the provisions and Sustainable Development Goal No. 11 “Make cities inclusive, safe, resilient and sustainable”, No. 12 “Ensure sustainable consumption and production patterns”, No. 13 “Take urgent measures to combat climate change and its impacts” [7].

These provisions characterize the implementation of the environmental component in the concept of sustainable development. At the same time, the research presented in this work is also aimed at optimizing the organization in the transportation of dangerous goods by optimally allocating empty cars through freight points. This will ensure economic stability, which is confirmed by the results of the research. Thus, the relevance of the chosen research topic is due to the desire for a balanced development of the economic and environmental components in the concept of sustainable development through the implementation of the proposed strategic approach to organizing the transportation of dangerous goods by railway in Ukraine.

Since the transportation of dangerous goods by railway is a specific type of transportation, with regard to the potential danger of transporting goods, the unconditional implementation of all preventive measures aimed at warning the occurrence of emergencies when organizing the transportation of dangerous goods, including by railway, is required from all entities in the transportation process [8–10].

Confirmation of the relevance and need to formalize a strategic approach to sustainable railway development in organizing the transportation of dangerous goods is statistical data on the number of dangerous goods transported in 2018-2022, as well as the number of accidents, transport events and emergencies that occurred in Ukraine during the transportation of dangerous goods for the same period [11]. These data are presented in tabular and graphical forms (table 1, table 2, figure 1). The materials provide statistical data under the classification of dangerous goods (classification by class, category, and packaging group) in line with State Standards of Ukraine (SSU) 4500-3 “Dangerous goods. Classification” depending on the type and degree of their potential danger according to indicators and criteria [12].

Data from table 1 and figure 1 show that the highest rates of dangerous goods transportation in Ukraine were in 2019 and 2020. In 2022, we see a rapid decline in the volume of railway transport, also due to certain problems in logistics.

A significant proportion of chemically hazardous facilities are concentrated on the territory of Ukraine, as well as a significant number of fire-hazardous facilities, which are usually located next to railway tracks or have their private tracks. At the above potentially hazardous facilities, large quantities of hazardous substances are extracted, processed, transported, stored, and consumed, which in any case require further safe transportation [13–15].

Considering the above, in modern conditions, it is especially relevant to review the current technology for transporting dangerous goods, including in bulk, along the Ukrainian railway network, and to find ways to improve it to prevent the occurrence of emergencies, which increased in the period from 2018 to 2022 by 22 percent (table 2).

It should also be noted that complex European integration processes relating to Ukraine and its transport system [16–18], different levels of economic development, and the characteristics of the productive and consumer specialization in the EU countries and Ukraine will lead to the fact that the volume of transport of dangerous goods in Ukraine and beyond will steadily increase [19]. This requires the search for effective tools to optimize the organization of dangerous goods transportation by railway in Ukraine.

The work is devoted to formalizing a strategic approach to organizing the transportation of dangerous goods by introducing a system of operational control during transportation, temporary storage of dangerous goods, and formalizing the optimal allocation of empty cars

Table 1. Percentage ratio in the number of dangerous goods transported following the class of dangerous goods from 2018 to 2022.

Danger class	2018	2019	2020	2021	2022
Class 1 Explosive Materials	15.89	10.88	10.52	9.35	10.16
Class 2 Gases	23.20	16.08	15.35	16.23	17.71
Class 3 Highly flammable liquids	10.39	18.07	20.73	18.04	16.32
Class 4.1 Inflammable solid	4.81	4.88	6.64	7.21	10.17
Class 4.2 Substances capable of self-ignition	8.36	7.12	6.92	6.07	5.87
Class 4.3 Substances that emit flammable gases interacting with water	3.38	3.67	3.36	2.23	3.46
Class 5.1 Oxidizing substances	7.06	10.57	7.93	9.36	8.92
Class 5.2 Organic peroxides	12.72	6.56	7.02	8.01	10.49
Class 6.1 Toxic substances	3.86	1.72	5.36	4.02	1.72
Class 6.2 Infectious substances	0.00	$1 \cdot 10^{-6}$	$1 \cdot 10^{-5}$	0.00	0.00
Class 7 Radioactive Materials	0.00	$1 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	0.00	$4 \cdot 10^{-6}$
Class 8 Corrosive Substances	4.51	6.22	9.67	10.84	3.50
Class 9 Other hazardous substances	5.80	14.23	6.50	8.65	11.66
In total	100.00	100.00	100.00	100.00	100.00

Table 2. Number of transport events with dangerous goods.

Number of	2018	2019	2020	2021	2022
Transport events	130	141	147	154	161
Lost	29	17	11	6	8
Injured	9	7	11	6	4

among freight points to ensure the implementation of the concept of sustainable development of railway transport in Ukraine.

2. The operational control system for the transportation and temporary storage of dangerous goods

An analysis of transport events related to the transportation of dangerous goods [11] shows that the so-called "human factor" remains decisive in the issue of ensuring safety [20–22]. In modern conditions, it can and should be assessed even at the stage of admission to work with dangerous goods by introducing a unified system of professional training, qualified selection, and certification of personnel whose activities are directly linked to dangerous goods.

In solving this problem, an important role is assigned to the audit apparatus, its professional selection, and advanced training.

Railway transport is equipped with automation facilities at a fairly high level. At the same time, research is aimed at reducing the number of technical equipment failures and personnel errors. The developed multi-level system for controlling and ensuring the safety of train traffic allows, in addition to performing direct control and safety tasks, to detect potentially dangerous situations. In this case, the dispatch apparatus (assistant station masters, train dispatchers) is given a corresponding signal, and the priority for processing information that comes from the control and monitoring object is set. The system also provides for the development of predicting

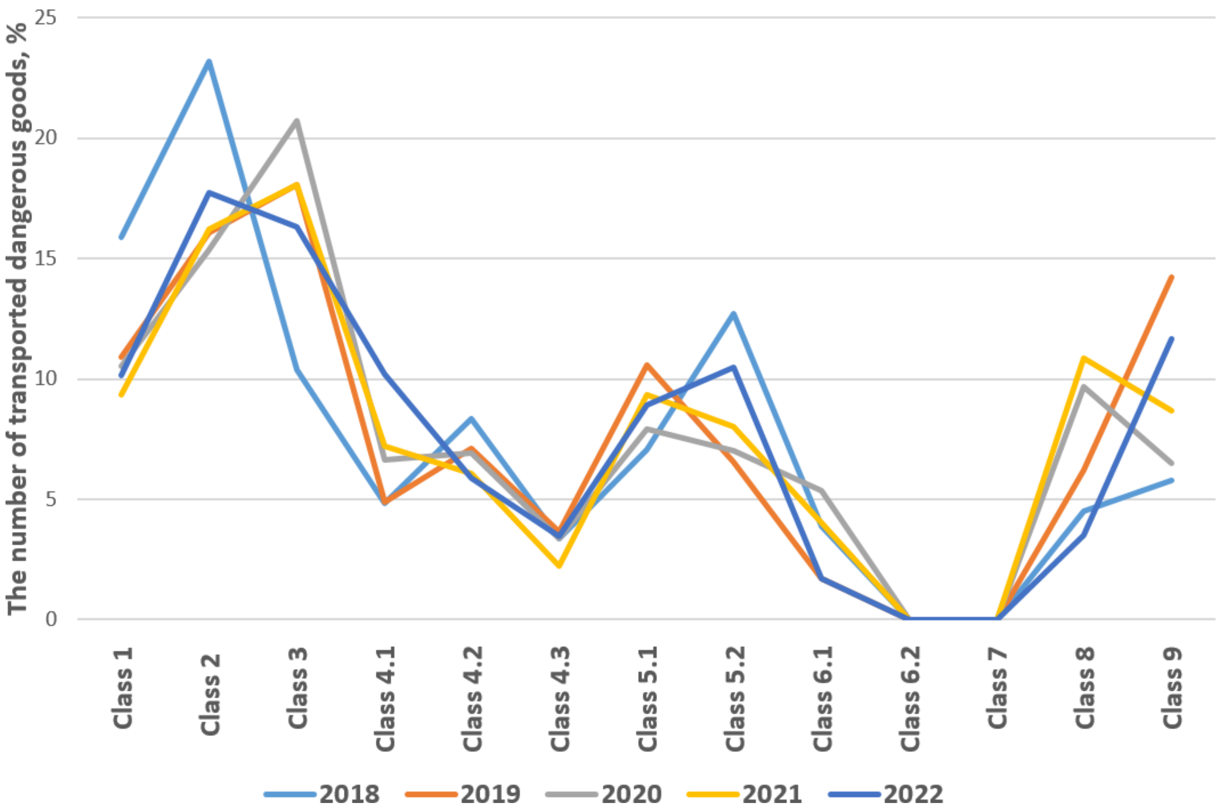

Figure 1. The number of transported dangerous goods in 2018-2022, in percentages.

the development of the situation in the event of accidents or emergencies and the development of model options for switching on backup control subsystems and ensuring the safety of train traffic.

In general, the implementation of the system involves reducing, and in some cases eliminating, the influence of the human factor on the safety of train traffic. To do this, erroneous actions of the dispatch apparatus and incorrect operation of devices in the event of a dangerous failure or unauthorized interference in their operation are blocked.

Environmental control points at border checkpoints play an important role when organizing the international transport of dangerous goods.

One of the main problems when transporting dangerous goods, including in bulk, is the insufficient level of reliability of rolling stock. An analysis of recent accidents associated with the transportation of bulk dangerous goods shows that in several cases rolling stock with an extended service life was used (for example, shippers have the majority of such specialized tanks). The tanks used do not have technical means to reduce the evaporation of petroleum products, casings to protect drain devices from impacts on the ground, and the boiler body is structurally unable to withstand an impact on the ground when there is a tank derailment. New generation tanks having a reinforced boiler body are practically not being introduced. The railway management is taking the initiative to renew the tank fleet. In light of this, it would make more sense to incentivize shippers of dangerous goods to upgrade their cars. In addition, it is necessary to tighten control when accepting bulk dangerous goods for transportation from the shipper, especially paying attention to the following points:

- control of the technical condition of tanks, including control of non-interference in their design without agreement with the manufacturer;

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- monitoring compliance with the conditions for loading goods into cars following established rules and instructions for tanks;
- control of correct completion of transportation documents, availability of necessary permits and licenses;
- control of compliance with the rules of escort and security.

When organizing the transportation of dangerous goods in bulk, it is necessary to monitor compliance with the transportation conditions provided for by the rules. For this aim, using modern automation tools, it is proposed to develop and equip tanks with technical means that reduce the evaporation of petroleum products during transportation in tanks. In addition, it is possible to install sensors that monitor and signal the state of dangerous goods during transportation. Information about deviations in the state of the control object is immediately transmitted to the provided levels of automated systems and the staff makes a prompt decision on further actions.

As a rule, the onset of a destructive process with dangerous freight (seepage, leakage, evaporation, etc.) begins with a slight depressurization of the container and can subsequently result in a significant negative impact on the environment, both during transportation and temporary storage of dangerous goods at the transfer station.

Moreover, if depressurization occurs along the way, then the dangerous freight can leave a trail of tens or even hundreds of kilometers long during the time from the beginning of the depressurization process until the moment it is detected. Therefore, it is very important to define the beginning of an emergency as soon as possible and begin to neutralize its consequences.

Creating a system to prevent transport incidents when transporting dangerous goods will undoubtedly reduce environmental and economic damage.

The operational control system for the transportation and temporary storage of dangerous goods includes a set of technical systems, devices, and measures to monitor the condition and location of dangerous goods, determine the onset of emergency (pre-emergency) situations and accidents, process information and transfer it to dispatch control centers for developing solutions to prevent emergencies, localize and neutralize the consequences of accidents.

The system for operational monitoring of the condition of transported and stored dangerous goods includes the following technical subsystems and devices:

(i) subsystems for monitoring the technical condition of containers for the transportation of dangerous goods and the condition of them themselves to determine their release into the environment using sensors;
(ii) subsystems for collecting information from control sensors, processing it, and transmitting it to a repeater installed on the locomotive;
(iii) subsystems for transmitting information from the locomotive (train, car, warehouse) to train dispatchers and processing it.

To determine the economic efficiency of implementing an operational control system during the transportation and temporary storage of dangerous goods, research is needed to define the resulting economic damage that causes costs for:

(i) liquidation of the accident and its consequences and restoration of traffic;
(ii) compensation for damage to the environment (including to the population) – fines and compensation;
(iii) losses from the cessation of the transportation process during the liquidation of the accident (including damage to vehicles);
(iv) possible payments for freight insurance.

Determining such average costs will allow us to evaluate the effectiveness of implementing the system, and organizational and technical solutions for eliminating accidents and their consequences.

Sensors control for monitoring the condition of dangerous goods can be made in the form of sensors that can not only signal the occurrence of leaks of substances, but also indicate their locations (by using an additional substance that can change the colour), and also allow them to be quantitatively assessed. Monitoring sensors together with the unit of a primary information collection must meet the technical requirements. In addition, they must have protection systems against dynamic loads, vibration, external damage, exposure to aggressive substances, and unauthorized penetration.

The placement and fastening of sensors and the primary information unit on special tanks must be permanent and have connectors for connecting the information transmission system.

The issue of reducing the threat of an emergency with dangerous goods transported in bulk through the territory of Ukraine plays an important role since accidents accompanied by spills of hazardous liquids lead to significant environmental damage to the environment.

In this regard, it is rational to develop and implement technology to eliminate the consequences of transport accidents with dangerous goods. In addition, it is possible to develop a methodology and determine environmentally acceptable routes for dangerous goods to reduce the risk of an emergency.

Considering that more than 90 percent of liquid freight consists of petroleum products, great attention must be paid to improving the organization of their transportation. The achievements of scientists make it possible to optimize the car flows of petroleum products. In this case, important conditions are the routing of their transportation and the organization of empty tank car flows.

Routing of railcar flows of petroleum products is a particularly effective measure for mass export transportation to seaports, which allows for reducing freight delivery times and speeding up the turnover of railcars.

Also, one of the sources of reducing costs and car turnover is the rational allocation of empty tanks for loading. At the same time, it is taken into account that in the case of loading a freight similar to the dumped one into a tank, there is no need for hot working of the tanks (cold working is sufficient), and this can significantly reduce the downtime of tanks at loading stations and the costs associated with processing.

The rational allocation of empty tanks for loading consists in increasing the degree of conformity of the structure of tanks arriving for loading, according to the names of the dumped and filled petroleum products. This is possible by increasing the depth of information that is transmitted to loading stations about the names of dumped petroleum products from tanks arriving at their address in empty tank trains, and about the use of this information when distributing empty tanks for loading. The depth of information means the availability of the necessary information not about one composition of empty tanks for filling, but about 2...3 or more. Thus, with an increase in information to three trains, the proportion of tanks sent for loading of petroleum products similar to the dumped one increases by 2.5...3 times compared to the availability of information about only one train. Accordingly, a reduction in costs for washing and steaming operations is achieved and the turnover of tanks is accelerated.

The depth of required information can be increased by using modern information technologies. It is necessary that the dispatch apparatus make a timely decision on the assignment of trains of empty tanks to one or another loading station and that the necessary information is transmitted to them in advance to enable the rational allocation of tanks for loading.

Thus, the allocation of empty cars is a key and rather complex management task. The authors propose an optimal solution to the problem of distributing empty cars on freight points as one of the methods for optimizing the organization of transportation of dangerous goods by railways.

3. The description of the mathematical apparatus

Problems of the type under consideration can be divided into two groups depending on how fully all the factors associated with finding the optimal option for allocating empty cars are considered:

(i) optimization is done only from the viewpoint of the best use of the capacity of cars, and the costs associated with the movement of empty cars between freight points are not taken into consideration;

(ii) optimization of the process in the allocation of empty cars is carried out according to the criterion of overall operating costs associated with the supply of cars to freight points and with the transportation of goods by railways.

Ignoring the costs of supplying empty cars can be justified only if they do not differ significantly from each other or are insignificant in their absolute value.

In its simplest form, the problem of allocating different-type cars to freight points depending on the static load was formulated by A. B. Kaplan. In mathematical formulation, this problem is written as follows:

$$R^* = y_{ij}^{min} \sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij}, \tag{1}$$

if

$$y_{ij} \geq 0, i = 1, 2, \ldots, n; j = 1, 2, \ldots, m, \tag{2}$$

$$\begin{cases} \sum\limits_{i=1}^{n} y_{ij} P_{ij} = Q_j; \\ \sum\limits_{j=1}^{m} y_{ij} \leq n_i. \end{cases} \tag{3}$$

The main goal of drawing up an optimal allocation plan is to minimize the number of empty cars y_{ij}, required to transport a given amount of freight Q_j, if restrictions are imposed on the number of cars (3). In this case, at each freight point, there is only one type of freight j, the statistical load of which P_{ij} when transported in cars of the i-th type is given, and the costs of supplying empty cars are neglected. The sources of empty cars arriving at the freight points at the station are both unloading points and cars arriving from neighbouring stations.

The task of the type under consideration should be formulated differently if there is a shortage of empty cars:

$$R^* = y_{ij}^{max} \sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij} P_{ij}, \tag{4}$$

if

$$y_{ij} \geq 0, i = 1, 2, \ldots, n; j = 1, 2, \ldots, m, \tag{5}$$

$$\sum_{j=1}^{m} y_{ij} = n_i; \tag{6}$$

$$\sum_{i=1}^{n} y_{ij} P_{ij} \leq Q_j. \tag{7}$$

In this formulation, the optimization problem lies in finding such y_{ij}, that would maximize the linear form (4), representing the amount of freight loaded into n_i of delivered cars. At first sight, the optimal choice for distributing empty cars that mostly satisfies the requirements for the best use of capacity and tonnage is one in which only cars of one type are delivered to freight points.

However, with a significant number of freight points and a lack of empty cars of the "optimal" type, constructing such a distribution plan using heuristic methods seems impossible, and then the problem posed can only be solved using linear programming methods since functionals (1) and (4) and restrictions (3), (6) and (7) are linear.

4. Results

Let us consider a numerical example for conditions when there is a shortage of empty cars at the station. At two freight points there are freights in the amount of $Q_1 = 540$ tons and $Q_2 = 620$ tons, the volumetric weight of the freight is $y_1 = 0.3$ tons/m^3 and $y_2 = 0.75$ tons/m^3.

The station has three types of covered cars with the following characteristics for cars of the first type $P_1 = 62$ tons, $V_1 = 107$ m^3 in the amount of $n_1 = 8$, for cars of the second type $P_2 = 62$ tons, $V_2 = 120$ m^3 in the amount of 12 and for the third type of cars $P_3 = 62$ tons, $V_3 = 90$ m^3 in the amount of 6. The static loads of the cars are as follows: $P_{11} = 32$ tons, $P_{12} = 62$ tons, $P_{21} = 36$ tons, $P_{22} = 62$ tons, $P_{31} = 27$ tons, $P_{32} = 62$ tons.

The condition is set – to ensure the loading of all freights with a volumetric weight of $y_1 = 0.3$ tons/m^3. We will substitute the initial data of the task into expressions (4) — (7) and after transformations we obtain

$$R = 32y_{11} + 62y_{12} + 36y_{21} + 62y_{22} + 27y_{31} + 62y_{32} \tag{8}$$

or

$$R_1 = 1.2y_{11} + 2.3y_{12} + 1.3y_{21} + 2.3y_{22} + y_{31} + 2.3y_{32}, \tag{9}$$

$$y_{ij} \geq 0 \ (i = 1, 2, 3; j = 1, 2), \tag{10}$$

$$\begin{cases} y_{11} + y_{12} = 8; \\ y_{21} + y_{22} = 12; \\ y_{31} + y_{32} = 6. \end{cases} \tag{11}$$

$$\begin{cases} 32y_{11} + 36y_{21} + 27y_{31} = 540; \\ 1.2y_{11} + 1.3y_{21} + y_{31} = 20; \\ 62y_{12} + 62y_{22} + 62y_{32} \leq 620. \end{cases} \tag{12}$$

$$y_{12} + y_{22} + y_{32} \leq 10. \tag{13}$$

Let us exclude from expressions (9), (11) and (13) variables y_{12}, y_{22}, y_{31}, y_{32} and after simplification we obtain

$$R_2 = 0.46y_{11} + 0.7y_{21}; \tag{14}$$

$$y_{11,21} \geq 0; \tag{15}$$

$$0.2y_{11} + 0.3y_{21} \leq 4. \tag{16}$$

Condition $1.2y_{11} = 1.3y_{21} \leq 20$ is less strong than (16).

From conditions (11) it implies

$$\begin{cases} y_{11} \leq 8; \\ y_{21} = 12. \end{cases} \tag{17}$$

The task is to find such y_{11} and y_{21}, that would maximize the linear form (14). Since the task has been reduced to determining two variables, it can be solved graphically (figure 2). The search direction is shown by an arrow going from the origin of coordinates, since according to the condition it is necessary to maximize the functional (16), which grows with increasing

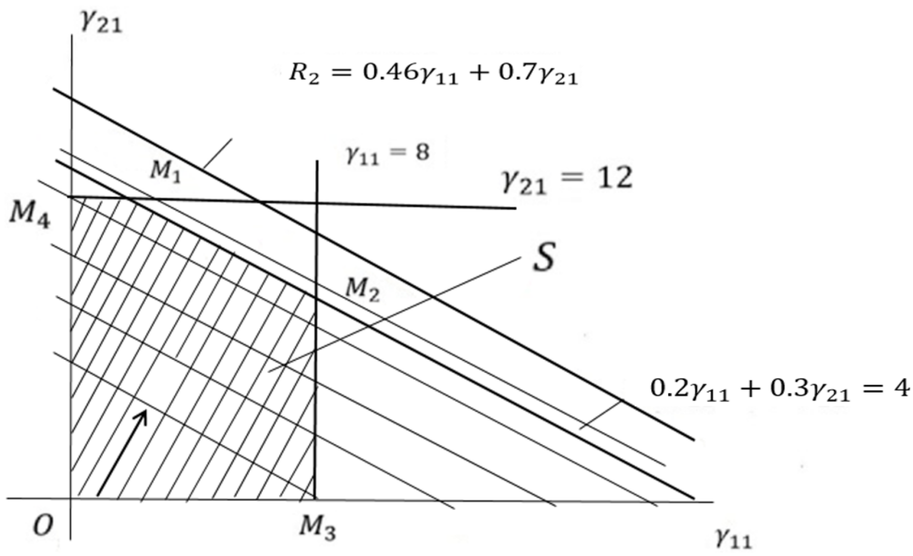

Figure 2. Graphical method for searching for the optimal option in allocating empty cars according to the criterion of maximum static load.

y_{11} and y_{12}. The desired solution should be sought in the area S, bounded by polygon $M_1M_2M_3OM_4$. Apparently, the coordinates of points M_1 and M_2 (that are farthest from the origin of coordinates) will correspond to the optimal solution.

Solving equations $0.2y_{11} + 0.3y_{21} = 4$ and $y_{11} = 8$, together, we determine the coordinates of point $M_2 : y_{11} = 8, y_{21} = 8$. As a result of the joint solution of the equations $0.2y_{11} + 0.3y_{31} = 4$ and $y_{21} = 12$ we obtain the coordinates of point $M_1 : y_{21} = 12, y_{11} = 2$. To establish the optimal solution, we substitute the coordinates of the points M_1 and M_2 into expression (14) and as result we have $R_2(M_2) = 9.28, R_2(M_1) = 9.32$. Thus, the coordinates of point $M_1 : y^*_{21} = 12$ and $y^*_{11} = 2$ are the optimal solution. Using equitation (11) and (12), we calculate the remaining components of the optimal solution: $y^*_{12} = 6,\ y^*_{22} = 0,\ y^*_{31} = 2,\ y^*_{32} = 4$. For this solution, the value of the functional will be equal to $R = 1100 tons$ and the balance of unshipped freight will be $(540 + 620) - 1100 = 60$ (tons).

The proposed method for finding the optimal option in distributing empty cars according to the criterion of maximum static load is a distinctive option for solving the problem of distributing empty cars in railway transport in comparison with currently existing methods. For example, in [23], the optimization model for the problem of distributing empty freight cars at a railway site is characterized as a combination of the flow task with minimum cost with the task of selecting a vehicle route. In paper [24], the problem of distribution of empty cars in the Chinese railway system takes into consideration the requirements of timeliness of demand for empty cars. Based on this a spatiotemporal network is created to describe the process of distributing the empty cars, where, in terms of the types of cars and network capacity, an integer programming model is proposed, allowing to minimize the total costs in the distribution process. In line with the obtained results, the authors of [24] concluded that many train routes must be scheduled to guarantee the timely delivery of empty cars to the station. Thus, the proposed method for finding the optimal option for distributing empty cars according to the criterion of the maximum static load is a relevant tool for supporting operational decision-making on the rational distribution of empty cars, which is recommended to be used to optimize the transportation process in railway transport in general, and when organizing the transportation of dangerous goods particularly.

5. Conclusions

Thus, due to the increasing attention of the world community to the global problems of humanity and the strategy for creating equitable and dynamic economic growth, sustainable transport is becoming one of the most important areas of further development. Sustainable transport has a positive impact on the environmental, social and economic stability of society.

Based on the research, we can conclude that the realization of the proposed strategic approach in optimizing the transportation of dangerous goods, which is determined by the implementation of an operational control system for the transportation and temporary storage of dangerous goods and the realization of the optimum allocation of empty cars among freight points, will ensure:

- improving transportation technology, increasing the level of their implementation, and ensuring the prevention of emergencies with dangerous goods during transportation on the Ukrainian railway network;
- realization of the "National Transport Strategy of Ukraine for the period of up to 2030" by solving the problem of increasing the level of safety in transport by introducing a system of operational control during the transportation and temporary storage of dangerous goods in order to ensure a high level of safety during the transportation of dangerous goods;
- compliance with the principles;
- realizing the concept of sustainable development, since the goal of the research corresponds to the three goals of sustainable development in concordance with the official document of the UN General Assembly "Transforming Our World: The 2030 Agenda for Sustainable Development" (goals 9, 11-13 [7]).

It is also worth noting that the need for the modern development of railway transport and technological systems in a single transport space, the development and implementation of effective transportation process management systems require the creation of new and adjustment of existing methods for the distribution of freight and car flows [23, 24]. Therefore, with a view to optimizing the transportation process in railway transport in general, and when organizing the transportation of dangerous goods in particular, the use of the proposed method for finding the optimal option for distributing empty cars according to the criterion of maximum static load is a relevant tool for supporting operational decision-making, which will provide a solution to the important operational task of rational distribution of empty cars among cargo points.

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