CONTROL PROCESSES

UDC 656.2
DOI: 10.15587/1729-4061.2022.265668

BUILDING A MODEL FOR PLANNING RAPID DELIVERY OF CONTAINERS BY RAIL UNDER THE CONDITIONS OF INTERMODAL TRANSPORTATION BASED ON ROBUST OPTIMIZATION

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This paper considers the possibility of devising a technology of fast railroad communication for the transportation of containers between the port and customer enterprises in the course of intermodal transportation. The purpose of technology development is to reduce the share of the use of trucks on intermodal routes and thus solve a number of related environmental, transport, municipal, and economic problems. The devised technology is based on the principles of bringing the railroad as close as possible to the end points of the route, minimizing the number of intermediate modes of transport, and enabling the maximum speed of movement of containers by rail. For this purpose, the use of MetroCargo™ freight terminals and CargoSprinter modular trains is proposed. In the course of the study, the task to reliably plan the operation of the fleet of such trains for the delivery of containers between the port and enterprises under the conditions of "noisy" initial data was set and solved. To this end, the problem was formalized in the form of a model of mixed programming, based on the principles of robust optimization. To optimize the model taking into consideration the principles of robustness, a procedure was proposed that uses a two-circuit genetic algorithm. As a result of the simulation, it was found that the resulting plan was only 6.5 % inferior to the objective criterion of the plan, which was compiled without taking into consideration robustness. It was proved that the devised model makes it possible to build an operational plan for the delivery of containers by rail, which is close to optimal. At the same time, the plan is implemented even in the case of the most unfavorable set of circumstances in the form of delays, shifts in the time windows of the cargo fronts, etc., that is, under the actual conditions of the transport process

***Keywords:** intermodal container transportation, modular container trains, robust optimization, double-circuit genetic algorithm*

Received date 15.07.2022
Accepted date 26.09.2022
Published date 30.10.2022

***How to Cite**: Parkhomenko, L., Butko, T., Prokhorov, V., Kalashnikova, T., Golovko, T. (2022). Building a model for planning rapid delivery of containers by rail under the conditions of intermodal transportation based on robust optimization. Eastern-European Journal of Enterprise Technologies, 5 (3 (119)), 6–16. doi: https://doi.org/10.15587/1729-4061.2022.265668*

1. Introduction

The growth in container flows traveling by water, land, and air transport has not stopped since April 1956 when American entrepreneur Malcom McLean first sent a batch of containers from Newark to Houston on a converted tanker, thereby revolutionizing world trade. The revolutionary use of containers in the field of international transportation was that they provided an opportunity to reduce the cost of money and time in carrying out cargo operations by several dozen times, and, by reducing transport costs, significantly reduce the cost of imported goods. However, the mass movement of goods in international traffic is still a complex and responsible process, which, in addition to the sea transport, involves land transport, including rail transportation. The success and efficiency of this process depends on the reliability of all links of the intermodal transport system. The most important link that should enable the interaction between land and sea modes of transport, including through timely and high-quality planning and execution of cargo operations, are port container terminals.

Container terminals of seaports have been in a state of constant modernization and re-equipment since 1990s. However, along with the increase in the volume of modern terminal equipment, the container flows that they have to maintain are growing rapidly. From 1990 to 2021, the total annual container flow increased more than 10 times and now exceeds 800 million TEU. Thus, even those with the latest equipment, modern port terminals face a lot of problems, which in particular are associated with the use of a large number of units of automotive rolling stock, including as auxiliary modes of transportation. Consequently, the further involvement of road carriers on intermodal routes faces a number of insurmountable restrictions.

Under such conditions, a rational way to develop intermodal transportation is to devise and introduce new technologies that will enable the restraint of the use of automotive equipment and resolve a whole bunch of related problems – from transport and technical to municipal and environmental. However, the key to solving these tasks is the development of fundamentally new transport technologies that will enable cost-effective and competitive rail delivery of containers. Therefore, research into the construction of the foundations for such technologies is relevant.

2. Literature review and problem statement

Intermodal container transportation is characterized by the involvement of a large number of enterprises, equipment, rolling stock, infrastructure facilities that belong to various sectors of the economy and whose technological processes cover various areas of human activity. Thus, the system of intermodal transportation is a source of complex technical, economic, environmental, and social problems, which in turn attract researchers who work at the junction of a wide variety of scientific fields. However, of particular interest to scientists are the problems of the functioning of railroad transport as part of the intermodal transportation system and the problems of interaction between field and sea transport.

In [1], with the help of methods of mixed-integer programming, the authors simultaneously consider submitting a plan for transshipment of containers between ships, yards, and trains, and the schedule of train departure. However, not enough attention is paid to the process of forming trains. In [2], the problem of profitability of railroad operators is solved when interacting with sea transport during intermodal transportation under conditions of changing conditions and unstable pricing. The model uses the principles of robust optimization but the complex problem of interaction between sea and rail carriers is proposed to be solved only through the redistribution of income, that is, purely in the economic plane. In [3], the same authors propose a solution to a similar problem of interaction between marine and railroad operators using a dynamic programming model but only economic rather than technical measures are also proposed. In [4], the problem of organizing intermodal transportation is solved on the basis of the model of finding the optimal balance of energy costs between rail and sea transport, but this approach can only affect the choice of route and does not solve the technical problems of interaction when changing modes of transport in ports. In [5], it is proposed to solve the problem of interaction of modes of transport in an intermodal terminal based on the optimization of its parameters using multi-agent models as part of the AnyLogic software, but this approach can be useful only at the design stage and, moreover, it still does not solve even the problems of ecology and the territories adjacent to the port. Paper [6] examines the challenges facing researchers of the problems of interaction between the port terminal and rail transport, highlights in detail a large number of important problems of both strategic and operational planning but does not provide any models for their solution. Study [7] considers ways to optimize the interaction between the port and the railroad in the first turn by agreeing on the schedule of departure of trains and the plan for transshipment of containers entering the port in order to increase the share of direct transshipment of containers from ships to trains, but the practice of recent years has revealed the limitations of such approaches, especially if they are used without taking into consideration the probabilistic component of transport processes. Fundamentally new technical or technological solutions for solving the problem of overloading port terminals were also not presented in the work, but only an increase in the capacity of cranes and shunting facilities was proposed. In [8], the problem of forming container trains for the delivery of containers from the port of Genoa to consignees in the depths and in the north of Italy is considered. The proposed model makes it possible not only to rationally form blocks from fitting platforms but also considers a more detailed level – the formation of blocks of containers that are loaded onto the platforms. However, it should be stated that this model can only significantly reduce the delivery time and is not aimed at providing fast rail communication for the transportation of containers. In [9], the possibility of organizing an effective long-distance railroad connection between Asian countries and the ports of Northern Europe (Scandinavia, the Baltic countries) and the Mediterranean (Greece) for the transportation of containers during intermodal transportation is considered. The ReOrient project provides a solution to the main problems of compatibility of railroad systems in Europe, such as the presence of a large number of different alarm systems, centralization and blocking (SCB), various standards of traction current, communication, etc. These problems significantly hinder the development of container rail transportation throughout Europe.

Thus, the problem of interaction between rail and sea modes of transport is complex. It is closely connected with the problems of the capacity of port terminals, the negative impact on the urban infrastructure adjacent to the terminals, and environmental problems. Recently, however, another important problem has been added to this whole bunch of problems: in general, the possibility of the existence of rail container transportation over short and medium distances. After all, for various reasons, rail transport loses competition to the road in this market segment due to many factors and not only technical, such as the speed of delivery, etc. but also economic, including those that are not directly related to the transportation process. Therefore, this problem is complex and thus will require comprehensive approaches to address it. However, modern developments, both in the fields of port equipment and railroad transport, and in the field of information technology, give a certain optimism along the way.

3. The aim and objectives of the study

The aim of this work is to devise technology for the use of railroad transport for the rapid transportation of containers on the land section of the route during intermodal transportation, which will be able to improve the interaction between the railroad and the port and will allow railroad enterprises to successfully compete with road transport in the intermodal transportation market.

To accomplish the aim, the following tasks have been set:

– to develop approaches that will enable fast and cheap delivery of containers by rail, if possible, according to the door-to-door scheme from the port to the consignee;

– to build a flexible model of operational planning of the railroad enterprise for the delivery of containers, which will minimize the cost of container hours during the formation of trains and make it attractive for customers to use railroad transport at short and medium distances.

4. The study materials and methods

The object of this study is the process of land delivery of containers during intermodal transportation. The subject of the study is the technology of fast delivery of containers using railroad transport. The main hypothesis of the study is as follows: at the present stage of development of technical means of railroad transport, as well as achievements in the fields of computation, information processing and management, there is an opportunity to devise a technology for transporting containers by rail as part of the intermodal transportation process. This technology will be able to significantly replace road transport and thus solve a number of problems associated with the transfer of container flows from sea transport to land transport and their advancement along the land section of the route.

The tasks of operational planning of freight railroad transportation are usually operated by a large number of actors and therefore there is always a lack of completeness of the necessary information and the randomness of events. Thus, the statement of the problem acquires a certain uncertainty. Uncertainty in the initial data of the problem makes it difficult to obtain a high-quality management solution. Optimization problems dealing with uncertainty in data or variables, the nature and form of representation of which may be different, are usually attributed to the class of stochastic optimization problems. However, this class is the least studied of the entire set of optimization problems, which predetermines the fact that the problems of this class are of considerable interest to theoretical researchers. At the same time, it is also of even greater practical interest due to the fact that uncertainty in one form or another is inherent in any processes of the real world. Therefore, the development of the theory and obtaining reliable methods for solving problems of this class is the key to improving control systems in many areas of production. However, the tasks that can be attributed to this class are very diverse. Some authors believe that the nature of uncertainty is of fundamental importance. As noted above, uncertainty may be due to a lack of information or, for example, the probabilistic nature of a particular process or phenomenon. Therefore, the classical approach to the formulation and solution of stochastic optimization problems involves the maximum use of available statistical information on the processes under study, such as the parameters of statistical laws of distribution, etc., and its representation and processing using the mathematical apparatus of probability theory. However, this approach is very complex and costly because it requires the collection and processing of a large number of statistical data and still does not guarantee the possibility of taking into consideration all the necessary factors. Another important modern paradigm in the field of stochastic optimization is to obtain reliable (robust) solutions. As it has been proven [10], most real optimization problems are very sensitive to deviations of the initial data. For example, a deviation in the vector of calculated data from real data by only 1–2 % can lead to a deviation of the calculated optimum from the real one by several tens of percent, which completely neutralizes the practical value of the solution. In order to overcome this problem, an area was developed, which is termed “robust optimization”. Robust optimization can be seen as an addition to the stochastic programming approach to solve optimization problems with incompletely defined data, which in its terminology is called “noisy”. Robust optimization involves obtaining such a solution to a stochastic problem that would not lose its practical value even under conditions when all stochastic variables will take values that correspond to the most unfavorable scenario of development of events. From the point of view of managing the operation of modular trains along the polygon during the delivery of containers, it may seem that the worst-case scenario is when all the values of the duration of the movement of trains between the stations will take their maximum values. However, given that this problem is also a combinatorial optimization problem, this statement may turn out to be false. For example, if one train overcomes a section in the minimum time and arrives at a certain freight front faster than another train, freight operations with it will also begin earlier. In this case, the other train will be forced to wait, which in turn may cause it to be late until the closure of the freight front on another access track according to its work plan. Thus, looking for the best solution from the worst scenarios, robust optimization implements the principle of minimax. Thus, therefore, the magnitude of probability in robust optimization practically does not matter and therefore such variables as, for example, the magnitude of the duration of the movement of trains between stations or the time windows of availability of certain transport resources, such as, for example, freight fronts, it is advisable to represent in the form of interval numbers. In addition, in this work, we used methods of mathematical modeling; in the process of developing the procedure for optimizing the model, the modern mathematical apparatus of genetic algorithms (GA) was used.

5. Results of studying the possibility of devising a technology for fast delivery of containers by rail in the implementation of intermodal transportation

5. 1. Outlining approaches to simplifying the transfer of container flows and forming the basics of fast rail technology

The collapse of logistics mechanisms around the world, which happened in a matter of months, will be the trigger for many processes in the field of transport and primarily in the field of intermodal transportation. These processes will inevitably lead to the transformation of existing transport technologies towards unprecedented flexibility, variability, and intellectualization. Watching the events of 2021 leaves no doubt that not only will the world never be the same again but that intermodal transportation technologies will never be the same again. As experience has shown during the pandemic, the main problem of intermodal transportation was the collapse caused by the congestion of container terminals. The section from the port to the consignee, despite the constant improvement of technology, remains the most problematic part of the journey. On the one hand, it is quite clear that it is impossible to solve it at the expense of road carriers, given the further increase in the volume of intermodal transportation. The further development of road container transportation is hampered by an ever-increasing number of restrictions, such as, for example, environmental restrictions, restrictions on the maximum carrying capacity of trucks, etc. In addition, the cost of renting or owning heavy trucks that are capable of carrying 40 or 53-foot containers is high. In addition, for the transportation of each such container, you need not only a separate expensive heavy truck but also a separate driver. Also very acute is the problem of lack of capacity of roads, especially in the port area, which is also often located on the territory of large cities or megacities. On the other hand, a railroad is traditionally used to deliver containers inland. However, there are also many problems. One of the main problems from the point of view of the intermodal operator is that the use of container trains does not exclude the need to involve truckers in the transport chain. The need to use road transport is due to the fact that many consignees are remote from the main railroad lines. Consequently, on the "last mile" of the intermodal route, trucks are almost always used. In addition, such a scheme provides for additional operations of transshipment and storage.

Thus, the use of motor trucks in the implementation of intermodal transportation has many drawbacks and creates a number of additional problems. Instead, the use of rail transport is more promising both from the point of view of intermodal operators and from the point of view of seaports because the greater the capacity of the port-railroad link, the more cargo the port will be able to attract and process and, accordingly, increase its earnings. For customers, rail transport is potentially more attractive compared to road consideration of factors such as tariffs, greater level of safety, independence from weather conditions, etc. However, an important economic factor is the speed of delivery and rail transport at short and medium distances is significantly inferior to road transport. However, an increase in the delivery time even for a day, especially for an enterprise that receives or sends large batches of containers, can lead to significant losses in view of the fact that in this way there is a slowdown in the movement of its working capital. And the importance of this factor is only growing because expensive goods are usually transported in containers, and due to the high inflation of recent times, their cost is constantly growing. The use of rail transport at short and medium distances is currently impractical because it is inferior to automobile by the speed of delivery. This is because currently rail transport is used in intermodal transportation in the form of route container trains, or fitting platforms with containers are included in, for example, precinct trains. Under such conditions, additional time is spent on the accumulation of trains, and in the case of precinct trains, time is also spent on reforming trains. In addition, the accumulation time of container trains is also increased due to the delays in containers on the berths as a result of the cluttering of container platforms near the berths.

Thus, the intermodal transportation system consists of a number of subsystems, the capacities of which must be well harmonized to prevent bottlenecks in the transport chain. In order to meet the demand for container transportation, it is absolutely necessary to invest not only in the introduction of new technical means and restructuring but also in operational management technologies [11]. Therefore, in order to minimize or completely exclude road transport from the intermodal transportation scheme, it is necessary to bring the railroad tracks as close as possible to the final points of departure or destination of goods as practically possible. And such an opportunity actually already exists because many large and medium-sized enterprises both in Europe and in the United States have their own so-called "access tracks", which connect them with the main railroad lines. Therefore, it is necessary to devise a transport technology that would meet the technical requirements for the use of access roads for the delivery of containers from the port "to the door" of consignees and would at the same time be economically viable. At the same time, the integration of the railroad and port is also one of the most important strategic elements of its development both in terms of economy and in terms of marketing. There are ports where tight integration of railroad and port infrastructure using modern port equipment has already been implemented, which eliminates the need to use other types of transport when overloading containers from ships to trains. Such integration not only simplifies the organization of the port's work but also significantly increases the chances of the railroad to intercept orders for the transportation of valuable goods from road carriers, which is very important under modern conditions of fierce competition in the transport market. Such integration also makes it possible to increase the capacity of the land section of the route, which is directly adjacent to the port. This is achieved by eliminating the need to cross the space of the city with congested roads with wheeled trucks such as, for example, auto platforms, straddle carriers, or reach stackers, which is used to transport containers entering the berth to the terminal. However, the rapid growth in container traffic volumes has called such a model into question. The main reason is that a large number of containers needed terminals with a large area, although seaports were still among the largest consumers of land in megacities. Another reason is that not only the number of containers has increased significantly but also counterparties, such as cargo owners, consignees, freight forwarders, intermodal operators, etc.

The obvious fact is that the primary requirements that need to be met are the requirements for rolling stock. First, the useful length of the tracks of freight areas can be very limited and able to accept a composition that contains only a few cars. Secondly, these tracks are overwhelmingly non-electrified. In addition, the rolling stock must be capable of changing the direction of movement and move in both directions along the main railroad lines at a sufficiently high speed.

Rolling stock that meets these requirements already exists, these are modular five-car freight trains, which were first built in Germany in 1990s. These trains belong to the CargoSprinter class – after the name of the first such train, which was developed and built in 1996 by Windhoff GmbH in cooperation with the state-owned rail freight operator DB Cargo and the airport operator Fraport. Obviously, Fraport was interested in this train precisely as a rolling stock for transporting small batches of air containers. The word "sprinter" in the name indicates that the purpose of this train was to quickly transport goods over short distances. The relatively high speed of this train is primarily due to the small mass. CargoSprinter trains do not have a locomotive, and each car is a motor platform, in the upper part of which there is a platform for loading containers, and in the lower part there is a diesel generator modules and/or traction motors. Thus, CargoSprinter trains belong to motor-car rolling stock, which predetermines their high specific power, which is defined as the ratio of engine power to the mass of rolling stock. Additional weight reduction is also achieved through the use of Jacobs bogies to link motorless cars to each other. Thus, even if you connect several such trains into one, it will still be able to move much faster than a regular container train. CargoSprinter specifications make it possible up to 7 trains to be coupled together.

At one time, CargoSprinter's promising project actually failed. However, that failure did not occur because of its technical imperfection or technological lack of demand but for completely different reasons associated with the difficulties of producing individual spare parts. Now, more than 20 years have passed, and production technologies have advanced significantly. In addition, completely different technologies have appeared that can make these modular trains even more advanced and economical. Under modern conditions, it would be advisable to make them electric, powered by the mains while driving on the main line and from batteries while driving on access roads or tracks of cargo areas for cargo operations. In any case, the cost of repairing and maintaining these trains if they are involved in intermodal transportation will amount to an inconspicuous share of costs, especially against the background of an almost tenfold increase in tariffs for container transportation, which took place only during 2020–2021.

Consequently, CargoSprinter trains will bring intermodal carriers closer to customers without the use of road transport. However, as noted above, to create a synergistic effect, it is important to integrate the railroad with the port as much as possible. The best option for integration is one that will minimize the need for intermediate storage of containers and the use of additional types of intermodal transport such as Richstakers or rail gantry cranes, etc. Technically, this task seems very difficult, and it is. However, there is a ready-made solution on the market – the MetroCargo™ system. MetroCargo™ systems are modular freight railroad terminals equipped with complex precision electro-mechanical computerized systems that are designed to load and unload container trains under an automatic mode [12, 13]. MetroCargo™ systems make it possible to drastically (by more than 10 times) reduce the time spent on cargo operations.

5. 2. Construction of a model for compiling an operational plan for the delivery of containers using modular trains

Thus, it is proposed to organize the process of transporting containers using the CargoSprinter fleet of modular trains. To this end, it is necessary to build a model of operational planning of their work. The model should provide a departure from the traditional practice of using rail transport in the implementation of intermodal transportation, which is limited only to direct route container trains or the inclusion of fitting platforms with containers in the composition of full-fledged freight trains, the accumulation of which during the construction and reconstruction takes a lot of time. The model should carry out a rational distribution of applications for the transportation of containers between modular trains, as well as plan in detail the route and order of operations with each of them.

In addition, the model should provide the possibility of obtaining a reliable operational plan under the real conditions of the transport process, during which there are systematic deviations of the times of occurrence of events and the duration of transport operations from the planned or regulatory values, as well as a certain level of uncertainty associated with the accuracy of the information provided by customers.

The primary component of the source data should be a set of containers. Each element of this set is a tuple containing attributes such as the moment in which the container is available for loading (after unloading from the container ship at the port or after the container is delivered by the consignor to the cargo area of the access track and the start of its operation); its mass; length in feet; number of the top of the railroad network graph corresponding to the consignee's access track; the moment of time of completion of the cargo area of the access track or the moment of the end of the process of loading the container ship; time of expiration of the delivery time. Access tracks are railroads intended for transport services of one or more enterprises that are connected to the general network of railroads by continuous rail and belong to a railroad or enterprise [14]. In addition, the initial data are the parameters of the railroad network: the topology of track connections, which is given by the graph structure and the vertices of which represent railroad stations and freight areas of access tracks, and arcs represent railroad races between separate points. In addition, for each arc, "windows" should be indicated, which are not occupied according to the schedule and during which a modular container train can be sent. These windows should be calculated taking into consideration the type of signaling between the stations ("auto-locking", ("semi-automatic locking", etc.). The initial data for solving this problem should also contain a set of cargo points. The characteristic of each item should contain information about the time "windows" of its operation, the average loading and unloading time of one container. Thus, a port can also be represented as a loading point.

It should also be noted that in order to enable the possibility of using the model under real conditions, it must take into consideration the influence of the flows of random events, which is constantly experiencing any transport process. This is especially true of the process of intermodal transportation, which involves several types of transport, including those whose normal functioning directly depends on weather conditions, which in turn can be difficult to predict even for a short time period. As you know, any elements of the transport system are exposed to random failure flows: rolling stock, elements of transport infrastructure, signaling, communication and information support devices. A significant delay in the arrival of the vessel, the closure of the railroad track, the breakdown of the modular train – all these events can cause that the already adopted plan for the delivery of containers will be impossible to fulfill. Such rare events are not only very difficult to predict but it is also impractical to take into consideration when forming a plan. To level their impact on the transport process, it is more expedient to adjust the plan operationally, that is, to make repeated calculations taking into consideration new information about the current state of the system. Consequently, it is necessary to provide for the possibility of making calculations not only from a certain initial position but also from any current position. However, there is still some kind of uncertainty in the process of transporting containers using modular trains that must be taken into consideration. It is associated with the peculiarities of the technological process on the railroad. One of the features of CargoSprinter trains is their high speed. Speed is their significant advantage, because in this way they can be sent from the station without actually violating the existing schedule of trains. However, the time to move from one station to another is not a constant value and may vary within certain limits. Even with the constant speed of the CargoSprinter train, the delay in its departure from the station may occur due to the fact that at this time another train departs, besides, it also takes some time to release the first block of the section by this train. In addition, if not a fast or high-speed passenger train moves ahead of the CargoSprinter train but a heavy freight train, then it will also limit the speed of movement of the modular train. At single-track sections, if there is already an oncoming train between the stations, it is necessary to wait for its arrival at the station to be able to leave the train for the run, which can also take considerable time. Another factor that is a common reason for the increase in train running time is the speed limits associated with repairs between the stations.

However, the most negative impact on the degree of uncertainty of the planning task is made by cargo fronts and access roads of enterprises because they almost never have a clear schedule of operation; besides, they may not be available for some time also due to the service of other customers because several enterprises can jointly use one access track in order to minimize costs. Thus, the objective function of the robust optimization model, which represents the operating costs, can be written as follows:

$$F(c,x,n,\Psi,\tau)= \\ =\max_{(\Psi,\tau)}\left\{\begin{array}{l} e_{tk}\sum_{i=1}^{n}\left(\begin{array}{l} d\left(p_0^i,x_1^i(c_i)\right)+ \\ +\sum_{j=2}^{\#x_i} d\left(x_{j-1}^i(c_i),x_j^i(c_i)\right)\end{array}\right)+ \\ +e_{th}\sum_{i=1}^{n}\psi\left(i,\#x_i\right)+ \\ +\sum_{i=1}^{n}\sum_{k=2}^{\#x_i} e_{i,j}^{pen}\theta\left(\psi(i,j)-\tau''_{i,j}\right)+ \\ +e_{cpk}\sum_{i=1}^{n}\left(\begin{array}{l} d\left(p_0^i,x_1^i(c_i)\right)\left(q_{\max}^i-q_{0,1}^i\right)+ \\ +\sum_{j=2}^{\#x_i} \left(\begin{array}{l} d\left(\begin{array}{l} x_{j-1}^i(c_i), \\ x_j^i(c_i)\end{array}\right)\times \\ \times\left(q_{\max}^i-q_{j-1,j}^i\right)\end{array}\right)\end{array}\right)\end{array}\right\}\to\min_{(c,x,n)}, \quad (1)$$

where c is a variable subset of the total set of containers considered for transportation within the planned period;

c_i – a variable subset of set c, which contains containers that are intended for transportation by an i-th modular train;

x – a set containing the sequences of transportation by all modular trains during the planned period;

n – the number of working fleet of modular trains;

$x_i(c_i)$ – a subset of the set x, containing the sequence of transportation by the i-th modular train and which depends on the subset c_i;

$\#x_i$ – power of a subset x_i, equal to the number of points (cargo fronts) on the route of the i-th train;

e_{tk} – the cost of a train/kilometer;

e_{th} – the cost of a train hour;

e_{cpk} – the cost of an empty container-place-kilometer run;

$e_{i,j}^{pen}$ – the penalty for late spotting of the train by one hour at the j-th freight front on the route of the i-th train;

$\theta(\ldots)$ – Heaviside function that returns 1 if its argument is greater than 0, otherwise returns 0;

$\tau'_{i,j}$ – the moment of time of the start of the j-th freight front on the route of the i-th train, which is given by the interval number;

$\tau''_{i,j}$ – the moment of time of completion of the j-th freight front on the route of the i-th train, which is given by the interval number;

τ – a set of tuples, each i-th element of which contains 2 interval numbers $\left\{\tau'_j,\tau''_j\right\}$, which determine the time frame for the functioning of the j-th cargo front;

$d\left(x_{j-1}^i(c_i),x_j^i(c_i)\right)$ – the distance in the railroad connection between j–1th and j-th points of the route of the i-th train;

$d\left(p_0^i,x_1^i(c_i)\right)$ – the distance in the railroad connection between the starting point of the route (0) of the i-th train in which it is at the time of the beginning of the planning period and the first points of the route (1), which is set by the variable vector x;

Ψ – a set containing the values of the moments of time of the end of freight operations with trains on the freight front, each element of the set is the result of a calculation using the function $\psi(i,j)$;

$\psi(i,j)$ is a function that returns the value of the moment of time of the end of freight operations with the i-th train on the j-th freight front of its route and the beginning of the movement to the next freight front. This function can be set by using the following recursive formula:

$$\psi(i,j)=\begin{cases}\max\left(\begin{array}{l}\tau^0+t_{i,0,1}^{mov}, \\ \tau'_{i,1},\tau_{i,1}^{pl}\end{array}\right)+t_{i,1}^{co} & j=1. \\ \max\left(\begin{array}{l}\psi(i,j-1)+t_{j-1,j}^{mov}, \\ \tau'_{i,j},\tau_{i,j}^{pl}\end{array}\right)+t_{i,j}^{co} & j>1,\end{cases} \quad (2)$$

where τ^0 is the time of the beginning of the planned period;

$t_{i,j-1,j}^{mov}$ – variable time of movement of the i-th train between j–1th and j-th points of the route, which does not take into consideration the waiting time of freight operations;

$\tau_{i,j}^{pl}$ – the moment in time of placing containers by the enterprise on the site of the freight front of the j-th access track (from that moment they are ready for loading on the i-th train);

$t_{i,j}^{co}$ – duration of cargo operations on the j-th freight front with the i-th train;

As part of this function, the function max is used because the moment of commencement of freight operations with the train is defined as the maximum value of three values: the moment of arrival of the train to the freight front, the moment of the start of work of the cargo front, and the moment of availability of containers for loading (the moment of placing containers by the shipper to the freight front site). If on this freight front with this train only container unloading operations are performed, then the value of the quantity $\tau_{i,j}^{pl}$ is taken as 0.

The first term is the costs associated with the movement of trains. The second term represents the costs associated with the time spent on the direct implementation of transportation, as well as the expectation and execution of cargo operations. The third term is the costs arising in the form of fines in case of late delivery of containers. For some points at which containers are unloaded, they may be irrelevant but for some they may be significant. The most illustrative example is when the late delivery of containers to the port for loading on a ship can cause a delay in the vessel with the payment of the corresponding fine (demurrage). Or, even if the vessel was not detained and its owners or operators had the right, according to the contract, to send it without waiting for a container consignment for loading, still shipbuilding companies charge a fine from intermodal operators in case of reservation of transportation capacities without presenting goods for transportation. This fine, which for example, at MSC (Mediterranean Shipping Company) is called "no show bookings surcharge", is at least USD 300 per 1 TEU. The fourth term represents the additional costs associated with the mileage of empty container spaces in the train. This term is actually a penalty function that is used to increase the efficiency of the use of rolling stock by minimizing the degree of underloading of modular trains and the magnitude of their mileage in this state.

Optimization of this function must be carried out taking into consideration the technological limitations inherent in the process of transporting containers.

The first constraint narrows the area of permissible solutions in such a way that when performing freight work at any freight point of any train, it is possible to load more containers onto it than its maximum container capacity:

$$\sum_{k=1}^{m}\left(\# c_{i,k}^{load} - \# c_{i,k}^{unload}\right) \le q_{\max}^{i}, \quad \forall m \in x_i, \quad i = 1..n. \tag{3}$$

The second constraint is necessary to ensure that working fleet of modular trains can perform the entire set of operations without violating the time limits of the planned period:

$$\max \psi\left(i, \# x_i\right) \le \tau^{ph}, \quad \forall i, i = 1..n, \tag{4}$$

where τ^{ph} is the planning time horizon.

The third constraint is necessary to ensure that each modular train is able to perform freight operations at each point of its route until its closure:

$$\max \psi\left(i, j\right) \le \tau''_{i,j}, \forall i, \forall j, i = 1..n, j = 1..x_i. \tag{5}$$

The use of the max function in constraints, which include variables that are affected by uncertainty, is due to the need to ensure the robustness of restrictions.

The next step is the process of optimizing the model. It should be noted that over the past two decades, certain achievements have been made in the direction of solving the problems of robust optimization. For example, approaches were formulated in works [15, 16] that make it possible, through certain transformations of the objective function and limitations, to represent the problem of robust optimization in the form of a convex programming problem. This problem is proposed to be solved using a specially developed method of ellipsoids. However, these approaches can only be effective under certain conditions. In particular, they assume that the model has a smooth objective function. However, in the problem of constructing an operational plan for the operation of modular trains, this condition is not met because it belongs to the class of problems of combinatorial (that is, discrete) optimization. Thus, the effective solution to this applied problem, as well as any complex production problem in robust statement, requires the development of an individual optimization method. The specificity of this problem, as well as many applied problems in general, lies in the fact that they usually do not require finding the absolute optimum of the objective function but only approaching it with a certain accuracy. In such circumstances, attempts to develop analytical methods should be abandoned and other classes of methods, such as, for example, heuristic methods, should be preferred. One of the main directions of heuristic optimization methods are genetic algorithms (GA). Genetic algorithms as a candidate for use in solving this problem have a number of advantages. Firstly, they make it possible to automate the process of solving complex problems, even those that have a large dimensionality, due to the possibility of efficient use of computer computing power. Secondly, they have no restrictions on use only with smooth objective functions, and therefore can be used to solve combinatorial optimization problems.

The complexity of the task of planning work of modular trains in robust statement lies in the fact that in order to find a reliable plan, it is necessary to simultaneously minimize and maximize the objective function. For smooth objective functions, there is an ellipsoid method [17] but the possibility and success of its use depends on many factors, including not least the experience and skill of the researcher. In the case of a given planning problem, we are dealing with the problem of discrete optimization and therefore the application of this method is a priori impossible. To optimize the built model, a method based on the use of a modern mathematical apparatus of GA was proposed [18]. The idea of the method is to cascade the application of two GAs. The scheme of the algorithm of the proposed method is shown in Fig. 1. External GA is used to find the optimal values of the vector of control variables corresponding to the minimum cost and, accordingly, the minimum of the objective function, which is represented by the fintes function of GA; the internal GA is used to serve the values of the vector of interval variables, which mainly represent the duration of operations that simulate the most unfavorable scenario for a given instance of the vector of control variables.

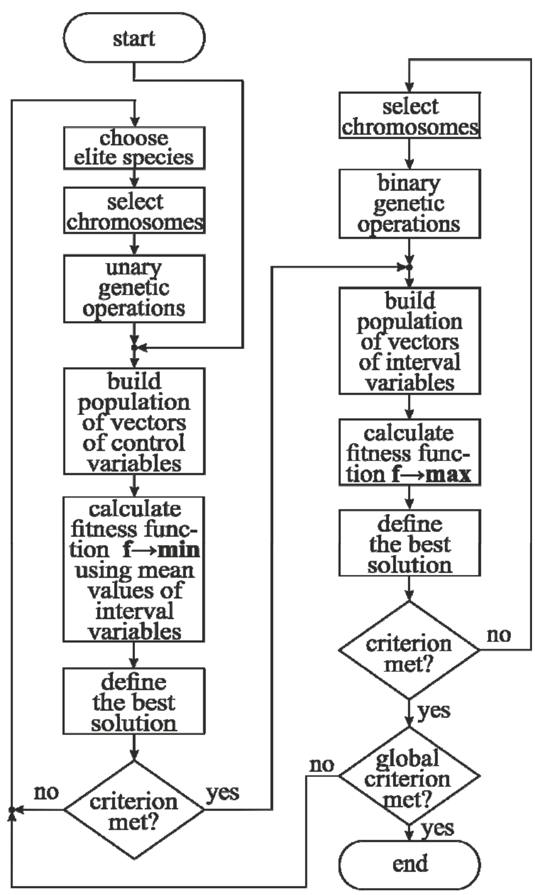

Fig. 1. Block diagram of a cascade genetic algorithm for solving the problem of constructing an operational plan for the operation of modular container trains in robust statement

Such an approach using two GA contours would theoretically require significant amounts of calculations, especially in the case of a large dimensionality of the problem. To reduce the computational load, it is advisable to simplify the calculations in the subpath of the algorithm as much as possible.

Based on the built mathematical model and the proposed algorithm, by using the MATLAB language, a procedure for its optimization in the form of software was developed. With the help of this software, modeling was carried out on an abstract polygon (Fig. 2), which consists of several dozen railroad stations, to which the access tracks of enterprises are adjacent. One railroad station (station No. 1) is adjacent directly to the port and equipped with special MetroCargo™ cargo equipment for port terminals. As a result of the optimization process, a diagram of the routes for fulfilling orders for the delivery of containers was constructed (Fig. 2).

In addition, as a result of the optimization process, an operational plan for the operation of modular container trains was compiled when fulfilling orders in the form of a schedule (Fig. 3).

The resulting plan is aimed at the implementation of 15 orders for the transport of containers both from the port to the cargo yards of customer enterprises and in the opposite direction. In addition, this number includes requests (2 applications) for the transportation of containers (including empty ones) between enterprises or between enterprises and land container terminals located within the polygon. In the resulting operational plan, 4 modular trains are involved because it was this number that was determined by the model as the minimum necessary to satisfy all applications. As can be seen from the schedule (Fig. 2), despite the fact that the configuration of the windows of the cargo fronts of enterprises is the most unfavorable and on several access tracks the duration of the operation of freight fronts was generally no more than 2÷3 hours, the total losses associated with non-production downtime of rolling stock were only 0.33 train hours (downtime of train No. 4 near station No. 1) and 0.66 container hours (the train was loaded with two containers). In addition, during the simulation, it was found that the received operational robust plan turned out to be only 6.5 % worse than the target model criterion (total operating costs) from the plan, which was obtained without taking into consideration uncertainty in the form of "noisy" initial data. However, in the event of the worst combination of source data values, the implementation of the usual plan would generally be impossible without prompt adjustment, and even with the use of adjustment, it turned out to be up to 40 % more expensive compared to the robust plan.

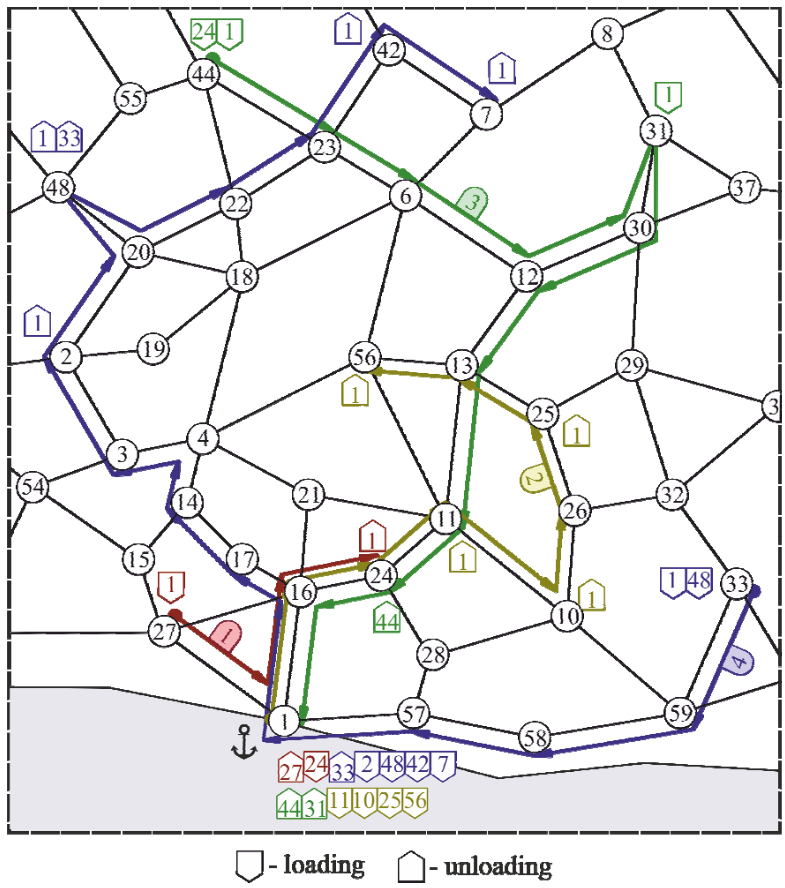

Fig. 2. An abstract railroad polygon and a scheme of routes for the execution of orders for the delivery of containers, built as a result of the optimization process

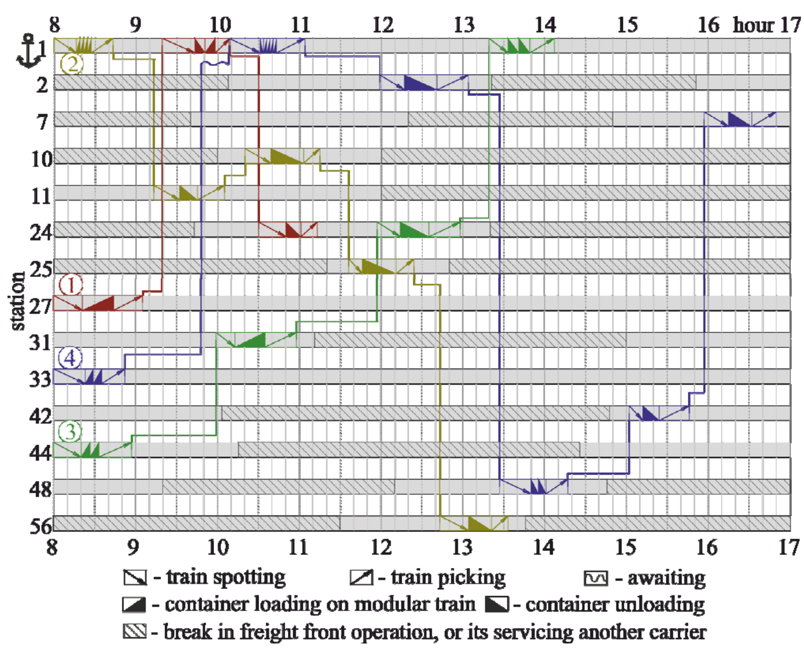

Fig. 3. Schedule of modular container trains when fulfilling orders for the delivery of containers, obtained as a result of the optimization process

6. Discussion of results of studying the possibility to devise technology for fast delivery of containers

Investigating the technological process of intermodal transportation in terms of the interaction of sea carriers with other modes of transport, and primarily road transport, revealed the existence of a number of diverse interrelated problems. It has been proven that solving or significantly improving the state of these problems requires reducing the use of road transport, which is used in the implementation of intermodal transportation, and especially that which interacts with intermodal port terminals. It was possible to develop approaches to solve this set of problems due to the fact that there are already on the market, albeit separately, such modern technical solutions as, for example, systems for direct transshipment of containers from a ship to train (MetroCargo™ epuipment) and modular container trains such as CargoSprinter. However, the heyday of their mass use is still ahead and depends entirely on the concepts and technologies of their application, which have yet to be developed. Our study is exactly considering the development of an information and technological solution, which represents a model of operational planning of the fleet of modular trains and which is a necessary superstructure over the above-mentioned proposed technical base. The task of constructing an operational container delivery plan was formalized as a robust optimization model, which contains a robust objective function (1) and robust constraints (3) to (5). The use of robustness made it possible to enable a high level of adequacy of the model to the real conditions of the transport process. To ensure maximum detail in the calculation of operating costs, which are the criterion of the objective function of the model, depending on the management decisions made, it was necessary to formalize complex space-time interdependences between transport operations. This was done by introducing the time interval calculation function into the model, which uses recursion (2). An important component of the successful application of the optimization model in practice is the existence of a procedure for its optimization. The calculation of robust optimization models, especially in discrete space, is a separate task of exceptional complexity because even for smooth continuous objective functions there is only one analytical method, moreover, the possibility of applying which in practice is extremely limited. However, the key to the success of solving this problem in the first place was that in the course of practical application of the model, finding a global optimum with analytical accuracy is desirable but not critically important. Secondly, it was possible, using a modern mathematical apparatus of soft computing, to develop and implement a procedure for optimizing the model in the form of software, which is based on the proposed two-circuit genetic algorithm (Fig. 1) and makes it possible to obtain an operational plan with sufficient accuracy in rational time. The resulting plan (Fig. 3), by determining the required number of rational distribution of applications between them and the sequences of their implementation based on the model, enables the execution of all sets of orders within the time limits of the planned period (from 8:00 to 17:00 hours) under the most unfavorable conditions. At the same time, the total loss of time due to non-production downtime of modular trains was only 20 minutes. In addition, the model's determining the sequence of operations occurs simultaneously with determining the optimal route for following modular trains in the railroad polygon (Fig. 2). To this end, the optimization procedure also uses graph algorithms, such as Dijkstra algorithm and others. Thus, it should be noted that the proposed model varies not only with economic factors as in [1–3] in order to self-regulate the intermodal transportation system but makes it possible to solve management problems in the technical plane. In addition, the developed model not only determines the optimal delivery routes, as in [4], or is able to simulate the process of delivery of containers only at the simulation level as in [5], but makes it possible to get ready-made complex management decisions at the level of tactical and operational planning. In addition, the proposed model uses the latest approaches and makes it possible to go beyond both traditional technologies of interaction between rail and sea transport, as well as traditional technologies for organizing container rail transportation, on which study [7] is based.

It should also be noted that the implementation of the proposed technology will be associated with certain difficulties. The negative trend associated with the transition of enterprises to road transport during the delivery of containers has led to the fact that a significant number of access roads are in an abandoned state and will require certain repairs to re-commission. In some countries, such as, for example, the United States, this trend is caused by the low speed of delivery of containers by rail compared to road transport and the favorable tariffs of road carriers, in other countries, such as Eastern European countries, it is caused by economic instability and falling industrial production due to the global economic crisis, pandemic, etc. It should also be noted that the adequacy of the received operational plan for the operation of modular trains can be ensured only if the real values of the quantities that are represented in the model by environment variables in the form of interval numbers do not go beyond these intervals during the implementation of this plan. Therefore, the boundaries of these intervals should be estimated with the greatest possible accuracy in the preparation of the initial data. Unreasonable expansion of the boundaries of these intervals may contribute to compliance with this requirement and getting the actual data within the intervals but the operational plan obtained in this way may be much less optimal, that is, there may be a significant deterioration in the value of the target criterion.

The disadvantages of the study include the fact that in the course of its conduct an assumption was made, which suggests that a modular train, having a high speed of movement, can be sent by dispatch order from the station in front of any freight train practically without causing its delay both at the station and between the stations. However, there are many countries in which the movement of freight and passenger trains occurs along the same railroad lines. The speed of passenger rolling stock is higher than the speed of modular container trains, so they cannot be sent in front of a passenger train without allocating a separate line of schedule. Thus, the influence of the schedule on the speed of advancement of modular trains between stations is taken into consideration only in general form, without taking into consideration the specific data of the schedule. In addition, the schedule also provides technological windows for track repair and other types of traffic restrictions that were also not taken into consideration in the study.

In the course of practical use of the developed model, one should take into consideration the limitations associated with computational complexity because a combinatorial problem, moreover, in a robust statement, may require significant computing resources. Thus, it is necessary to ensure that the capacities of the computer system correspond to the dimensionality of the problem.

In the light of the further development of the model, it should take into consideration in more detail the processes of movement of modular trains in railroad sections because in many countries there is a lack of capacity of railroad infrastructure, especially in port areas. By the way, it is allowed to perform the coupling of modular trains and following in a coupling state by the railroad tracks of the passing part of the route. This will make it possible to economically utilize the capacity of railroad lines and reduce the cost of transportation, especially in countries with high-cost threads of the train schedule. Therefore, the possibility of coupling modular trains should be taken into consideration in further research. Thus, the proposed approach in conjunction with the built model can be considered as the basis of a new technology for the use of railroad transport in the implementation of intermodal container transportation.

7. Conclusions

1. An approach has been formed to solve a set of problems related to the interaction of the sea with land modes of transport in the port and port terminals, as well as environmental and municipal problems associated with the dominance of road transport on land sections of the route in the process of intermodal transportation. As part of this approach, it was proposed to replace road carriers with rail carriers through the introduction of technical solutions, such as modern systems for direct container transshipment from vessel to MetroCargo™ train and the use of modular container trains of the CargoSprinter type as part of the intermodal transportation system. This will increase the efficiency of interaction between railroad and sea carriers under the conditions of intermodal transportation: minimize the need to store containers on sites near berths as well as in warehouses of port terminals, reduce the number of cargo operations, radically reduce the use of intermediate intermodal road transport such as, for example, rich stackers, portal carriers, mobile cranes, etc., both in the port and terminals and in near-port municipal areas. And increase the speed of delivery of containers at short and medium distances, enabling, if possible, delivery "to the door" without the use of road transport.

2. In order to enable high efficiency of the use of the proposed technical means and the functioning of the intermodal transportation system as a whole, a model of operational planning of work of the fleet of modular trains of the railroad operator was built, which delivers containers at short and medium distances during the intermodal transportation process.

This model, taking into consideration a certain level of uncertainty of the initial data regarding the time frame of transport operations, makes it possible to calculate a reliable operational plan that is provided under the most unfavorable conditions, in the sense of a combination of values of interval variable initial data, will make it possible to perform the task of delivering containers on time, in full and with minimal costs, which was proved during the simulation.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

References

1. Yan, B., Jin, J. G., Zhu, X., Lee, D.-H., Wang, L., Wang, H. (2020). Integrated planning of train schedule template and container transshipment operation in seaport railway terminals. Transportation Research Part E: Logistics and Transportation Review, 142, 102061. doi: https://doi.org/10.1016/j.tre.2020.102061
2. Liu, D., Yang, H. (2012). Dynamic Pricing Model of Container Sea-Rail Intermodal Transport on Single OD Line. Journal of Transportation Systems Engineering and Information Technology, 12 (4), 122–127. doi: https://doi.org/10.1016/s1570-6672(11)60216-x
3. Liu, D., Yang, H. (2013). Optimal Slot Control Model of Container Sea-Rail Intermodal Transport based on Revenue Management. Procedia - Social and Behavioral Sciences, 96, 1250–1259. doi: https://doi.org/10.1016/j.sbspro.2013.08.142
4. Fan, Q., Jin, Y., Wang, W., Yan, X. (2019). A performance-driven multi-algorithm selection strategy for energy consumption optimization of sea-rail intermodal transportation. Swarm and Evolutionary Computation, 44, 1–17. doi: https://doi.org/10.1016/j.swevo.2018.11.007
5. Muravev, D., Hu, H., Rakhmangulov, A., Mishkurov, P. (2021). Multi-agent optimization of the intermodal terminal main parameters by using AnyLogic simulation platform: Case study on the Ningbo-Zhoushan Port. International Journal of Information Management, 57, 102133. doi: https://doi.org/10.1016/j.ijinfomgt.2020.102133
6. Ambrosino, D., Asta, V., Crainic, T. G. (2021). Optimization challenges and literature overview in the intermodal rail-sea terminal. Transportation Research Procedia, 52, 163–170. doi: https://doi.org/10.1016/j.trpro.2021.01.089
7. Yan, B., Zhu, X., Lee, D.-H., Jin, J. G., Wang, L. (2020). Transshipment operations optimization of sea-rail intermodal container in seaport rail terminals. Computers & Industrial Engineering, 141, 106296. doi: https://doi.org/10.1016/j.cie.2020.106296
8. Morganti, G., Crainic, T. G., Frejinger, E., Ricciardi, N. (2020). Block planning for intermodal rail: Methodology and case study. Transportation Research Procedia, 47, 19–26. doi: https://doi.org/10.1016/j.trpro.2020.03.068
9. Nair, R., Miller-Hooks, E. D., Mahmassani, H. S., Arcot, V. C., Kuo, A., Zhang, K. et. al. (2008). Market Potential for International Rail-Based Intermodal Services in Europe. Transportation Research Record: Journal of the Transportation Research Board, 2066 (1), 21–30. doi: https://doi.org/10.3141/2066-03
10. Ben-Tal, A., Nemirovski, A. (2002). Robust optimization – methodology and applications. Mathematical Programming, 92 (3), 453–480. doi: https://doi.org/10.1007/s101070100286

11. Kozan, E. (2000). Optimising container transfers at multimodal terminals. Mathematical and Computer Modelling, 31 (10-12), 235–243. doi: https://doi.org/10.1016/s0895-7177(00)00092-3
12. Metrocargo and MetrocargoCity innovative solution for intermodal shipment. Available at: http://www.bestufs.net/download/Workshops/BESTUFS_II/Vilnius_Sep07/BESTUFS_Vilinius_Sep07_Ferraris_I-Log.pdf
13. Parkhomenko, L. O., Kalashnikova, T. Yu., Prokhorov, V. M. (2021). Pidvyshchennia interoperabelnosti zaliznychnoi transportnoi systemy Ukrainy pry zdiisnenni intermodalnykh konteinernykh perevezen na osnovi tekhnolohii MetroCargo™. Innovations and prospects of world science – Proceedings of IV International Scientific and Practical Conference. Vancouver, 312–317.
14. Prokopov, A., Prokhorov, V., Kalashnikova, T., Golovko, T., Bohomazova, H. (2021). Constructing a model for the automated operative planning of local operations at railroad technical stations. Eastern-European Journal of Enterprise Technologies, 3 (3 (111)), 32–41. doi: https://doi.org/10.15587/1729-4061.2021.233673
15. Ben-Tal, A., Goryashko, A., Guslitzer, E., Nemirovski, A. (2004). Adjustable robust solutions of uncertain linear programs. Mathematical Programming, 99 (2), 351–376. doi: https://doi.org/10.1007/s10107-003-0454-y
16. Ben-Tal, A., Nemirovski, A., Roos, C. (2003). Extended Matrix Cube Theorems with Applications to μ-Theory in Control. Mathematics of Operations Research, 28 (3), 497–523. doi: https://doi.org/10.1287/moor.28.3.497.16392
17. Shor, N. Z. (1985). Minimization Methods for Non-Differentiable Functions. Springer, 164. doi: https://doi.org/10.1007/978-3-642-82118-9
18. Yang, T., Kuo, Y., Cho, C. (2007). A genetic algorithms simulation approach for the multi-attribute combinatorial dispatching decision problem. European Journal of Operational Research, 176 (3), 1859–1873. doi: https://doi.org/10.1016/j.ejor.2005.10.048