

Automated system of freight traffic optimisation in the interaction of various modes of transport

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ABSTRACT

Advances in information technology have contributed to increased transport efficiency. The use of the latest information technologies allows automating all the information technology activities of transport enterprises that take part in the processes of organising freight traffic. Automation of transport logistics provides increased efficiency and optimisation of transportation. Due to the introduction of automated routing, accounting and planning systems at transport enterprises, transport logistics is reaching a new level. The purpose of the study is to develop an automated control system for the operation of the production and transport complex, based on the use of the latest information technology – Embarcadero RAD Studio XE10 visual programming system. It will help to optimise the transportation of mineral construction materials using the road, railway, and water modes of transport, the change of which occurs at the goods transshipment points. To solve this problem, a mathematical economic model and an automated control system for the operation of the production and transport complex have been developed. The proposed method would take into account the technical and technological capabilities of land and water modes of transport and the capacity of transshipment points, at which the cost of transporting goods will be minimal. Using the software package, the base for the transportation of mineral construction materials was calculated. The obtained initial transportation plan for each type of delivery was optimised, taking into account the production capacities of manufacturers and the needs of customers. The results of the optimal distribution of goods between different modes of transport are given (taking into account their production capacities), their change takes place in transshipment points. The results obtained allow optimal use of the technical and technological capabilities of vehicles and handling mechanisms. Based on the mathematical economic model, an automated control system for the operation of the production and transport complex has been developed, it has the form of a software package. The calculation of the initial (reference) freight traffic plan was carried out and the optimisation of the initial plan for these transportations was performed for each of the delivery options. The operability of the developed software package has been confirmed experimentally, which gives reason to offer it for the use in industrial production associated with the movement of sizable freight traffic.

Keywords: Automation, Industrial-transport complex, Transshipment points, Freight delivery, Software package

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1. Introduction

Transport belongs to the field of material services production, performs transportation of people and goods, provides distribution and delivery of raw materials, and products of industry and agriculture to all regions of

the country and abroad. The main task of transport is full and timely satisfaction of needs of a national economy and the population in transportations, increase in efficiency and quality of a transport network. Given the leading role of transport in a market economy, transport management is allocated to a separate field, called transport logistics [1; 2]. Transport logistics contains a number of elements, the main of which are: freight; consolidating stations; transport hubs; transport network; rolling stock; freight handling facilities; participants in logistical processes; shipping containers and packaging. A special place in the transport logistics system belongs to transport hubs (places of loading, unloading, transshipment). Transport hubs are those elements of transport systems in which the transportation process begins and ends, the redistribution of freight flows is carried out.

There is an interaction of mainline, as well as industrial, and urban modes of transport. Powerful handling equipment is concentrated in the hubs, most warehouses, and bases of long-term storage of goods, where the majority of material handlers work. The efficiency and quality of the entire transport system depends on the successful operation of transport hubs [2]. The main reserves for improving the transport and logistics process are in the rational organisation of interaction of participants in the supply chain, coordination of their interests, and the search for mutually beneficial and suitable solutions. Advances in information technology can significantly increase the efficiency of transport logistics, and information and computer support have a proper place among the key logistical functions [3; 4].

Much attention of researchers has been paid to the theory and practice of the organisation of freight traffic. Thus, the paper [5-10] presents the study of routing optimisation by the criterion of minimum delivery time. The paper [11; 12] considers the methods of route selection based on alternative sampling. Instead, the paper [13-18] uses methods for modelling routes in transport systems based on fuzzy logic. The heuristic model of route selection is considered in the paper [19-21], and in [22-24] the quantum model of route selection in transport systems is investigated. In addition, the method of transporting goods using containers is described in [10]. The results of modelling the choice of routes using data from the Global Positioning System (GPS), focused on heavy-duty trucks that perform long trips, are given in [25-30]. In addition, the paper [31] describes the differential method of determining the location of land vehicles, using the GLONASS/GPS, using special processing algorithms. Probabilistic methods of controlling the movement of ships and other objects, using satellite navigation systems, are considered in [32-37].

Analysis of these papers shows that these studies use various analytical approaches to the organisation of freight traffic and modes of operation of individual elements and parts of logistics systems. However, in these and many other studies, the organisation of freight traffic using one type of transport, land (road or railway), or water (river or sea) is considered. At the same time, the issues of organising freight traffic with the simultaneous use of different modes of transport (land and water) remain unresolved [38-40]. All this gives grounds to assert that it is expedient to conduct a study on the optimisation of freight traffic in the interaction of railway, road, and water transport.

To develop and study the mathematical and computer model of the production and transport complex (PTC) it is necessary to solve the following tasks:

1. To develop a mathematical economic model of how PTC works, which would take into account the technical and technological capabilities of land and water transport and the capacity of transshipment ports, where the cost of transporting of goods will be minimal;
2. To develop an automated PTC control system (to develop an interface of the master form and individual modules, to design a database and write a programme) on the basis of the mathematical economic model. Implement it in the form of a computer software package, in the object-oriented programming system Embarcadero RAD Studio XE10;
3. On the basis of the formed ordering table, to calculate the initial plan of freight traffic on each of delivery types, taking into account the production capacities of manufacturers and customer needs;
4. To optimise the obtained basic plan of freight traffic. The minimum costs for transportation and handling of goods are taken as the optimality criteria [41-45].

2. Material and methods

The object of the study was a production and transport complex consisting of m points of extraction (production) of mineral construction materials (sand, gravel, rubble), which must be transported to n destinations, using different modes of transport, which change in transshipment points. The subject of the study were models, methods, and software tools for optimising the transportation of mineral and building

materials, using road, railway, and water transport. The aim of the study was to develop an automated control system for the production and transport complex, based on the use of the latest information technologies, namely – the Embarcadero RAD Studio XE10 visual programming system. Then use it to optimise the transportation of mineral construction materials, using land and water transport. When solving the problem of optimising freight traffic, using different modes of transport, it is necessary to take into account a large number of technological factors. They include features of each of the transport modes, the dynamics of production conditions and other difficulties. It should be noted that there is no generally accepted classification of tasks of this type. The main difficulties in developing such a classification are due to the multifactorial nature of operational management tasks [46-49].

The solution of such complex problems is reduced to the formulation in mathematical equations and the solution of optimisation problems according to predetermined optimality criteria. The optimality criteria in the optimisation problems are taken as some economic function. For example, for transport logistics systems, these are the costs associated with the operation of transport or materials-handling vehicle. The most complete are the criteria that express the profit from the operation of the transport system – the maximum freight turnover, the minimum cost and time for delivery, the minimum cost of freight-handling. This study proposes a way to overcome such difficulties. The method is based on the fact that the use of the latest information technologies and systems helps to increase the efficiency of transportation. Information systems of logistics automation allow to computerise activity of the transport enterprises participating in the organization of freight transportations. The automation of transport logistics is essential to improve efficiency and optimise freight traffic. Due to the introduction of automated routing, accounting and planning systems at transport enterprises, transport logistics is reaching a new level [50-52].

Production and transport complex (PTC) consist of m points of extraction (production) of mineral construction materials (sand, gravel, rubble, etc.) – A_i ($i=1, 2, \dots, m$). Goods from m extraction points X_i ($i=1, 2, \dots, m$) must be transported to n destinations B_j ($j=1, 2, \dots, n$), where X_i – volume of shipment from extraction (production) points); B_j – final delivery points of mineral construction materials. The capacities of mining points a_i and material requirements at points of b_j are known.

Transportation takes place according to the following options [53-56]:

1. Freight shipment X_{ij} directly from production points A_i to destinations B_j by land transport (railway).
2. Freight shipment by water transport – in this option, the transportation of goods is carried out in several stages:
 - a) transportation of goods X_{ik} from the same production points A_i to river (sea) ports of departure D_k ($k=1, 2, \dots, p$) by land transport (road);
 - b) transportation of goods X_{ks} from river (sea) ports of departure D_k by water transport to ports of destination G_s ($s=1, 2, \dots, r$), where G_s – river ports of destination of goods;
 - c) transportation of goods X_{sj} from the ports of destination G_k directly to the delivery points B_j by land transport (road).

To solve this problem, it is necessary to develop an economic and mathematical model of PTC, which would take into account the technical and technological capabilities of land and water transport and capacity of transshipment ports, at which the transportation cost will be minimal. The mathematical economic model of optimal interaction of road, railway, and water transportation consists of the objective function, the system of restrictions (certain conditions) and the conditions of non-negativity of variables [57-60].

For this task, the objective function is written as follows:

$$Z = \sum_{i=1}^m \sum_{j=1}^n C_{ij} X_{ij} + \sum_{i=1}^m \sum_{k=1}^p C_{ik} X_{ik} + \sum_{k=1}^p \sum_{s=1}^r C_{ks} X_{ks} + \sum_{s=1}^r \sum_{j=1}^n C_{sj} X_{sj} \rightarrow \min \quad (1)$$

where: C_{ij} – the cost of transporting a unit of freight from the i -th production point to the j -th delivery point directly, without changing the land mode of transport; X_{ij} – volumes of goods transported directly from production points to destinations by land transport (railway); C_{ik} – the cost of transporting a unit of freight from the i -th production point to the k -th port of departure, taking into account the cost of transshipment of goods from one mode of transport to another; X_{ik} – volumes of goods transported from extraction points to river ports of departure by land transport (road); C_{ks} – the cost of delivery of a unit of cargo from the k -th port of departure to the s -th port of destination by water transport, taking into account the cost of intra-port

transshipment of cargo; X_{ks} – volumes of goods transported from river ports of departure to ports of destination by water transport; C_{sj} – the cost of transporting a unit of cargo from the s -th port of destination to the j -th delivery point, taking into account the cost of transshipment of goods from one mode of transport to another; X_{sj} – volumes of delivery from ports of destination directly to places of delivery by land transport (road) [61]. The objective function (1) receives the minimum value under certain conditions. The first condition is to balance production and consumption:

$$\sum_{i=1}^m a_i = \sum_{j=1}^n b_j, \quad (2)$$

where: a_i – capacity of extraction points; b_j – material requirements at delivery points.

The second condition provides for balancing the volume of delivery by the direct option and with the use of water transport, with the volume of production and consumption:

$$\sum_{i=1}^m X_{ij} + \sum_{k=1}^p X_{ik} = \sum_{i=1}^m a_i, \quad (3)$$

where: X_{ij} – volumes of goods transported directly from extraction points to destinations by land transport (railway); X_{ik} – volumes of goods transported from extraction points to river ports of departure by land transport (road); a_i – capacity of cargo extraction points:

$$\sum_{j=1}^n X_{ij} + \sum_{s=1}^r X_{sj} = \sum_{j=1}^n b_j, \quad (4)$$

where: X_{ij} – volumes of goods transported directly from extraction points to destinations by land transport (railway); X_{sj} – volumes of goods transported from ports of destination directly to delivery points by land transport (road); b_j – material requirements at delivery points.

An important condition is to take into account the processing capacity of transshipment ports:

$$\sum_{k=1}^p X_{ik} = \sum_{s=1}^r X_{sj} \leq \sum_{k=1}^p Q_{ks}, \quad (5)$$

where: X_{ik} – volumes of goods transported from extraction points to river ports of departure by land transport (road); X_{sj} – volumes of goods transported from ports of destination directly to delivery points by land transport (road); Q_{ks} – processing capacity of river ports of transshipment when delivering goods from the k -th port of departure to the s -th port of destination by water transport [62-65].

The final condition is to determine the integrity of the variables, i.e., the values of the variables must be equal to or greater than zero:

$$X_{ij}, X_{ik}, X_{ks}, X_{sj} \geq 0, \quad (6)$$

where: X_{ij} – volumes of goods transported directly from extraction points to destinations by land transport (railway); X_{ik} – volumes of goods transported from extraction points to river ports of departure by land transport (road); X_{ks} – volumes of goods transported from river ports of departure to ports of destination by water transport; X_{sj} – volumes of goods transported from ports of destination directly to delivery points by land transport (road);

It is seen from equation (1) that the mathematical economic model, which describes the work of PTC, consists of four terms. The far-left term describes the cost of delivery X_{ij} directly from extraction points A_i to destination points B_j by land transport (railway). The second term on the left describes the cost of transportation X_{ik} from the A_i extraction points to the river (sea) ports of departure D_k by land transport (road). The second term on the right describes the cost of transportation X_{ks} by water transport, from river (sea) ports of departure D_k to ports of destination G_s . The far-right term describes the cost of transportation X_{sj} from the ports of destination G_k directly to delivery points B_j by land transport (road).

After construction of mathematical economic model, the problem of optimum distribution of land and water transport on transportation and transshipment of freights is solved. The best option for the interaction of land and water transport is provided if positive values of X_{ij} , X_{ik} , X_{ks} , X_{sj} are found at which the minimum of the objective function (1) is achieved, which reflects the total reduced costs for transportation and transshipment.

The solution to the problem is to find the initial plan using different modes of transportation, which change at transshipment points, using the North-East Corner Method, followed by finding the optimal plan of transportation by the method of potentials [66-70].

3. Results and discussion

Based on the mathematical economic model (1), an automated control system for the operation of PTC, in the form of a computer software package, has been developed. One of the newest information technologies is used to develop an automated system – the object-oriented programming system Embarcadero RAD Studio XE10, which combines Embarcadero Delphi XE10 and Embarcadero C++ Builder XE10 [20]. Embarcadero RAD Studio XE10 is an integrated programming environment, developed by Embarcadero, which combines tools for rapid application development for different platforms and databases. Embarcadero RAD Studio XE10 runs on Microsoft Windows 7/10 operating system. Embarcadero RAD Studio XE10 integrated programming environment also supports application development for Microsoft Windows x86 and x64 operating systems, Mac OS x86, Apple iOS and Android [71-73].

Computer software package is represented by a programme that allows to create delivery tables, to find initial plans for the freight traffic of different transport modes, which change at transshipment points. The programme contains a database that stores tables of data on existing stocks in warehouses of manufacturers, ports of departure and delivery of goods, and customers of goods. Also, in the database there are tables of costs of transportation of cargo between the corresponding points and tables of handling costs at transshipment points. The software package consists of the main form Form1, from which separate subforms (modules) are loaded (Figure 1) [74-77].



Figure 1. The main form window

When clicking on the "Delivery registration" button on the main form (Figure 1), the window of this subform opens (Figure 2). The "Delivery registration" subform consists of the following items of the main menu: 1) Delivery point; 2) Customer; 3) Freight. With the help of the "Delivery registration" subform the list of customers of the corresponding shipment is formed, and certain supplier of the corresponding freight is selected. The method of delivery can be chosen by land (railway, road) and water transport. Figure 2 shows the "Delivery point" window of the "Delivery registration" subform. Using this window, the delivery address of the corresponding customer and port of delivery, if transportation is carried out by water, is specified. It is also possible to search for the delivery point using the drop-down list (ComboBox extension of the component palette), or choose from the table at the bottom of the window, which is implemented on the basis of the StringGrid extension. When all the necessary data has been filled in the "Delivery point" window of "Delivery registration" subform click "Next" to go to the "Customer" and "Freight" windows. The "Customer" and "Freight" windows of the "Delivery registration" subform have a look similar to the "Delivery point" window [78]. The "Customer" window indicates the responsible person receiving the cargo (name, contact numbers). It is possible to find the customer in "Customer" window, similar to finding the delivery point. The "Cargo" window allows to select the type of freight (sand, gravel, rubble). After filling in all the windows of the "Delivery registration" subform, click "Confirm delivery" (it appears in place of the "New address" button. If all three windows of the "Delivery registration" subform are filled in correctly, the message "Delivery request added successfully" appears. After that, add the next customer until the ordering table is formed [79].



Figure 2. Delivery point window

Freight shipment is performed by land transport (railway, road) and by water transport. A corresponding button on the main form (Figure 1) opens a window of a specific subform for delivery (Figure 3). The subform A→B allows to optimise the shipment X_{ij} directly from extraction points to destinations by land (railway). First, on the basis of the ordering table, the "Transport table" (transport task) is formed. To do this, select the type of freight (top left block "Freight selection"). Types of freight are: river sand, sea sand, pit sand; gravel, granite rubble, limestone rubble [80; 81]. The freight selection is implemented using drop-down lists, based on the extensions of the ComboBox component palette. Then click "Select". Then supplier is selected from the list of warehouses of manufacturers (below on the left the "Supplier" block). This feature is also implemented using the ComboBox extension, which is associated with a table that lists the manufacturers in whose warehouses the required freight is stored. The amount of the necessary shipment is specified in the "Edit" component window. After clicking the "Add" button in the "Supplier" block, the name of the respective supplier is added to the "Transport table" (table rows), which is implemented on the basis of the StringGrid component. Similarly, a list of consignees is created using the "Consignee" block (lower to the left). To do this, first in the ComboBox extension associated with the customer table, select the name of the materially responsible person and the address of the consignee's company, then enter the volume in the "Edit" component window. The name of the corresponding customer is added in the "Transport table" (table columns), after clicking the "Add" button in the "Consignee" block [82].

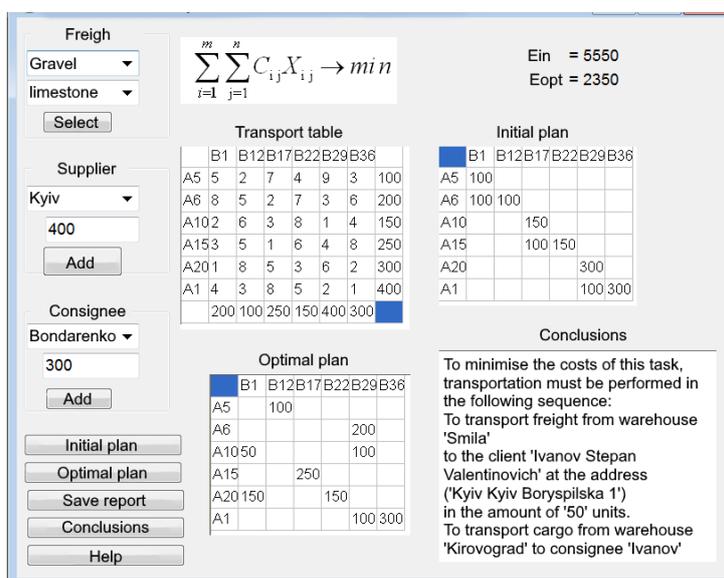


Figure 3. Direct delivery subform window

Thus, the whole "Transport table" is formed, which includes a list of suppliers (table rows) and consignees (table columns). Next the cost of delivery from suppliers to consumers is added in the cells of this table on the basis of transportation costs tables. On the basis of the "Transport table", using the "Base plan" button, there is an initial plan of a transport task by a North-West Corner Method. The results of the calculation are added in the "Base plan" table (Figure 3) [83-88]. With the help of the "Optimal plan" button, after finding the initial plan of the transport task, the optimisation of the initial plan by the potential method is performed. The final results of the optimisation of the initial plan are added in the "Optimal plan" table. The "Conclusions" button adds the optimisation results in text format into the "Conclusions" table (bottom right), which are stored on the hard disk in the Otchet.txt file using the "Save Report" button. The initial plan (E_{in}) and the optimised plan of transportation (E_{opt}) are shown in top right called in notional currency units (c.u.) (top right). The "Help" button displays an additional form with the reference materials necessary to perform the relevant calculations. The help contains tables of data on suppliers and consignees, ports of departure and delivery. Also, in the initial plan there are tables of costs of freights transportation between the corresponding points and tables of handling costs in transshipment points. The "Exit" button terminates the program at any stage of its execution [89; 90].

According to the initial conditions of this task, the delivery using water mode transport is performed in several stages. In the software package it is implemented by means of the following subforms (Figure 1):

1. Subform A→D allows to optimise the freight traffic X_{ik} from extraction points A_i to river (sea) ports of departure D_k by land transport (road).
2. Subform D→G allows to optimise the freight traffic X_{ks} from river (sea) ports of departure D_k to ports of destination G_s by water transport.
3. Subform G→B allows to optimise the freight traffic X_{sj} from the ports of destination G_s directly to delivery points B_j by land transport (road).

The corresponding button on the main form (Figure 1) opens a certain subform window for the freight shipment using water transport. These subforms are similar to the subform of optimisation of transportation in the direct variant (Figure 3), except for the transportation costs added to the "Transport table", which correspond to:

- a) transportation costs between extraction points A_i and ports of departure D_k (subform A→D);
- b) transportation costs between ports (subform D→G) [91-94];
- c) transportation costs between delivery ports G_s and final delivery points B_j , respectively (subform G→B).

The calculation data on land and water transportation costs, performed with a computer software, are presented in Table 1. Column 3 of Table 1 shows the calculations of the initial plan of transportation for each of the delivery options, i.e., almost without any mathematical and economic justification.

Table 1. Calculation data on freight traffic

Sr. No.	Delivery options	Initial transportation plan, E_{in} (c.u.)	Optimal transportation plan, E_{opt} (c.u.)	Estimated savings, E (%)
1.	Direct delivery (subform A→B)	5550	2350	57.66%
2.	Transportation from extraction points to ports of departure (subform A→D)	6500	4000	38.46%
3.	Transportation by water mode of transport (subform D→G)	7100	5800	18.31%
4.	Transportation from ports of destination to delivery point (subform G→B)	12100	5200	57.02%
	Total	31250	17350	44.48%

The column 4 of Table 1 shows the results of the optimisation of the transport problem, performed by the method of potentials. Column 5 contains the estimated amount of savings E , performed separately for each delivery method using the equation:

$$E = (E_{opt} - E_{in}) / E_{in} \times 100 \text{ ‰} \%, \quad (7)$$

where: E – savings; E_{opt} – optimal transportation plan; E_{in} – initial transportation plan. Savings E , in (7) were

estimated as a percentage of the initial plan E_m of freight distribution.

The analysis of results shows that the optimisation of direct transportation by land transport (railway) provides significant savings and is 57.66%. Significant savings can also be obtained by optimising the transportation from extraction points to river ports of departure by land (road), which is 38.46%, as well as by optimising the transportation from ports of destination directly to delivery point (by road), which is 57.02%. Optimisation of cargo delivery by water transport provides the smallest savings, only 18.31%. Table 1 shows that the total amount of savings, when using the developed automated control system of PTC, is 44.48%. Thus, the findings show that under these accepted conditions, greater savings can be obtained by optimising the transportation of mineral construction materials using land transport [95-98].

4. Conclusion

Thus, the use of the latest information technologies and systems helps to increase the efficiency of transportation. Information systems of logistics automation allow to automate all activity of transport enterprises participating in freight transportation. This study presents the mathematical economic model and the automated control system of PTC operation in the form of the computer software. The system of object-oriented programming Embarcadero RAD Studio XE10 allows to optimise the distribution of mineral and construction materials during transportation. The software package allows to organise the optimal use of handling facilities at the transshipment points (given their production capacity). It helps to reduce the expenses on vehicles and transshipping gear for the transportation of freight. The scientific novelty of the study is due to the proposed mathematical economic model for PTC control. It allows to formalise technological processes in the transshipment points of different transport modes. The model was further developed in solving the transport problem to optimise freight transport using land and water transport. The practical value is that the developed software can be implemented in real industrial production, in order to optimise the movement of significant freight flows, using different transport modes, which can change at the transshipment points.

Directions for further research are the development of mathematical economic models and software to conduct studies on freight traffic optimisation based on minimum delivery time. It is relevant in emergency situations (natural disasters, fires) and for transportation of perishable products (fruits and berries, dairy products) and more.

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