

Запропоновано двохкритеріальна оцінка раціональності застосування системи постачання, яка базується на врахуванні часу доставки при виконанні умови «точно в строк» та сукупних витрат на доставку вантажу. Оцінено вплив стохастичних параметрів перевізного процесу на результат функціонування транспортної системи. Побудовано прогноз песимістичного сценарію застосування унімодального та мультимодального перевезення в міжнародному сполученні

Ключові слова: унімодальне перевезення, мультимодальне перевезення, час доставки, стохастичний процес, екстремальний експеримент

Предложена двухкритериальная оценка рациональности использования системы поставки, которая базируется на учете времени доставки при выполнении условия «точно в срок» и совокупных затрат на доставку. Оценено влияние стохастических параметров перевозочного процесса на результат функционирования транспортной системы. Построен прогноз пессимистического сценария использования унимодальной и мультимодальной перевозки в международном сообщении

Ключевые слова: унимодальная перевозка, мультимодальная перевозка, время доставки, стохастический процесс, экстремальный эксперимент

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RESEARCH OF EFFECTIVENESS OF UNIMODAL AND MULTIMODAL TRANSPORTATION INVOLVING LAND MODES OF TRANSPORT

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1. Introduction

Transformation processes in economic relations of European countries, going on in the last decades, lead to significant changes in the functioning paradigm of economic systems in the countries of the European space. Creation of the free trade zone has led to integration of trade and economic systems of the countries, resulting in formation of a common macro system. Under such conditions, there occurred qualitative and quantitative changes in operation of all components of economic systems, which obviously include the transport industry. The delivery geography got extended with an increase in transportation distances, regulations and legal conditions of transportation changed as a result of formation of common economic space. All this, accordingly, led to changes in economic expediency of application of unimodal and multimodal transportation technologies, which under new operation conditions require more detailed research.

In this case, special attention should be paid to stochastic processes, which occur in transport systems, particularly those involving several kinds of transport [1], as well as to the impact on efficiency of application of a transportation system.

A relevant direction of research is to assess all the possible combinations of delivery systems between a couple of the most remote countries of Europe, such as Ukraine and Italy, which were selected as an example. This allows us to construct the factor space with maximum amplitude of variation of transportation distances. In turn, taking into account stochastic elements of the transport process makes it possible to expand the area of forecasting of effects of delivery system operation in the international traffic and to evaluate the pessimistic scenario of functioning of a transportation system. The proposed procedure of evaluation of results of the system's functioning enables us to form a strategy of application of unimodal and multimodal technology with high efficiency.

2. Literature review and problem statement

Multimodal transportations play an important role in the international logistics and are characterized as a mode of transportation with the use of two or more kinds of transport without changing the way of packaging at cargo transfer from one kind of transport to another [2]. Accordingly, unimodal transportation is characterized by application of one kind of transport, which performs the functions of secondary and main transport at the same time, for example in the framework of solving classical transport problems [3]. Under such conditions at unimodal transportation, motor transport acquired the widespread use on the basis of extensive development of communication routes and relative ease of carrying out load handling operation. If we consider land transportation, a delivery system can be of two types: unimodal (motor transport) and multimodal (a combination of motor and railway transport). Efficiency of application of a certain service can be assessed by delivery time [4–7], or by cargo delivery costs [1, 2, 8–14].

In the case of prediction of delivery time, it is possible to use the deterministic [4–6] and the stochastic [7] approaches. In addition, there are studies [5], in which the model “just in time” is constructed, based on economic-mathematical methods taking into account fines for late cargo delivery to its destination. In this case, one solves the problem of efficient transportation routing, which provides cargo delivery within terms, defined by the contract, with minimization of total costs of cargo delivery throughout the network. This procedure can be used when addressing the problem of choice of a rational system of cargo delivery in the international traffic. But the deterministic approach, used as a basis, similarly to [4], does not make it possible to make an accurate forecast regarding the actual arrival time of a transport vehicle for unloading.

Paper [6] deserves attention, despite the field of implementation – urban passenger transport. The approach, developed on the paradigm of removing everything extra from the system (“everything that does not improve the product”), can be also applied to systems of servicing of material flows involving several modes of transport. A possibility of taking into account or levelling negative environmental impacts of a transport system can be regarded as a removal of everything “extra” in this context. This allows an increase in stability of functioning of a delivery system and, accordingly, more accurate prediction of the outcome of functioning (delivery time or costs).

Under conditions when there is a large number of sources of disturbance of a transportation systems, taking into account stochastic processes that occur during delivery allows prediction of the results of functioning with a certain degree of reliability. Thus, in article [7], it is proposed to construct a confidence interval based on the hypothesis of the normal character of distribution of the basic stochastic elements of a transport system. But in the conducted research, attention was paid only to international motor transportation (unimodal connection), which does not allow us to apply the derived characteristics to multimodal transportation.

Along with approaches that are based on taking into consideration cargo delivery time, the methods of streamlining of delivery systems, based on optimization of costs of transportation systems’ functioning, have become widely used. Application of mathematical methods allows us to determine the optimal state of a system through conducting

single-criterion [9–14] or multicriteria optimization [8] of parameters of a transport system. Within this framework, there is some commonality between all the methods and approaches: the technological process is described by the model with a particular totality of bases (sets) [9, 10]. The first basis reflects a totality of input parameters that can be changed in the process of transport system management. The second basis corresponds to the selected criterion of efficiency of a transport system functioning. The third basis makes it possible to take into account environmental disturbances, which cause a negative impact on the technological transportation process. The fourth basis describes technological relationships between the subsystems of the transport system, which serves a material flow as a whole between a consigner and a recipient or locally in a transport hub at the interaction of transport modes. This approach allows us from the standpoint of the systems analysis to determine distinctly the range of parameters, which a researcher can operate in order to obtain a rational state of a transport system and take into account stochastic aspects of the technological transportation process in the model. If the number of consigners and recipients within one multimodal delivery system increases, difficulty of solution of the optimization problem increases by a nonlinear function, which in [11] is proposed to be solved by step-by-step optimization. In each iteration, we solve the problem of rational fixing of turnover packaging to the rolling stock and, accordingly, distribution of rolling stock by transportation routes. But within the service polygon with an insignificant number of consigners and recipients, the problem of rationalization of this system does not imply a procedure of stepwise optimization. This is due to its simple composition from the standpoint of the theory of systems analysis.

In the framework of construction of a multimodal transportation model, it is possible to take into account a process of intermediate storage at a transport hub [14] and downtime of vehicles waiting for transshipment to the main transport [13]. In this case, intermediate storage is not required if we use an additional criterion of a decrease in time it takes a material flow to pass through the supply chain, if it is technologically possible to exclude this process from the system. Thus, according to results of analytical research, we can conclude on the possibility of performing multicriteria optimization. In this case, consideration in the model of stochastic components of the technological delivery process is an important requirement.

Thus, as a result of the analytical review of existing methods and models in terms of studying effectiveness of multimodal and unimodal transportation systems, it is possible to draw a conclusion on the possibility of performing multicriteria optimization with necessity to take into account in the model the stochastic components of the technological delivery process.

3. The aim and objectives of the study

The aim of present research is to evaluate effectiveness of application of unimodal and multimodal transportation systems, taking into account stochastic characteristics of the transportation process. This will make it possible to determine the economically reasonable area of application of a particular transportation technology under conditions of maximum approximation of the model to characteristics and

conditions of functioning of a transport system. In turn, this should increase the value and efficiency of usage of both a model and results of modeling in development of managerial decisions on increasing efficiency of functioning of delivery systems of enterprises.

To accomplish the set goal, the following tasks had to be solved:

- to substantiate theoretically and to prove experimentally the stochastic character of passage the border control, technical motion speed of trucks and placement of requests for international transportation;
- to develop a model of cargo delivery time on condition “just in time”, taking into account stochastic parameters of the transport process;
- to construct a mathematical model of assessment of cargo delivery costs for unimodal and multimodal transportation by land kinds of transport;
- to develop regression model for prediction of delivery time on condition “just in time” at unimodal and multimodal transportation options;
- based on results of the experiment, to generate optimistic and pessimistic scenarios for functioning of a unimodal and multimodal delivery systems, as well as to determine effectiveness of application of each option on the example of supplies between Ukraine and Italy.

4. Materials of research in rational schemes for international cargo transportation by land kinds of transport

4. 1. Procedure for determining delivery time under “just in time” condition

Perfect condition of a delivery system “just in time” can be analytically represented as mathematical expression:

$$\Delta T = |T_{del} - T_{cont}| \rightarrow 0, \tag{1}$$

where ΔT is the deviation between actual delivery time and delivery term according to the contract, days; T_{del} is the actual delivery time, days; T_{cont} is the delivery time according to the contract, days.

But this idealized statement is unattainable under actual conditions of implementation of the transport process. It is obvious that condition (1) can be satisfied at some assumptions, under which ΔT will be equal to zero only on condition of approaching it. In this regard, it is advisable to apply criterion of minimum deviation of actual delivery time from the one, specified in the contract for supply of material values, which will make it possible to perform assessment of alternative delivery systems more correctly:

$$\Delta T = |T_{del} - T_{cont}| \rightarrow \min. \tag{2}$$

Delivery time is actually a function of a certain list of parameters (factors) that, making an impact of a particular character on it, form the final value. The variable nature of these parameters allows us to draw a conclusion about possibility to describe magnitude of delivery time with the help of confidence interval. Using the theory of mathematical statistics, T_{del} can be considered as magnitude x with parameters \bar{x} and σ^2 . It is obvious that every delivery will differ from the other one by the time it takes to realize it between the pair: a consigner and a recipient. Based on this, it can be

argued that there is a possibility to determine statistical estimates \bar{x} and σ^2 , with the use of which confidence interval is constructed based on the Chebyshev inequality.

$$T = P\left(|\bar{x} - MX| \leq k \times \frac{\sigma}{\sqrt{n}}\right) \leq 1 - \frac{1}{k^2}, \tag{3}$$

where n is the value of total sampling; MX is the mathematic expectations.

Coefficient k is determined according to pre-set level of confidence probability from the following equation [15]

$$\alpha = 1 - \frac{1}{k^2}. \tag{4}$$

Accordingly, after performing transformations, we obtain:

$$k = \frac{1}{\sqrt{1-\alpha}}. \tag{5}$$

Thus, according to (3)–(5), we form the model of cargo delivery time:

$$T_{del} = T_{av.del} + k \cdot \frac{\sigma}{\sqrt{n}}, \tag{6}$$

where $T_{av.del}$ is the mean value of delivery time by a certain supply scheme, obtained as a result of simulation, days; n is the number of measurements or iterations within simulation, units.

Since determining of actual delivery time is possible only by means of simulation, it is necessary to provide high accuracy of the model. This is done based on the necessary level of confidence probability α , pre-set by a researcher, and performance of a sufficient number of iterations at modeling – n . Certainly, according to the law of large numbers, it is possible to perform 384 iterations [16] to solve the stated problem but such an approach is useful in the absence of the possibility of statistical estimation of the required number of experiments (iterations). In the case of distribution of studied magnitude by the normal law, there is a possibility of distinct assessment of the volume of measurements, which guarantee the required reliability:

$$n = \frac{k^2 \cdot \sigma^2}{\epsilon^2}, \tag{7}$$

where σ^2 is the variance of delivery time, days²; ϵ is the permissible error of observations, days.

The possibility of applying formula (7) is formed based on the hypothesis about normal distribution of actual cargo delivery time. The hypothesis is based on the assumption of existence of a significant number of factors that cause an impact on the progress of a material flow in export-import direction, and therefore, according to the central boundary theorem, the total time of execution of all cargo delivery operations will be divided according to the normal law.

In turn, it is proposed to present the mathematical basis of the model of delivery time in the additive form with consideration of the following components:

$$T_{del} = \sum_{i=1}^m t_{pi} + \sum_{j=1}^k t_{cj} + \sum_{r=1}^s t_{hr} + \sum_{z=1}^y t_{nz} + \sum_{w=1}^f t_{qw}, \tag{8}$$

where t_{pi} is the duration of a vehicle's on the motion on the i -th section of the route, days; t_{cj} is the duration of the j -th rest of the vehicle's operator at driving a vehicle during cargo delivery, days; t_{hr} is the duration of performance of the r -th loading-unloading operation, days; t_{nz} is the duration of passing border and customs control, years; t_{qw} is the duration of waiting for departure of the main kind of transport or cargo transshipment between them in the transport hub, days; m is the number of route sections, which are served by different carriers, units; k is the number of necessary rests of vehicle's operators during delivery performance, units; s is the number of cargo operation per vehicle, units; y is the number of border and customs checkpoints, where it is necessary to perform the check of vehicles and proforma invoices, units; f is the number of technologically necessary delays for performing the process of cargo transfer from one kind of transport (carrier) to the other, units.

Under such statement of the problem, there is a possibility of taking in account stochastic elements of delivery process. Thus, for example, duration of vehicle's (motor transport) will be determined by technical speed, which is a normally distributed random magnitude [17]. In turn, duration of passage of the border and customs control is determined by the number of vehicles in line, which is also a random magnitude. Having determined the nature of distribution of this magnitude, it is possible to estimate time of vehicles' passing the border and customs control and to predict actual delivery time. As for t_{qw} in (8), it can be equal to zero when we use unimodal service with one carrier. In the case of application of motor and railway transport (as main), there is a need of taking into account time of fitting of modes of transport and assessment of possible cargo transshipment time. This can, in turn, lead to a significant increase in delivery time, since it is necessary to consider time of placement the transportation request and existing schedule of main transport motion.

Based on the above, the authors put forward a number of hypotheses about the nature of changes of random magnitudes that require experimental verification. These include motion speed, formation of a vehicles' queue at the border checkpoint and duration of waiting for departure of the main kind of transport.

Motion speed is a normally distributed magnitude, which is why motion of a vehicle on the i -th section of the route is the following function:

$$t_{pi} = f(l_i, \mu_V, \sigma_V^2), \quad (9)$$

where l_i is the length of the i -th section of a route, km; μ_V is the mathematic expectation of technical speed, km/h; σ_V^2 is the variance of technical speed, km/h.

Formation of a queue at the border checkpoint follows the Poisson law. Based on this, time of checkpoint control is represented as function:

$$t_n = f(\lambda, Y), \quad (10)$$

where λ is the parameter of the Poisson law, which characterizes mean intensity of vehicles' arrival at a border checkpoint, units; Y is the throughput capacity of a border checkpoint, unit/day.

Duration of waiting for departure of the main kind of transport directly depends on the moment of placement of

the request for transportation, which is proposed to be described by the uniform law of distribution. Therefore, waiting time is function of the following parameters:

$$t_q = f(a, b), \quad (11)$$

where a, b are the parameters of uniform law of distribution.

4. 2. Procedure of assessment of effectiveness of application of alternative freight traffic of land kinds of transport

Criterion of effectiveness of application of specific freight traffic in international transportations is the level of reduction of delivery costs:

$$E = \max \nabla(C_{del}) - \min \nabla(C_{del}), \quad (12)$$

where C_{del} is the delivery cost, UAH.

In this statement, all possible options for delivery by combination of transport-technological schemes are considered. But complete fitting of all existing delivery options is not performed, as it is obvious that within the framework of international transportation by land kinds of transport, for example, the use of light-duty vehicles is not effective. On this basis, a primary list of all possible options is formed, i. e. ∇ .

Based on the conducted analytical research, the key components of total cargo delivery costs in international traffic were formed, namely:

$$C_{del} = f(C_{tr}, C_l, C_{im}, C_{ins}, C_{forw}), \quad (13)$$

where C_{del} is the delivery cost, UAH; C_{tr} is the transportation cost, UAH; C_l is the cost of performance of cargo handling operations, UAH; C_{im} is the cost of immobilization of money to cargo, UAH; C_{ins} is the cost of insurance of rolling stock, UAH; C_{forw} is the payment for using services of a transportation-forwarding company, UAH.

In the case of consideration of motor transport, transportation costs are formed based of the standard articles of expenses:

$$C_{tr}^a = f(C_{fuel}, C_{tires}, C_{oil}, C_{mr}, C_a, C_{sal}, C_{daily}, C_{gen}), \quad (14)$$

where C_{fuel} is the fuel cost, UAH; C_{tires} is the tires' renovation cost, UAH; C_{oil} is the lubricants cost, UAH; C_{mr} is the cost of maintenance and repairs of rolling stock. UAH; C_a is the costs of depreciation materials, UAH; C_{sal} are the expenses for drivers' salary, UAH; C_{daily} is the cost of drivers' daily allowances, UAH; C_{gen} are the general economic costs, UAH.

In the case of cargo transportation by railway, transportation costs are determined according to the tariff guidelines with regard to the chosen transportation scheme. Analytical dependences for calculation of costs of transportation by carriage shipment (15) and 20-pound containers (16) are given below [18]:

$$\begin{aligned} C_{tr}^{rail(v)} = & (418,09773 + 30,9702 \times k_L) + \\ & + (108,41293 + 8,03059 \times k_L) + \\ & + (6,01477 + 0,44553 \times k_L + 0,02848 + 0,00211 \times k_L) \times \\ & \times L_{dr} \times k + (1,30448 + 0,09663 \times k_L) \times L_{dr} \times k, \end{aligned} \quad (15)$$

$$C_{tr}^{rail(c)} = (170,33611 + 15,4851 \times k_L) + (34,30332 + 3,11848 \times k_L) + (3,04901 + 0,27719 \times k_L) \times L_{dr} \times k + (0,45412 + 0,04128 \times k_L) \times L_{dr} \times k, \tag{16}$$

where $C_{tr}^{rail(e)}$, $C_{tr}^{rail(c)}$ are, respectively, the costs for transportation by carriage dispatching and in 20-pound containers, UAH; k_L is the coefficient that characterizes intensity of cargo operations; k is the coefficient of adjustment of costs of rolling stock operation depending on delivery distance; L_{dr} is the distance of delivery by railway transport, km.

$$k = 0,34269452157 \cdot e^{-0,0024963503286 \cdot L_{dr}} + 0,9004016125. \tag{17}$$

Costs for performance of cargo handling operations are formed based of direct duration of performance of these operations and a tariff rate for one hour of handling mechanism operation:

$$C_l = S_{1hour} \cdot T_l \cdot T_{day}, \tag{18}$$

where S_{1hour} is the costs of performance of cargo handling operations, UAH/h; T_l is the duration of cargo handling operations, days; T_{day} is the duration of working of a cargo handling point per day, hours.

Taking into account in (13) of costs for immobilization of money in cargo is caused by 100 % pre-payment delivery, which leads to freezing of the buyer's money in goods until the moment of their arrival at the warehouse. Calculation of this component is not strictly necessary, but considering the logistic approach to formation of a supply chain, it would be correct to include losses (even indirect) of all entities of a delivery system. According to this statement, costs for immobilization of money in cargo (goods) will be formed based on the following indicators:

$$C_{im} = f(C_{1t}, Q_{cargo}, d, T_{del}), \tag{19}$$

where C_{1t} is the costs of one ton of cargo, UAH/t; Q_{cargo} is the volume of cargo batch, ton; d is the discount rate, %; T_{del} is the delivery time, days.

During international transportation of cargoes by motor transport, the need for rolling stock insurance arises, which is a mandatory procedure for all carriers. It should be noted that the insurance period is longer than the period of a single delivery, so the amount of money, spent to purchase the insurance policy is corrected by coefficient k_{ins} , which reduced annual insurance costs to trip costs:

$$k_{ins} = \frac{T_{del}}{D_c}, \tag{20}$$

where k_{ins} is the coefficient of reduction of annual vehicles' insurance costs to trip costs; D_c is the calendar days, units.

Costs of payment for services of a transport-forwarding company (TFC), as a rule, are formed based of three main components: transportation costs, performance of cargo handling operation and insurance. The percentage of deductions of TFC is accepted equal to 10, as the average market rate.

Thus, we identified all of steps of formation of all total costs for cargo delivery in international traffic at alternative options of transportation systems, involving land kinds of transport. The next step is to conduct experimental studies of functioning

of alternative delivery options and to determine the most effective transportation option in international traffic.

5. Experimental research into efficiency of cargo transportation by land kinds of transport in international traffic

5.1. Experimental research into the character of stochastic processes of flow in supply chain

According to experimental research, we made an assumption that a queue formation at the border checkpoint is guided by the Poisson law. This is substantiated by the character of a queue formation: every car arrives independently (i. e. arrival time does not depend on arrival time of other vehicles – condition of absence of afteraction). This process takes place over a short period of time, for example, one hour. In this case, density of vehicles' arrival is constant (stationarity condition). Ordinality condition is satisfied, as every vehicle arrives separately from the others. To prove this hypothesis, field measurements were conducted at border point of Yagodin – Doroguzk. Using the method of instant observations at intervals of 20 minutes, the records keeper fixed the number of vehicles in line. Examination was performed in the period from 16.08.2016 to 19.08.2016. The resulting array of data was statistically processed in Statistica software product in order to test the hypothesis about the compliance with the Poisson law. The results are shown in Fig. 1 (Fig. 1, *a* – 16.08, Fig. 1, *b* – 17.08, Fig. 1, *c* – 18.08, Fig. 1, *d* – 19.08).

The resulting value λ was reduced to the average weighted by the parameter of level of confidence probability. Thus, the final value λ that describes the average number of vehicles that arrive for service in one hour is equal to 6.57. Queue formation and downtime of vehicles, waiting at the border checkpoint, occurs because of the number of requests for servicing exceeds the throughput capacity of the checkpoint. In this case, there arises the need to assess average downtime while waiting to be serviced, which is offered to perform by the following model [19]:

$$t_b = \frac{Z \cdot T_{shift}}{Y}, \tag{21}$$

where t_b is the time of waiting to be serviced at the border checkpoint, hours; Z is the number of vehicles in line, units; T_{shift} is the duration of a work shift at the border checkpoint, h; Y is the throughput capacity of a checkpoint, vehicle/day.

Generation of data on the number of vehicles that are waiting in a queue to be serviced, is performed using simulation of random variables in the MS Excel add-on "Random Number Generation". Array of data is modeled by the Poisson law. The resulting numerical series is subsequently used for modeling of time of waiting to be serviced at the border checkpoint according to (21).

Another parameter, which also has a stochastic nature, is motion speed of vehicles along the route. It makes direct impact on cargo transportation duration and leads to fluctuation of this time within certain limits. The nature of changes in motion speed of a vehicle in this case is important and requires to be established. To determine the law of distribution of technical speed of motor vehicles, we used the data of tachograms. The hypothesis of normality of this indicator was verified in Statistica software product. As a result, the hypothesis was not refuted with level of confidence probability equal to 0.87 and parameters of the law of distribution: mathematical expectation is 53.92 km/h and variance is 28.48 km²/h².

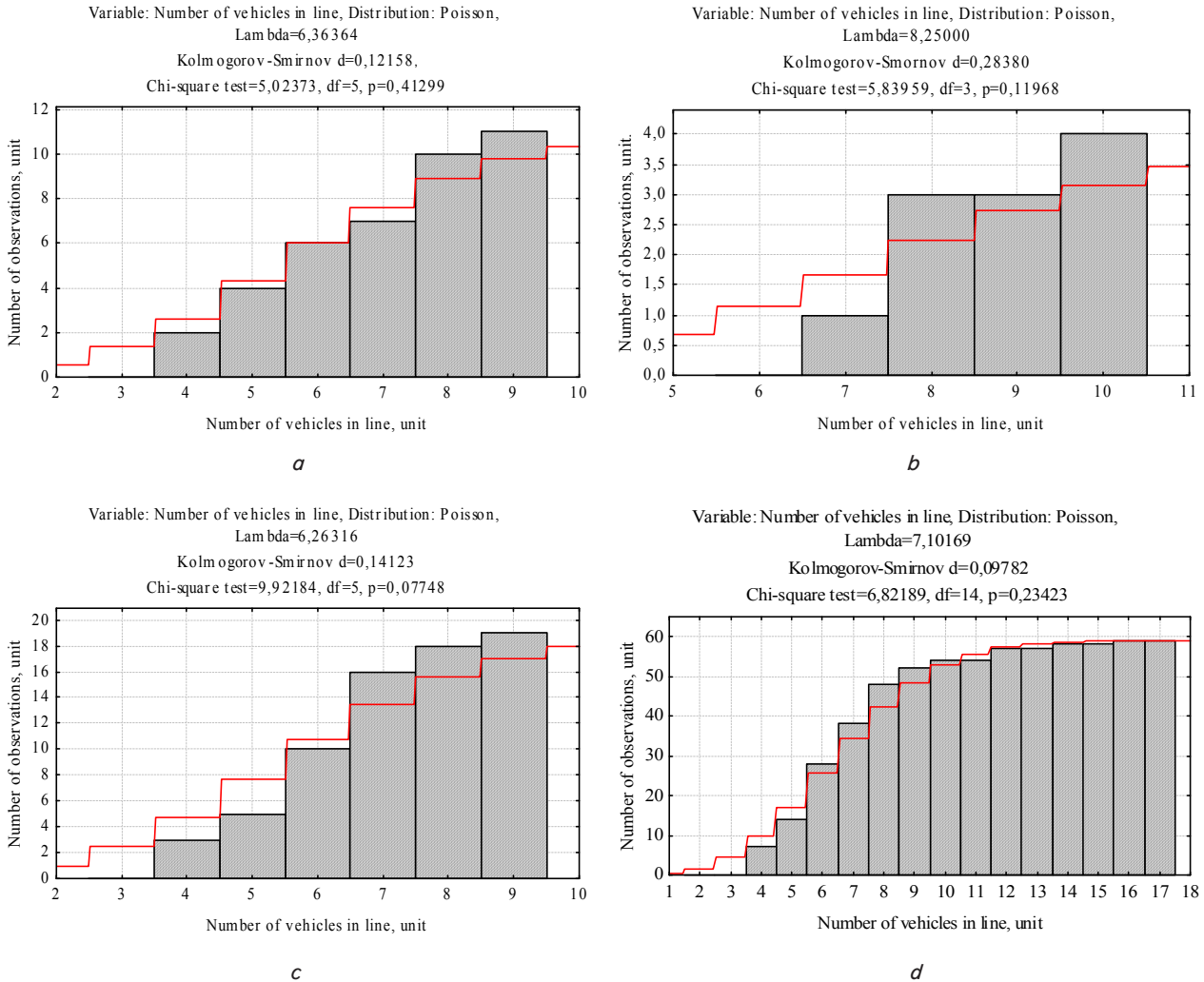


Fig. 1. Histogram of distribution of the number of trucks in queue at the border point: *a* – data as of September, 16, 2016, *b* – data as of September, 17, 2016, *c* – data as of September, 18, 2016, *d* – data as of September, 19, 2016

When using multimodal communication, there arises the need to coordinate the operation of the interacting kinds of transport in order to perform transshipment of cargo. In this case it is not possible to completely eliminate unproductive delays in motion of the material flow (temporary storage of cargo or vehicles' downtime, for example, at container transportation while waiting for loading on the train). In formation of the flow of transportation requests, the process of placement of requests is random, therefore, there arises the need to determine the law of distribution of given magnitude for prediction of duration of unproductive downtime. The fact is obvious, that the time of placement of a transportation request is a continuous random magnitude. In this case, duration of unproductive downtime at a railway station will be determined:

$$t_q = t_{depi} - t_{ari}, \tag{22}$$

where t_{depi} is the departure time of a train, hour:min; t_{ari} is the arrival time of a truck at a railway station, hour:min.

In this case t_{depi} is a determined magnitude, since keeping to the schedule is a strict requirement for the railway transport. The random nature of vehicle's arrival at a railway station is caused by the fact that placement of a transportation request is a random magnitude and vehicle's motion

duration can also fluctuate, which was cited above. Analytically, it can be represented as follows:

$$t_{ari} = \xi + t_{pi} + t_l, \tag{23}$$

where ξ is the time of placement of a transportation request, hour:min.

The law of distribution of time of placement of transportation request was determined based on processing of transportation requests of a number of transport-forwarding companies in Kharkiv (Ukraine). As a result of processing, it was found that the character of transportation request placement is equally probabilistic and does not actually depend on the day of the week. The following statistical characteristics of the given random magnitude were established with confidence probability of 0.55: parameter $a=1.083$, $b=6,974$, mathematical expectation is 4.0346, variance is 3.0032. These statistical characteristics are the basis for simulation of time of request placement at multimodal transportation.

5. 2. Experiment planning and analysis of its outcomes

To describe all possible states of a delivery system, it is advisable to apply the theory of extreme experiments planning [20], which allows us through conducting a minimal number of measurements to get reliable data about all possi-

ble states of the system. In the case of linear dependence of a resulting feature signs on factors (parameters of a model), it is sufficient to perform variation of factors at two levels (minimum and maximum). In this case, the experiment plan of 2^n type is applied. A key element in development of the plan is to determine the number of variative factor features n that will be taken into account in the experiment and numerical values of extreme states [20].

For unimodal transportations, the plan of the experiment considered downtime at the border checkpoint and transportation distance (on the example of Ukraine – Italy route). Decoded version of the plan of the experiment for examination of the unimodal route is presented in Table 1. Replication of experiments for each series is achieved by inclusion of a random magnitude in the model – technical motion speed of a vehicle.

Table 1

Decoded plan of experiment for unimodal transportation option

Number of experiment series	Factors		Response function, T_{del}
	Downtime at border checkpoint, days	Delivery distance, km	
1	0.17	2,089	$T_{av.del1}$
2	0.72	2,089	$T_{av.del2}$
3	0.17	2,279	$T_{av.del3}$
4	0.72	2,279	$T_{av.del4}$

At multimodal transportation, two systems interact: motor and railway transport. This causes the necessity of taking into account more factors in the experiment plan: supply distance, dispatch distance and section motion speed of a train. Accordingly, the plan of the experiment in the decoded form is shown in Table 2.

Table 2

Decoded plan of experiment for multimodal transportation option

Number of experiment series	Factors			Response function, T_{del}
	Supply distance, km	Dispatch distance, km	Section motion speed of train, km/h	
1	131	138	28.29	$T_{av.del1}$
2	972	138	28.29	$T_{av.del2}$
3	131	1,208	28.29	$T_{av.del3}$
4	972	1,208	28.29	$T_{av.del4}$
5	131	138	54.83	$T_{av.del5}$
6	972	138	54.83	$T_{av.del6}$
7	131	1208	54.83	$T_{av.del7}$
8	972	1208	54.83	$T_{av.del8}$

Extreme values of supply and dispatch distances were determined based on matrices of the shortest distances of main roads, respectively, of Ukraine and Italy. For Ukraine, the transport hub of cargo delivery was the city of Kyiv, for Italy, it was the terminal, situated in the city of Milan (as the biggest transport hub in Italy), from where cargo was delivered.

Within each series, we performed estimation of a required number of experiments (7) to provide the data representability. At unimodal transportation option, this value totaled 18 experiments, at multimodal option, it was 115. After the experiment was completed, the hypothesis about

normal distribution of delivery time for two options was verified. The results are summarized in Table 3.

Table 3

Results of evaluation of character of changes in delivery time

Indicator	Transportation mode	
	unimodal	multimodal
Kind of distribution law	normal	normal
Chi-square test	9.878	14.504
Number of degrees of freedom, units	12	15
Confidence probability	0.626	0.488
Mathematical expectation, days	5.63	8.29
Variance, days ²	0.369	6.016

Based on results of the experiment of research in delivery time, two types of regression models (additive and multiplicative) were constructed, respectively for unimodal and multimodal transportation.

For unimodal transportation, the additive model has the form (24), the multiplicative has the form (25). Accordingly, for multimodal transportation – (26), (27).

$$T_{uni}^a = 0,102 + 0,9717 \cdot t_b + 0,0023 \cdot L_{del}, \tag{24}$$

where L_{del} is the delivery distance, km;

$$T_{uni}^m = 0,00578 \cdot t_b^{0,065} \cdot L_{del}^{0,903}, \tag{25}$$

$$T_{multimod}^a = 8,166 + 0,0024 \cdot l_{dtr} + 0,0021 \cdot l_{dfr} - 0,0654 \cdot V_{tr}, \tag{26}$$

where l_{dtr} is the distance of cargo delivery to a railway station; l_{dfr} is the distance of cargo delivery from a railway station, km; V_{tr} is the section motion speed of a train, km/h.

$$T_{multimod}^m = 6,0496 \cdot l_{dtr}^{0,1152} \cdot l_{dfr}^{0,1356} \cdot V_{tr}^{-0,3323}. \tag{27}$$

Table 4 shows characteristics of constructed regression models.

Table 4

Statistical characteristics of regression models of delivery time

Statistical characteristics	Model			
	Additive unimodal	Multiplicative unimodal	Additive multimodal	Multiplicative multimodal
Multiple correlation factor	0.9999	0.9996	0.9963	0.9948
Determination coefficient	0.9999	0.9993	0.9927	0.9898
F significance of regression	0.0009	0.0259	0.0001	0.0002

Based on an analysis of data from Table 4, we concluded on feasibility of application of models of additive kind.

Obtained numerical values of statistical ratings enable us you to predict delivery time on condition “just in time” with the use of model (6).

Along with this, based on the developed plans of experiments, costs of cargo delivery with the use of two alternative

schemes are estimated. Accordingly, results of the experiment for determining delivery costs are shown in Table 5.

Table 5

Results of prediction of cargo delivery costs in Ukraine – Italy direction

Indicator	Transportation mode		
	Unimodal	Multimodal	
		Scheme 1 (cargo carriage)	Scheme 10.2 (container on railway platform)
Mean value of delivery costs, UAH	61394.29	52127.57	44388.62
Variance of costs, UAH ²	21836266.13	459261810.6	459261849.5
Root mean square deviation of delivery costs, UAH	4672.93	21430.39	21430.4
Lower limit of confidence interval (confidence interval 0.95), UAH	56814.82	37277.06	29538.11
Upper limit of confidence interval (confidence interval 0.95), UAH	65973.76	66978.08	59239.13

Obtained statistical ratings of delivery costs enable us to predict effectiveness of application of each type of transportation. In this case, procedure of analysis of range of interval of changes in delivery costs in a fixed direction deserves special attention.

6. Discussion of results of research into efficiency of cargo transportation by land kinds of transport in international traffic

One of the criteria of reliability of a supply system is the possibility to level a negative impact of random disturbances that occur during the technological cargo delivery process. We propose to estimate it in the framework of this study by the length of confidence interval of delivery costs. To do this, in Fig. 2, we will graphically represent results of prediction of limits of confidence interval of delivery costs in Ukraine – Italy direction.

As Fig. 2 shows, stochasticity level between the unimodal and multimodal transportation schemes is different due to differences in intensity of influence of random constituents on the outcome of delivery system functioning and their number. It is obvious that the unimodal delivery scheme is better predictable, as the number of constituent elements in it is smaller than in the multimodal system. It is one of the major advantages, but, as it can be seen from Fig. 2, the left boundary (optimistic forecast) of possible delivery costs when using the motor traffic is located significantly to the right on the horizontal axis when multimodal transportation schemes are applied. As a result, economic effect at the optimistic forecast will be equal to UAH 19,537.76

and 27,276.71 per one trip for multimodal systems “cargo carriage” and “container platform” respectively.

But “pessimistic” assessment of financial outcome is more effective for economic forecasts, as it allows us to take into consideration unpredictable risks and to guarantee company’s loss-free activity. With this strategy of transportation effectiveness assessment, we get the following: UAH – 1,004.32 and 6,734.63 per one trip for multimodal systems “cargo carriage” and “container platform” respectively. Therefore, efficiency of application of a multimodal transportation option significantly decreases, which could be used at large volumes of transportation under condition of a linear increase in increment of effectiveness per one shipment (20-ton motor vehicle). In this case, we should take into consideration cargo delivery duration. Prediction of this indicator under conditions of functioning of “just in time” system for a unimodal system (motor transport) allows us to reduce time of vehicles’ rotation by 47 % (according to Table 3). This provides a higher delivery speed at an increase of costs only by 10.2 % (compared with unimodal and multimodal service “container platform”). In the case of application of the multimodal scheme “cargo carriage”, for example, when transporting unit-pack cargoes, application efficiency in comparison with the unimodal system is 1.5 %, i. e. it is not loss-free and ineffective. Thus, in the case of forecasting with consideration of all possible risks, the multimodal system “container platform” is the most attractive by the economic component. But it is considerably inferior to the unimodal transportation by the criterion of delivery time “just in time”.

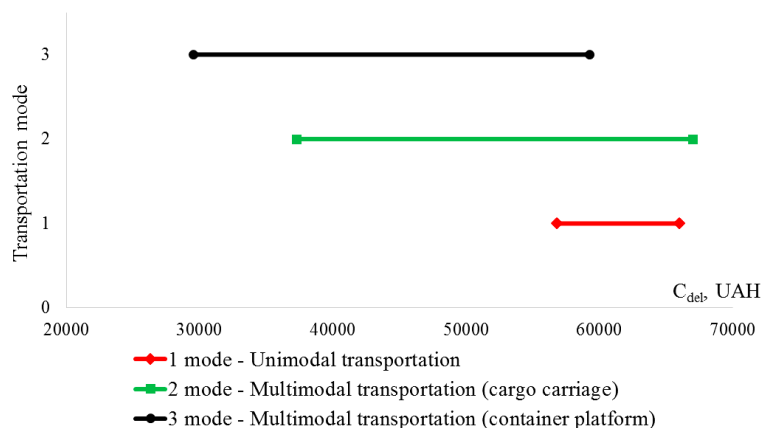


Fig. 2. Lengths of confidence intervals for delivery costs at various transportation schemes

Thus, the obtained results make it possible to use a more flexible approach to evaluation of economic efficiency of application of the unimodal or multimodal cargo transportation system over long distances. Unlike most of the existing research in this area, the authors offered the interval evaluation of possible cargo delivery costs and presented the level of variation of this total indicator depending on a transportation mode (unimodal or multimodal). It was experimentally proved that common scientific opinion about high efficiency of multimodal transportations based on railway transport can in practice be invalid in the case of a complex negative impact of a number of random characteristics. In the framework of this research, their number was insignificant, but even under such conditions, it was shown that reliability of a transportation system involving two or more kinds of transport can give economic result that may

significantly differ from the expected result, obtained with the common deterministic approach.

One of the shortcomings of this research is description of the factor space of only one transportation direction Ukraine – Italy. Its choice was due to existence of steady cargo traffic between the two countries, and a considerable delivery distance. This implies covering by the model and the results of the experiment of all other cargo-forming or cargo-absorbing points that are located on the route Ukraine – Italy. However, the type of the chosen object of research, at which only one major consigner and recipient of the goods formally exists, states a linear problem. This is a certain simplification of the structure of the object of research in the transport sector. Selection of this option of the material supply system can be explained the first step in solving the problem of construction of efficient integrated transport systems involving several kinds of transport and assessment of their effectiveness. The developed models require subsequent trial on a more powerful polygon of material services, on which costs optimization problem should be transformed from a linear to a matrix type, in which the number of consigners and recipients of products is more than one, and their spatial diversification is significant.

7. Conclusions

1. Conducted on-site observations of the truck service process at the border point of Yagodin – Doroguzk became the basis for verification of the hypothesis about formation a vehicles' queue according the Poisson law. For all days of measurements hypothesis was not rejected. The average number of vehicles in line amounted to 6.57. Along with this, it was experimentally proved that technical motion speed of trucks is a normally distributed random magnitude. Placement of requests for transportation in the international traffic obeys the uniform law.

2. It was proposed to estimate delivery time on condition "just in time" based on formation of confidence interval for mathematical expectation. For its construction, the Chebyshev inequality was taken as a basis. The model takes into account stochastic parameters of the transport process,

particularly: vehicles' motion speed along the route, fluctuations in time of passage of border checkpoints and delays in motion of the material flow at variation of time of placement of transportation requests and the schedule of railway trains.

3. Mathematical models for prediction of amount of cargo delivery costs for unimodal and multimodal transportation were implemented with the use of the additive method based on functional units: transportation costs, performance of cargo handling operations, costs of a buyer for immobilization of money in cargo, insurance costs and payment for services to transport-forwarding companies. Developed models of prediction of delivery costs are linear, all their components, listed above, have the same level of hierarchy, and therefore have a vertical relationship of additive type.

4. To predict total cargo delivery costs in direction Ukraine – Italy, type 2ⁿ plan was selected, since functional relationship between the factors and costs has a linear nature. For the unimodal transportation, downtime at the border checkpoint and delivery distance were accepted as factor features. For the multimodal transportation, respectively, they included supply distance, dispatch distance and section motion speed of a train. Replication of experiments in the study of unimodal delivery system was made by simulation of technical motion speed of trucks. At multimodal transportation, stochastic nature of the transportation requests placement was taken into account. It was experimentally proved that this significantly affects the amplitude of changes in total delivery costs and effectiveness of multimodal transportations.

5. The proposed interval estimation of total delivery costs allows generation of the optimistic and pessimistic scenarios of the supply system. It was proved that widespread information about high efficiency of multimodal communication when shipping distances are more than 500 kilometers is relevant under strictly deterministic conditions of delivery system functioning. In the framework of this research it was proved that the influence of random factors leads to a significant decrease in efficiency of cargo transportation by the multimodal system. And even at the distance of 2,300 kilometers, the unimodal delivery system, based on heavy-duty trucks, can compete with it.

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