Mathematical Modeling of Multimodal Transportation Risks

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Abstract

Research has shown that the risks of multimodal transportation depend as both on stochastic and fuzzy parameters.
Mathematical vehicles for the stochastic and fuzzy quantities are different. Therefore, a mathematical model is suggested to evaluate for the integral risk of cargo transportation. This makes it possible to use this model in support systems while making decisions on logistics of multimodal transportation. The use of a mathematical model requires careful analysis of all risks attributed to the multimodal transportation chain, possible overload options, and taking into account the entire spectrum of control activities.
After determining the most appropriate, from the point of view of risk minimization, the mode of transportation and its first links, the next stage of dynamic risk management is recursive review of the status vector of the chosen variant of the specified transportation route. For this information system it is necessary to process large data sets, while the suggested model economically uses computer resources and reduces the calculation time. The given mathematical model allows real-time changes in the transportation risk at specific stage to offer options for reducing integral risk, leverage it, in particular, choosing other routes and types of transport.

Keywords

Mathematical model - Multimodal transportation - Risks - Big data - Fuzzy variables - Stochastic parameters - Time-discretization - Dynamic system

Mathematical Modeling of Multimodal Transportation Risks

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Mathematical vehicles for the stochastic and fuzzy quantities are different. Therefore, a mathematical model is suggested to evaluate for the integral risk of cargo transportation. This makes it possible to use this model in support systems while making decisions on logistics of multimodal transportation. The use of a mathematical model requires careful analysis of all risks attributed to the multimodal transportation chain, possible overload options, and taking into account the entire spectrum of control activities.

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Keywords: Mathematical model · Multimodal transportation · Risks · Big data · Fuzzy variables · Stochastic parameters · Time-discretization · Dynamic system

1 Introduction

Multimodal transport can be considered as a system of separate subsystems. In this case, the subsystems are: the types of transport for the carriage of goods, points of overload, temporary warehousing, information support of transportation. From the point of view of multimodal transportation, as dynamic system for each level of cargo

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transportation, it is possible to consider different variants of use of separate subsystems, in particular: vehicles, routes of transportation, etc., changing them in real time.

The risks of transportation at each transportation stage for each of the subsystems can lead to an increase in the total cost of transportation, in an increase in the time of transportation, in the damage or loss of cargo. Therefore, it is advisable to choose variants of transport ways, in general, and variants of their stages with the lowest risks.

The mathematical formalization of multimodal traffic begins with a description of risks within a complex multilevel hierarchical system.

Determining the risks of multimodal traffic across Ukraine is complicated by the fact that these risks depend not only on deterministic values, but also on non-deterministic, stochastic ones. However, the task become even more complicated due to the fact that the distribution of risk probability could not be evaluated or risk could not be identified. Therefore, in the risk analysis, it is necessary to operate fuzzy values as well. The use of the apparatus of mathematical statistics and probability theory, suitable for the processing of stochastic data, for fuzzy values is not entirely correct. There is a logical question on which mathematical means to apply for the definition and prediction of integral risks of multimodal transportation of cargoes.

There are studies devoted to the analysis of risks during transportation, in particular, during multi-modal transportation, both in the presence of purely vague variables of these risks [1–4], and in the presence of strictly viable parameters of transportation risks [5–8]. In addition, there are well-known studies on finding and forecasting risks for specified routes or certain types of transport [9–14]. While, for example, logistic companies, which are planning multimodal transportation through Ukraine, in view of the presence of systemic risks in their practical work, must also take into account the backup route options at certain stages of transportation, so that they can be changed, if necessary. Therefore, mathematical models for computerized decision support systems (DSS) for the transportation of goods, their transshipment, the selection of the most efficient routes should be based upon dynamic mathematical models. Such models should include not only possible changes in the modes of transportation or in the routes of goods delivery at certain their parts, but also, it is desirable to point out to the main controlling factors to reduce the possibility or consequences of certain issues arising from the transportation of multimodal cargo. Therefore, the purpose of this work was to construct a mathematical model for a dynamic system of support and decision making of multimodal transportation taking into account both the risks depending on stochastic parameters and the risks determined by fuzzy variables.

Therefore, the purpose of this work was to build a mathematical model for a dynamic system of support of and decision making in multimodal transportations with the use of an effective method of finding integral risk in the conditions of stochastic and fuzzy local risk parameters.

2 The Mathematical Modeling of Multimodal Transport Risks

Since the task of multimodal transportation is hierarchical, at the first stage it is possible, using the principle of decomposition, to identify those units where the risk parameters are fuzzy values, which, do not require information from other parts of the transport chain to evaluate the risks of the traffic. Then the risks of transportation of cargoes at such links can be determined only with the use of methods of fuzzy logic. The principle of decomposition consists in the formal replacement of the task of finding the transportation risk of the selected option of the transport chain by the equivalent set of tasks of transportation by individual links of the specified chain. The execution of decomposition is carried out according to a certain algorithm. The first of the decomposition stages is the transformation of the selected route of cargo transportation into a formalized system suitable for the decomposition, the separation of individual subsystems according to selected features. The criterion for the relevance of the selection of individual subsystems will be such risk values, which will be in line with the risks of systems that include the whole set of subsystems. This can be determined without calculating the specific values of the risks of both systems and their respective subsystems. To do this we use the following method. When the risk-determining parameters are represented by a universal set X, then the fuzzy set A will be a set of sets $(x|\mu_{\mathrm{A}}(x))$ for $x \in \mathrm{X}$. Value of the function of belonging μ_{A} comply with $\mu_{\mathrm{A}} : \mathrm{X} \to [0, 1]$, and for a separate set $(x|\mu_{\mathrm{A}}(x))_i$ it shows the degree of affiliation of a particular value $\mu_{\mathrm{A}i}$ to the fuzzy set A. Then the statement of the problem of finding the minimum risk value, which is determined by the fuzzy set of parameters A, will take the form:

$$\min_x U(x) \quad \text{provided}\, x \in X \tag{1}$$

An implicit set can be used to solve a problem:

$$\{x^* : U(x^*) \geq U(x)\} \text{ provided } x \in \mathrm{X} \text{ and } x^* \in \mathrm{X} \tag{2}$$

This expression indicates that there may not be a single solution to the problem, but a set of such solutions, which corresponds to the purpose of the study. Since this expression formalizes the division of the system into subsystems, but does not determine the composition of sub-elements of subsystems, this expression can be considered in terms of the formation of compressed sets. The compression of a set X can be made in a tangent manner, so that the global minimum of the target function corresponds not only to the set X, but also to the compressed set for which the following is true:

$$V(X) \subset X \tag{3}$$

where $V(X)$- compressed set.

Moreover,

$$V(X) = \{x^* : U(x^*) \geq U(x)\} \text{ provided } x \in \mathrm{X} \tag{4}$$

As shown by the analysis of the multimodal transportation risks, which are determined by fuzzy variables, these variables can be described as fuzzy numbers of (L-R)-type. The membership function μ_A of such numbers is given using functions $L(x)$ and $R(x)$. These are functions of real variables which do not increase within the set of nonnegative numbers and have the following properties:

$$1.\ \ L(-x) = L(x); R(-x) = R(x); \tag{5}$$

$$2.\ \ L(0) = R(0)$$

where $x \in [c, d]$. Dots c - left limit and d - right limit of interval of fuzziness.

Accordingly, $[a, b] \in [c, d]$, where a, b the left limit and the right limit are the tolerance interval, respectively. Then the membership function can be reduced to an algebraic expression as follows:

$$\mu_{\mathrm{A}}(x) = \begin{cases} L[^{(a-x)}/_{c} & \text{for the case } x \in [(a-c), a]] \\ R[^{(x-b)}/_{d} & \text{for the case } x \in [b, (b+d)] \\ 1, & \text{for the case } x \in [a, b] \\ 0, & \text{for the case } x \notin [a, b] \end{cases} \tag{6}$$

Using the theory of graphs, multimodal transportation can be described as a coherent indicative graph. Each of its vertices can be divided into sets of vertices in such a way that the generated by the specified procedure subgraphs are also connected. Thus, it is possible to form the mathematical basis for the decomposition of multimodal transportation. An approximate graph can be represented in analytical form by the tensor equation of the following form:

$$WQ = V \tag{7}$$

where the tensor $\boldsymbol{W}$ - the probability of a certain traffic flow at certain stages of the entire route of carriage in a given time interval, the tensor $\boldsymbol{Q}$ - bandwidth of each individual section of the chain of transportation, tensor $\boldsymbol{V}$ - stochastic characteristic of the possibility of passing goods by each individual section of the chain of transportation.

The possibility of passing the cargo by a separate section of the chain of transportation is characterized by a matrix of vectors

$$\vec{\vartheta} := \varphi(\mathrm{P}, \vec{\tau}) \tag{8}$$

where $\vec{\vartheta}$ - the vector for estimating each of the set of event risk, can be represented by a linear matrix; P - the significance of the probability of the relevant risk factor; $\vec{\tau}$ - vector of consequences of specified risk.

It should be taken into account, that the consequences of this risk may vary, depending on its specific value. The risks of multimodal transportation are a dynamically system dispersed in time, which is characterized by the fact that the dimension of the vector of traffic graph is bigger than the vector of input parameters, on which the risk of transportation of cargo depends during the whole chain of transportation. After determining the most appropriate, from the point of view of risks minimization, the mode of transportation and its first links, the stage of dynamic risk management comes through. It includes the recursive reviewing of the status vector of the chosen variant of the specified transportation route. In our opinion, the most expedient mathematical tool for this, is the Kalman filter, because it is, unlike other filters, suitable not only and not so much for finding the vector of the state of the transport graph, but for controlling the uncertainty of the vector. Kalman's filter uses the Bayes theorem, which organically describes the dependencies between risks of each of the stages of multimodal transportation. That is, the probability of an event on the previous section of the chain of the carriage rout, denote it as $\boldsymbol{A}$, and the probability of the risk of transportation on it, respectively, denote ***P(A)***, affects the probability value on the next section of the chain, denote the section as $\boldsymbol{B}$, and the probability of transportation risk on it, respectively, ***P(B)***. Then, as it is known, according to Bayes' theorem, when the probability of transportation risk is $\boldsymbol{P}(\boldsymbol{A}) \neq \boldsymbol{0}$, $P(B|A) = P(A|B)P(B)/P(A)$. Then, according to the Bayes theorem, in the case when the probability of the transportation risk $\boldsymbol{P}(\boldsymbol{A}) \neq \boldsymbol{0}$. It is advisable to use the Kalman filter, which is widely used in economics for DSGE-simulation [9]. In this case, the mathematical model of multimodal transportation should take into account the fact inherent to the multimodal transportation of goods for which the state of carriage process in stage $\boldsymbol{B}$ depends on the state of the carriage process in the preceding stage $\boldsymbol{A}$. Then for the state vector of the transportation stage $\vec{Y}_A$, for which a certain static set is characteristic risks, can be written in form:

$$\overrightarrow{Y_A} = \overrightarrow{U_A}\overrightarrow{X}_B + \overrightarrow{W_A}\overrightarrow{s_A} + \overrightarrow{z_A} \tag{9}$$

where $\overrightarrow{U_A}$ - vector of change of the transportation process, inherent to the process of transportation at the stage B, $\overrightarrow{W_A}$ - control vector, which is accompanied by a matrix (set) of control actions $\overrightarrow{s_A}$, $\boldsymbol{w_k}$ - the Gaussian set of transportation risks, which is characterized by the risk matrix of the entire transport chain $\boldsymbol{\delta}$, the diagonal of which is the dispersion of the components of the specified risk vector, and outside of the diagonal there are the covariances of the risk components. For the risk matrix of the entire transport chain, $\mathbf{cov}(\mathbf{X}) \geq 0$. The initial state and the vectors of individual risk components of the entire transportation chain are independent values. The use of this method requires careful analysis of all risks on the multimodal transportation chain, possible overloads, and taking into account the entire spectrum of control activities. Without such an analysis, the use of the Kalman filter is not appropriate. This method allows to construct a system of control of the process of multimodal transportation with the dynamic change of individual parts of the chain of cargo transportation, depending on the risks increase at certain stages or changes in transportation conditions. Thus, one can in real time, taking control over the effects on the transportation process $\overrightarrow{s_A}$, reduce the risks, and achieve the minimization of the target function of cargo transportation - the cost of transportation, time or damage to the cargo. In the case, when functions $L(x)$

and $R(x)$ are linear functions, the fuzzy number is described as a trapezoidal, in particular, a triangular number.

The weight of each risk or the risk of each of the stages of transportation is the proportion of its impact on the value of the integral risk, that is, in an analytical form:

$$f_{sum} = \sum a_i \times f_i \tag{10}$$

where f_i - the value of i-th risk, or the risk of the i-th stage of transportation, a_i - weight of i-th risk.

Graphic interpretation of the search for integral risk consisting of two components is shown in Fig. 1.

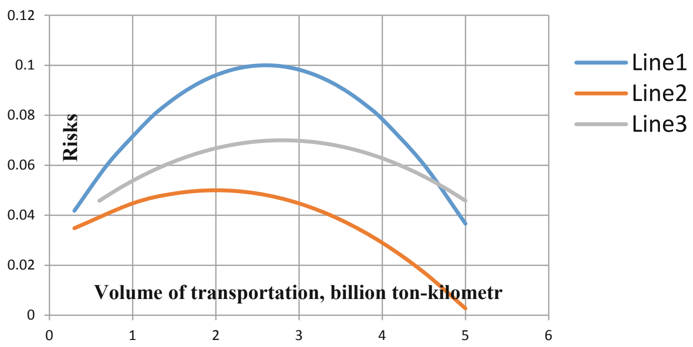

Fig. 1. Graphical interpretation of the search for integral risk consisting of two components. Row 1 - Transshipment risk, Row 2 - Tariff Risk, Row 3 - Integral Risk

The analysis of finding the integral risk of transportation including two risks, which have the biggest weight, related to tariff and transshipment of multimodal cargoes (Fig. 1), is characterized by the fact that the first one is stochastic and the second one is fuzzy. That is, this analysis clearly demonstrates the workability of the mathematical model, since the mathematical apparatus for calculating these risks are different, however, according to the suggested approach, they allow finding the integral risk of multimodal transportation. Handling risks were calculated for the ports of Yuzhkiy, Odessa, Chernomorsk, Kherson and Mariupol. The factors, that affect the risk of transshipment through each of these ports, are different and the risk magnitude for the ports varies significantly. After the risk assessment of routes passing through the named ports this allowed choosing the most efficient route in real time. For demonstration purposes (Fig. 1), the total risk of freight re-roll over the country's Black Sea ports is calculated as a sub-integral risk that combines local stochastic risks of transshipment through each of the named ports. Practical implementation of the model foresees the separate assessment of the risks of routes passing through so-called ports. A characteristic feature of local risks (Fig. 1) is their maximization for certain values of the multimodal turnover of the country. Reducing the value of integral risk by reducing its component - the risk of transshipment through the ports with an unacceptable risk level and the subsequent reorientation of cargo to other ports- made it possible to find levels of risk acceptable for maintaining the volume of cargo flows.

As the test of the DSS based on the suggested mathematical apparatus showed, increase in integrated risk of multimodal transportation (see Fig. 2) leads to an increase in the cost of transportation (line 1) at the interval of its real change, which, in turn, due to the competition between the Black Sea ports of other countries, gives the foreseen result - a decrease in the volume of bulk cargo (line 3) and container transportation (line 2). Thus, the integral risk of transportation makes it possible to predict not only the cost indicators, but also the volumes of total freight turnover and freight turnover by individual types of cargo.

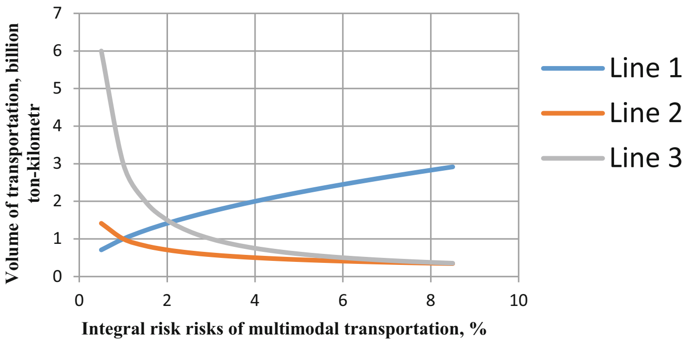

Fig. 2. Dependence of transportation costs and volume of bulk and container cargo on integrated risk

For this information system it is necessary to process large data arrays and the suggested model economically uses computer resources, reduces the calculation time. The given mathematical model allows real-time changes in the risk of transportation at some stage to offer options for reducing integral risk, leverage for this, in particular, to indicate other routes and modes of transportation.

The mathematical model was tested for the analysis of the transport of grain from the elevators of Kremenchuk to the ports of Odesa and the city of Chornomorsk. This made it possible to identify the risks at each stage of grain handling. It is revealed that at the stage of using the services of the railway company “Ukrzaliznytsya”, risks associated with transportation, tariff policy of the company-monopolist, regulatory risks of transportation can take undesirable values. The alternative option is suggested - use river transport at separate stages, this will increase the cost of transportation of grain by around 5%, but will reduce the consequences of the risk fluctuations for the integral risk value in their range of changes.

An alternative option is recommended - use river transport at separate stages, this will increase the costs by 5%, but will reduce the impact of tariff risk on the value of integrated risk. The practical results obtained confirmed the adequacy of the suggested mathematical model.

3 Conclusion and Future Work

The study showed that the risks of multimodal transport depend both on stochastic quantities and fuzzy parameters. Since it is not possible to use a single mathematical device to handle such risks, a mathematical model for calculating the integral risk of multimodal transportation of goods is suggested, which allows using different mathematical approaches for calculating different types of local risks at individual stages of transportation. The application of this mathematical model implies the need for a thorough risk analysis at each stage of the entire multimodal transportation chain. In addition, we must take into account all possible overload options, develop a list of all spectrum of control actions. This allows, first, to establish the most expedient way of transportation, based on minimal integral risk and the accompanying economic consequences from the point of view of minimizing risks. It is also possible at each link of the entire route of transportation to manage risks dynamically, by recursively reviewing the status vector of the selected version of the specified transportation path.

Since the task involves the processing of large data sets, it is extremely useful, when applying the developed mathematical model, to have the possibility of economic use of computer resources, to reduce the calculation time. Pilot application of the given mathematical model, as the core of the system of support and decision making for finding the best solutions when choosing a variant of the way of multimodal transportation, is promising. For the practical work of the logistics center, there is an opportunity with the means of suggested model to choose the variant of the transportation route with the lowest integral risk, as well as to manage its levers, and to choose other routes and modes of transportation. The test trials of the core of the system of support and decision-making proved the correlation between the increase in the integral risk of multimodal transportation and the cost of transportation, reduced transportation of bulk cargo and container traffic for the seaports of Odesa and Chornomorsk.

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