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Original Article

MODEL OF TRANSPORT SAFETY ASSESSMENT IN MULTIMODAL TRANSPORTATION SYSTEMS

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Highlights:

- safety level as a key factor in transportation route design;
- analysis of multimodal transportation safety assessment challenges;
- development of a new methodology for transport safety assessment;
- practical validation of purposed mathematical model.

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Abstract. In this paper methods, criteria and models of safety assessment of multimodal transportation systems are investigated. Today, new types of transportation systems are formed – multimodal transportation systems, which may be defined as the result of the synthesis of several transport systems, where different modes of transport are effectively interact. The need for such systems was formed due to the peculiarities of each mode of transport, its technological and technical characteristics, which restrain the ability to compete and promote transport interaction. In this context, the problem of transport safety assess of multimodal freight transportations becomes highly important. An analysis of modern scientific researches on topic of transport safety is conducted. Unfortunately, the considered approaches to transport safety have a set of disadvantages if the complex systems are considered in form of, for example, combined, multimodal or intermodal transportations: the problem of local optimum; the problem of safety management in case of transport company is not the actual infrastructure owner; the problem of unifying estimates for several modes of transport, and so on. The system's safety depends on its integrity and sustainable development, which is directly dependent on the objective conditions of its formation, development and operation. At the same time, the state of safety is directly dependent on subjective factors, the purpose of which is to ensure security, i.e., to preserve the integrity and maintain sustainable development and optimal functioning of the system. Thus, there is a conditional field of protection of transport system objects, which provides counteraction to a set of existing or perceived threats. In this context, modelling the transport safety assessment of multimodal freight is relevant and requires appropriate scientific developments. In the research, methods of mathematical modelling of transport systems were used in order to develop methodological approach that could be potentially used in improving the multimodal freight transportation safety. A methodical approach to safety assessment on the example of multimodal transportation, which takes into account the drawbacks of existing studies, is proposed. The practical application of developed model was demonstrated on the existing system of multimodal transportation. The developed safety assessment method may be potentially used both to assess the transportation route safety level and as key factor in optimal transportation route designing.

Keywords: transport safety, aviation safety, multimodal transportation, assessment, risk, reliability, critical failure.

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Notations

AMS – Amsterdam Schiphol Airport;
ATH – Eleftherios Venizelos Athens International Airport;
ES – emergency situations;
GR PIR – Seaport of Piraeus;
IEV – Igor Sikorsky Kyiv International Airport;
LIM – Jorge Chávez Lima International Airport;
NL RTM – Seaport of Rotterdam;
SAS – specialized airport services;
UA ODS – Seaport of Odesa;
US NYC – Seaport of New York and New Jersey;
USD – United States dollar.

Introduction

In world practice, the creation of integrated transportation systems in the form of intermodal and multimodal systems is an integral condition for the foreign trade relations development. Such systems are aimed to accelerate, reduce costs and simplify freight operations with consolidated standard cargo units. Multimodal transportation ensures the continuity of transportation process and requires not only organizational interaction of its participants, including shippers and consignees, but also integrated development of material and technical base of interacting modes of transport, introduction of common technologies, integration of communication systems and information. Logistic system's state assessment should be considered as the basis for technological operations planning of multimodal transportation. It allows the multimodal transportation operator to comprehensively approach the management of various transport modes and traffic optimization in order to reduce the total time of "door-to-door" delivery (Sokolova *et al.* 2021). With the increasing demand for multimodal transportation, the issue of transport safety assessment is becoming more important, particularly in preservation of cargo and vehicles in each section of the transportation process (Yanchuk *et al.* 2021).

The concept of "transport safety" is defined as a state of protection of transport infrastructure, which allows to ensure national security and national interests in the field of transport, sustainability of transport activities, the ability to prevent harm to human health and life, damage to property and the environment, and minimize economic loss during transport activities (Petrova *et al.* 2017). In the last decade, there is a clear trend of increasing the number of natural, man-made, social hazards that lead to emergencies or disasters that cause significant damage to the environment. In the transport sector, the risks are caused by: the high level of road accidents, the increasing of negative impact of transport on the environment, the reduction of the level of occupational safety on vehicles and transport infrastructure, the wear of vehicles and transport infrastructure, climate changes, etc.

The concept of "transport safety of multimodal transportation" covers a number of areas of safety: aviation safety and safety of road, rail, sea and pipeline modes of transport. In recent years, passengers processing at the airport have been constantly changing due to the implementation of different innovative technologies, directed to the improving aviation safety (Ivannikova *et al.* 2021). In this context, modelling the transport safety assessment of multimodal freight is relevant and requires appropriate scientific developments.

Analysis of scientific research about the transport safety assessment of foreign and domestic authors showed a variety of approaches to transport safety assessment. Basically, there are two recommended ways to approach the safety level assessment of transportation systems. On the one hand, it is necessary to 1st consider safety from the "positive" side – to evaluate the "reliability" (Huang *et al.* 2020), or "sustainability" (Wang 2019). Reliability characterizes the system's ability to maintain the properties necessary to fulfil a given purpose and function during a given period of time under defined conditions. Sustainability may be explained as an ability to maintain its current state and perform its functions under the influence of external factors and obstacles. On the other hand, safety assessment may be evaluated from the "negative" side. Those methods compare "safety" with concepts of incomplete or partial safety, which are described as "vulnerability" (Kumar, Xu 2017), or "risk" (Bogdane *et al.* 2019), or "danger" (Toan, Thuy 2022), or "threat" (Rodrigues 2021). In those methods, the "quality" concept plays an important role. In safety context, "quality" may be considered as the state of object protection from unauthorized interference – threats. It should be noted that there is a direct correlation between the quality of object's protection and its vulnerability, which means that the insufficient quality of the object's protection is its vulnerability (Hadj-Mabrouk 2020).

However, most of the modern methods of transport safety assessment are based on risk theory (Yanchuk, Pron 2020). A risk event as a mathematical category is a discrete event with dual properties such as probability and losses. Then the risk assessment as the amount of system's danger with the predicted risk event is set with points or indicators by risk analysis matrices (Nordfjærn, Rundmo 2018).

It is also worth to mention the methods that use "human factor" concept, due to its decisive importance in transport industry (Papadimitriou *et al.* 2020). Those methods are significantly different from the classical approach, which is primarily related to mathematical modelling, since the formalization of subject area is extremely complicated because of used mathematical apparatus. It requires the application of informal approaches, such as: heuristic and qualitative methods in combination with decision-making theory and systems engineering (Singh *et al.* 2022).

The main disadvantages of analysed approaches to transport system safety assessment may be presented as follows:

- ***problem of local modelling***: safety assessment is specific to single infrastructure object (or mode of transport) and should not be compared with other ones; in other words, the statement that transport hub with a higher safety rate and lower operations is "safer" than transport hub with a lower safety rate and a higher operation is not correct; therefore, it is necessary to expand models by a certain weighing coefficient, which takes into account the peculiarities of enterprises production indicators;
- ***problem of one-sidedness of transportation process safety assessment***: most of analysed methods purpose either the transport hub safety assessment, or risk events assessment on transportation routes; since multimodal transportation is characterized by the presence of a transport hub capable of several transport modes handling, in order to evaluate such system safety rate, it is necessary to conduct a symbiotic safety assessment at each stage of transportation process;

- ***problem of safety management***: analysed methods are appropriate only for transport companies that actually control the transport infrastructure; for other companies that do not affect safety level, but only use handling services, the issue of designing optimal transportation from the point of view of security becomes relevant.

Nevertheless, in the context of the multifaceted diversity of risk events inherent in multimodal transportation, the methodological aspects of emergency risk assessment and optimal multimodal route selection according to the level of transport safety remain insufficiently studied.

1. Method

The transportation process in multimodal system consists of successive stages of delivery and reloading of goods from one transport vehicle to another with their inclusion in the general transportation system. That is why multimodal transportation should be considered as a complex system, which is characterized by the integrated development of all modes of transport, terminal and warehousing, information and telecommunication technologies for freight traffic, and so on.

The purposed method for transport safety assessment modelling of multimodal transportation consists of transport hub safety assessment and risk assessment of critical failures on transportation routes. The 1st step is to estimate the reliability of transport hubs on a multimodal route.

The application of reliability theory for technical and information systems is common. It is clear that the elements of technical systems and elements of social information systems have different nature, properties and dependencies, but without related research, it is unfounded to claim that there are no possible analogies for characteristics of reliability. The processes that occur in them are complex random processes, which are associated with failures of various subsystems. Therefore, the subsystem reliability modelling requires the use of the concepts "redundant non-recoverable systems", "redundant recoverable systems", "non-redundant non-recoverable systems", "non-redundant recoverable systems" and related integral higher-order calculations, which are quite difficult to interpret (Rausand *et al.* 2020).

Hypothetically, transport infrastructure security system in transport hubs could be considered as a non-redundant recoverable system. For a non-redundant recoverable system, main reliability indices are: readiness coefficient K_r – the final probability of the system to be operational at any time; readiness function $K_r(t)$ mean time between failures T; system recovery time T_r; failure rate parameter $\omega(t)$. There are the following relations between these indices:

$$K_r = \frac{T}{T + T_r}; \tag{1}$$

$$K_r = \lim_{t\to\infty} K_r(t). \tag{2}$$

Reliability indices of recoverable and non-recoverable systems are related by the following integral equation:

$$\omega(t) = f(t) + \int_0^t \left(\omega(\tau)\cdot f(t-\tau)\right) d\tau, \tag{3}$$

where: $f(t)$ is the density of the time distribution before the failure of non-recoverable systems.

The solution of this integral equation does not allow to obtain the existing dependence of the readiness function on such indicators of system reliability as: probability of failure, failure rate, failure time, average recovery time, etc.

However, given that the security system is a combination of n-elements, the stationary indicators of the recovery system reliability can be expressed through the average operation time between failures and the average recovery time of system elements. The mean time between failures T, the average recovery time T_r and the readiness coefficient K_r are determined by equations:

$$T = \frac{1}{\sum_{i=1}^{n} \frac{1}{T_i}}; \tag{4}$$

$$T_r = \frac{\sum_{i=1}^{n} \frac{T_{ri}}{T_i}}{\sum_{i=1}^{n} \frac{1}{T_i}}; \tag{5}$$

$$K_r = \frac{1}{1 + \sum_{i=1}^{n} \frac{T_{ri}}{T_i}}. \tag{6}$$

In most practical cases, the system failure rate λ_s and the recovery rate μ_s of recoverable systems are known. Then reliability indices are:

$$T = \frac{1}{\lambda_s} = \frac{1}{\sum_{i=1}^{n} \lambda_i}, \tag{7}$$

where: λ_i – failure rate of system's i element;

$$T_r = \frac{1}{\lambda_s} \cdot \sum_{i=1}^{n} \frac{\lambda_i}{\mu_i}, \tag{8}$$

where: μ_i – recovery rate of system's i element;

$$K_r = \frac{T}{T + T_r} = \frac{1}{1 + \sum_{i=1}^{n} \frac{\lambda_i}{\mu_i}}; \tag{9}$$

$$K_r(t) = \frac{\mu_s}{\lambda_s + \mu_s} + \frac{\lambda_s}{\lambda_s + \mu_s} \cdot \exp\left(-\left(\lambda_s + \mu_s\right)\cdot t\right). \tag{10}$$

The readiness coefficient K_r and the readiness function $K_r(t)$ therefore can be hypothetically considered as certain assessments of transport safety.

The next step is to assess the statistical risk of critical failures on multimodal routes as a result of emergencies. Due to the lack of failures statistics, the risk may be overestimated/underestimated. Taking into account that not every emergency leads to a critical failure of elements (damage/destruction of vehicle or cargo, death of passengers or crew) the following algorithm supplements existing risk models.

Calculation of a priori probabilities of ES. The probability may be calculated as the ratio of the number of vehicles caught in the emergency N_a on a route l to the total number of vehicles passing through the route N_l:

$$P_j^s = \frac{\sum_l N_a}{\sum_l N_l}. \tag{11}$$

The calculation of the weighted average probabilities of events j (ES) occurrence using expert estimates is performed by the equations:

$$P_j^m = \frac{P_j^s + P_j^e}{2}; \tag{12}$$

$$\delta^2 = \frac{\left(P_j^s - P_j^e\right)^2}{2}; \tag{13}$$

$$P_j = \frac{P_j^s + 4 \cdot P_j^m + P_j^e}{\delta}, \tag{14}$$

where: P_j is the weighted average probability of occurrence of events j; P_j^s – a priori statistical probability of events j occurrence; P_j^m – the most probable value of events j; P_j^e – a priori (expert) value of the probability of events j occurrence; δ – dispersion coefficient.

The intensity of critical failures i for the time period T can be calculated using statistics for each section of the route l by the equation:

$$\gamma_{ij} = \frac{\sum_l N_i}{T \cdot \sum_l N_l}. \tag{15}$$

The probability of failure i during event j can be calculated by the equation:

$$P_{ij} = 1 - \exp\left(-\gamma_{ij} \cdot T\right). \tag{16}$$

Then probability of critical failures:

$$R_{ij} = \sum P_{ij} \cdot P_j. \tag{17}$$

The formalized methodological approach requires some adjustment, namely:

- the comparison of readiness coefficients of several transport hubs among themselves is not entirely appropriate, because the number of operations (cargo handling) can be different. In this case, the statement that transport hub with a higher value of readiness coefficient and a lower freight turnover is more reliable than transport hub with a lower safety index and a higher freight turnover is not correct. Therefore, a weighting coefficient based on the number of handled cargos of the transport hubs is introduced. This coefficient should be multiplied by readiness coefficient of transport hub in order to get comparative coefficient of readiness;
- the minimization of critical failures risk causes the need to mirror the safety indicator in order to operate the developed model for general optimization – minimization.

Developed transport safety assessments require methodological expansion by supplementing with criteria for transportation time (higher value of transportation time – higher risk) and transportation costs (transport company commercial component) (Table 1).

In order to obtain the relative values of the estimation factors of multimodal routes, it is necessary to apply the method of weights (Table 2).

The next step is to analyse the formed table of assessment factors using the criteria of decision-making in conditions of uncertainty (Gilboa *et al.* 2020), namely:

- Laplace criterion:

$$\bar{F} = F\left(\bar{X}, Y\right) = \min_{1 \le i \le m} \left(\frac{1}{n}\right) \cdot \sum_{j=1}^{n} a_{ij}; \tag{18}$$

- Wald's criterion:

$$\bar{F} = F\left(\bar{X}, Y\right) = \min_{1 \le i \le m} \max_{1 \le j \le n} a_{ij}; \tag{19}$$

- Hurwitz criterion. "Optimism coefficient" a is introduced within $0 \le \alpha \le 1$:

$$\bar{F} = F\left(\bar{X}, Y\right) = \min_{1 \le i \le m} \left(\alpha \cdot \min_{1 \le j \le n} a_{ij} + (1 - \alpha) \cdot \max_{1 \le j \le n} a_{ij}\right); \tag{20}$$

- Savage's criterion:

$$\bar{F} = F\left(\bar{X}, Y\right) = \min_{1 \le i \le m} \max_{1 \le j \le n} \left(a_{ij} - \min_{1 \le i \le m} a_j\right). \tag{21}$$

The multimodal route, which occurs most often as a result of using these criteria can be defined as optimal.

Table 1. Absolute values of multimodal routes assessment factors

Route	Time [h] $T \rightarrow \min$	Costs $C \rightarrow \min$	Risk $R_{ij} \rightarrow \min$	Non-safety on transport hub $(1 - K_r) \rightarrow \min$
MR_1	T_1	C_1	R_{ij1}	$(1 - K_r)_1$
MR_2	T_2	C_2	R_{ij2}	$(1 - K_r)_2$
…	…	…	…	…
MR_n	$\mathrm{T_n}$	C_n	$\mathrm{R_{ijn}}$	$(1 - K_r)_n$

Table 2. Relative values of multimodal routes assessment factors

Route	Time [h] $T \rightarrow \min$	Costs $C \rightarrow \min$	Risk $R_{ij} \rightarrow \min$	Non-safety on transport hub $(1 - K_r) \rightarrow \min$
MR_1	$\frac{T_1}{\max(T)}$	$\frac{C_1}{\max(C)}$	$\frac{R_{ij}{}^1}{\max(R_{ij})}$	$\frac{(1-K_r)_1}{\max(1-K_r)}$
MR_2	$\frac{T_2}{\max(T)}$	$\frac{C_2}{\max(C)}$	$\frac{R_{ij}{}^2}{\max(R_{ij})}$	$\frac{(1-K_r)_2}{\max(1-K_r)}$
…	…	…	…	…
MR_n	$\frac{T_n}{\max(T)}$	$\frac{C_n}{\max(C)}$	$\frac{R_{ij}{}^n}{\max(R_{ij})}$	$\frac{(1-K_r)_n}{\max(1-K_r)}$

2. Results

For practical application of the foregoing algorithm, three multimodal freight transportation routes were considered (Figure 1):

- multimodal route No 1 (MR_1): US NYC → NL RTM → AMS → IEV → warehouse.
- multimodal route No 2 (MR_2): US NYC → GR PIR → ATH → IEV → warehouse;
- multimodal route No 3 (MR_3): LIM → ATH → GR PIR → UA ODS → warehouse.

The transport hub's reliability assessment is based on the processing of statistical information on safety system failures of transport companies that have a direct or potential impact on the level of safety of transported freight.

Statistical information on security failures was obtained during the study of transport company annual reports, namely: RSG (2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020), LAP (2023), AIA (2014, 2015, 2016, 2017, 2018, 2019, 2020), PANYNJ (2014, 2015, 2016, 2017, 2018, 2019, 2020), PoR (2023), PPA (2014, 2015, 2016, 2017, 2018, 2019, 2020). Based on expert estimates and operational incidents in the performance of similar traffic flow hubs, hypothetical baseline data for the IEV and the UA ODS (MIU 2017) were formed (Table 3).

Based on statistical data, the system (a division of SAS) was analysed, which consists of the following elements: aviation security service; customs service; immigration service; health service; paramilitary police; airport security department. It was decided to choose 1 day as a unit of time in the evaluation process. These considerations lead to the following table of element failures (Table 4).

Table 3. Relative values of multimodal route assessment factors

Transport hub	Operating incidents	Acts of unlawful interference	Other
US NYC	83	19	0
LIM	146	25	5
NL RTM	46	9	0
GR PIR	82	0	0
ATH	111	0	0
AMS (13 years)	1	426	1
IEV	0	16	1
UA ODS	61	19	0

Table 4. Element failure rate

Element number	Failure rate λ_i [1/h]
1	0.08999
2	0
3	0
4	0
5	0.08999
6	0.00021

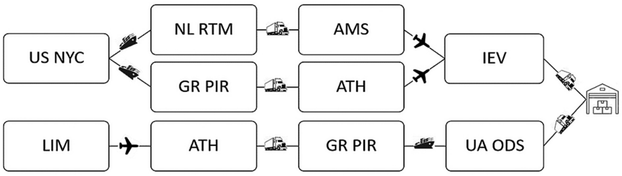

Figure 1. Scheme of route alternatives for multimodal freight transportation

System failure rate λ_s:

$$\lambda_s = 0.08999 + 0.08999 + 0.00021 = 0.18019 \tag{22}$$

for initial simplification, it was hypothesized that the recovery time of the studied system is the same and equal to 0.411 years, i.e., 150 days, therefore the intensity of the elements recovery μ is equal to 0.0316 days. Then the mean time between failures, the average recovery time and the readiness coefficient (Equations (7–9)) are equal to:

$$T = \frac{1}{\lambda_s} = \frac{1}{0.18019} = 5.5497 \approx 6 \quad \text{[days]}; \tag{23}$$

$$T_r = \frac{1}{\mu_s} = \frac{1}{0.0316} = 31.646 \approx 32 \quad \text{[days]}; \tag{24}$$

$$K_r = \frac{T}{T + T_r} = \frac{5.5497}{5.5497 + 31.646} = 0.1492. \tag{25}$$

The system may be considered as one element with failure rate λ_s and recovery rate μ_s, since the intensities of the elements recovery are the same. According to Equation (10):

$$K_r(t) = \frac{\mu_s}{\lambda_s + \mu_s} + \frac{\lambda_s}{\lambda_s + \mu_s} \cdot \exp\left(-\left(\lambda_s + \mu\right) \cdot t\right) =$$

$$\frac{0.0316}{0.21179} + \frac{0.18019}{0.21179} \cdot \exp\left(-0.21179 \cdot t\right). \tag{26}$$

The tabulated from 0 to 365 function (number of days in the one year) in 30-day increments (Table 5).

The transition time is 44 days is obtained from graph (Figure 2) of the readiness function (dynamic probability that the system is operational at any point of time *t*). The coefficient of readiness (final probability that the system is operational) is $K_r(t)$ = 0.1492.

The reliability of other transport hubs on multimodal routes is calculated similarly (Table 6).

A weighting factor is introduced, which is determined by calculating the share of turnover of each point in the system of transport hubs (Table 7).

Comparative values of non-safety ($1 - K_r$) of transport hubs are defined as the difference between one and the result of multiplying the coefficient of readiness of the transport hub and its weighting factor. Comparative value of non-safety of multimodal route is arithmetic mean of comparative values of non-safety of transport hubs (Table 8).

Therefore, multimodal route No 1 in terms of reliability of transport hubs is the safest.

The risk assessment is thereafter performed on the selected multimodal routes. During the review of scientific researches, a priori (expert) assessment of the risk of emergencies (Table 9) was determined.

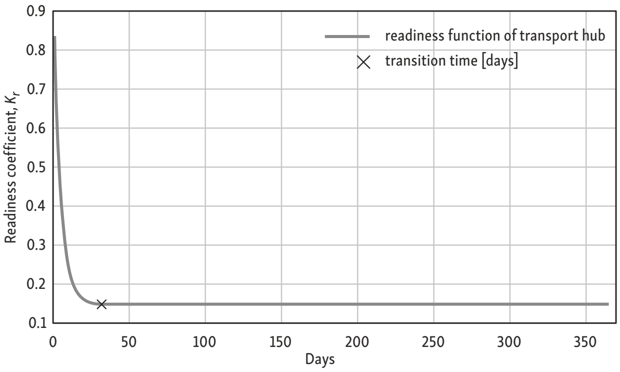

Figure 2. The readiness function of the SAS system of AMS

Table 5. The readiness function of the SAS system of AMS

Time t [days]	Readiness coefficient $K_r(t)$
0	1
30	0.1511
60	0.1492
90	0.1492
120	0.1492
150	0.1492
180	0.1492
210	0.1492
240	0.1492
270	0.1492
300	0.1492
330	0.1492
360	0.1492

Table 6. Reliability of transport hubs

Transport hub	Mean time between failures [days]	Average recovery time [days]	Transition value [days]
US NYC	18.2482 ≈ 18	12.1667 ≈ 12	62
NL RTM	17.0561 ≈ 17	12.1667 ≈ 12	61
AMS	5.5497 ≈ 6	31.646 ≈ 32	44
IEV	55.2853 ≈ 55	12.1667 ≈ 12	76
GR PIR	25.3485 ≈ 25	12.1667 ≈ 12	68
ATH	13.519 ≈ 14	12.1667 ≈ 12	56
LIM	6.6845 ≈ 18	12.1667 ≈ 12	39
UA ODS	22.2519 ≈ 55	12.1667 ≈ 12	66

Table 7. Weighting coefficient of transport operations

Transport hub	Weighting coefficient
AMS	0.0023
IEV	0.00024813
LIM	0.00038656
ATH	0.1209
US NYC	0.1110
NL RTM	0.6125
GR PIR	0.1244
UA ODS	0.0283

Table 8. Comparative values of non-safety of multimodal routes

Route	Non-safety on transport hub $(1 - K_r) \rightarrow \min$
MR_1	0.8939
MR_2	0.9464
MR_3	0.9585

Table 9. A priori (expert) assessment

Transportation	A priori (expert) assessment
Maritime	$3 \cdot 10^{-3}$
Road	$7.1 \cdot 10^{-3}$
Air	$1 \cdot 10^{-5}$

Statistical information on the number of vehicles involved in an accident or catastrophe on the route (Table 10) was obtained during the study of data from the statistical service of ICAO (2023), accident statistics in Ukraine (PPU 2021) and reports of EMSA (2018).

Based on Equations (11–17) the probability of risk of an accident or catastrophe in sea transportation US NYC → NL RTM is calculated by types of failures:

$$\gamma_{dmg} = \frac{N_{dmg}}{T_i \cdot S_T} = \frac{11537}{12777 \cdot 7} = 0.129, \tag{27}$$

where: γ_{dmg} – the intensity of damage to the vehicle in the event of an emergency during transportation; N_{dmg} – number of vehicles damaged in emergencies during transportation; T_i – period of studying the system, years; S_t – the number of vehicles in ES during transportation.

The probability of damage to the vehicle in emergency:

$$P_{dmg} = 1 - \exp\left(-\gamma_{dmg} \cdot T_i\right) = 0.595. \tag{28}$$

The risk of damage to the vehicle during transportation:

$$R_{dmg} = R_{exp} \cdot P_{dmg} = 0.003 \cdot 0.595 = 0.001785\,. \tag{29}$$

Similarly, calculate the risk of destruction of the vehicle during transportation:

$$\gamma_{dst} = \frac{N_{dst}}{T_i \cdot S_T} = \frac{91}{12777 \cdot 7} = 0.0010; \tag{30}$$

$$P_{dst} = 1 - \exp\left(-\gamma_{dst} \cdot T_i\right) = 0.00698; \tag{31}$$

$$R_{dst} = R_{exp} \cdot P_{dst} = 0.00698 \cdot 0.003 = 0.00002094. \tag{32}$$

The risk of a transport accident or catastrophe on the US NYC → NL RTM is determined by adding up the values of the risk of critical failures in emergency:

$$R_1 = R_{dmg} + R_{dst} = 0.0018. \tag{33}$$

The risk of a transport accident or catastrophe is calculated similarly for each type of multimodal route (Table 11).

Therefore, multimodal route №3 in terms of the risk of critical failures in an emergency is the safest.

Table 10. Obtained statistics of the risk of failures during the transportations

Transportation	Failures in the event of an emergency				Expert risk assessment
	Vehicle damage	Destruction of the vehicle	Fatal failures	Total number of emergencies	
US NYC → NL RTM	11537	91	0	12777	$3 \cdot 10^{-3}$
US NYC → GR PIR	4388	33	0	12777	$3 \cdot 10^{-3}$
GR PIR → UA ODS	4186	28	0	4636	$3 \cdot 10^{-3}$
NL RTM → AMS	15875	0	480	220321	$7.1 \cdot 10^{-3}$
ATH → GR PIR	17342	0	331	315124	$7.1 \cdot 10^{-3}$
LIM → ATH	0	0	0	0	$1 \cdot 10^{-5}$
AMS → IEV	0	0	0	0	$1 \cdot 10^{-5}$
ATH → IEV	0	0	0	0	$1 \cdot 10^{-5}$
IEV → warehouse	2590	0	138	78823	$7.1 \cdot 10^{-3}$
UA ODS → warehouse	229	0	49	15740	$7.1 \cdot 10^{-3}$

In order to analyse the optimality of a multimodal route and choose the “best” for a given indicator, it is firstly necessary to develop a summary table of factors for multimodal routes assessment, based on shipping time and costs, the reliability of transport hubs on the route and the risk of critical failures in emergency (Table 12 and Table 13).

Table 11. The value of risk on multimodal routes

Route	The value of risk
MR_1	0.0026
MR_2	0.0024
MR_3	0.0023

Table 12. Absolute values of factors of multimodal routs assessment

Route	Shipping time [h]	Shipping costs [USD]	Risk	Non-safety in transport hub
MR_1	15.62	4012.69	0.0026	0.8939
MR_2	17.4	3833.55	0.0024	0.9464
MR_3	17.45	4117.41	0.0023	0.9585

Table 13. Relative values of factors of multimodal routs assessment

Route	Shipping time [h]	Shipping costs [USD]	Risk	Non-safety in transport hub
MR_1	0.8951	0.9746	1	0.9326
MR_2	0.9971	0.9311	0.95522	0.9874
MR_3	1	1	0.9055	1

Table 14. Results of the analysis by the criteria of decision-making in conditions of uncertainty

Criterion	MR_1	MR_2	MR_3
Laplace	1.2674	1.2893	1.3018
Savage	0.1049	0.0661	0.0945
Hurwitz	0.3266	0.3526	0.3339
Wald	0	0.0029	0

The next step is to analyse the formed table of assessment factors of multimodal routes using the criteria of decision-making in conditions of uncertainty (Equations (18–21)). Results of the analysis are presented in Table 14.

According to results of calculations, the multimodal route No 1 is the optimal route from the point of view of transport safety: US NYC → NL RTM → AMS → IEV → warehouse. Shipping costs are 4012.69 USD, shipping time is 15.62 days.

3. Discussion

During the model development, the main shortcomings of existing safety assessment methods were taken into account, in particular: problem of local assessment modelling was solved by weighting coefficient (number of handled cargo); a combined safety assessment was developed that takes into account all aspects of multimodal transportation process: both operations in transport hubs and transportation between them; in order for the model to be applicable to companies that do not actually conduct a safety management, an algorithm for safe routes designing was developed based on suggested safety assessments, time factor and delivery costs.

The practical use of the proposed method allows at the designing stage of multimodal transportation routes to evaluate their alternatives, according to the selected criteria and take the necessary measures in order to improve transport safety. Another advantage of purposed approach is that the accuracy and calculation method is not affected by a transportation graph expand. Although, in that case, the evaluation time would be significantly increased. However, this problem may be solved by a program code development for automated calculation, for example, in MATLAB (*https://www.mathworks.com/products/matlab.html*) or *RStudio* (*https://posit.co/products/open-source/rstudio/*).

It should be noted that the issue of the accuracy of the recovery time parameter of transport enterprise’s safety system in case of various types of failures is debatable due to the fact that transport companies do not form the necessary database of statistical data and do not take into account the time features of the security system recovery period for various types of failures.

Conclusions

The economy globalization and modern supply chains development caused the creation of a transportation product that combines the services of various modes of transport in the most efficient and convenient way in form of multimodal transportation systems.

Unfortunately, the issue of transport safety assessment for multimodal transportation remains unstudied, because it is rather inaccurate to use existing approaches to safety assessment formation. Modern researches on this topic often focuses on single aspect of transportation process (for example, only the expert's risk assessment of transportation routes), neglecting others (for example, the assessment of transport hubs safety). For multimodal transportation systems, it is crucial to conduct a combined safety assessment, since transportation from one multimodal terminal to another may be performed by different modes of transport. Another disadvantage of the existing methods is the single-levelling problem, which make it impossible to conduct a comparative analysis of several transport hubs without corresponding balancing coefficients. In addition, in cases, where a transport company is not the actual owner of transport infrastructure, but appears as a user of handling services of 2nd parties and, therefore, makes no influence the safety management, the only way to ensure the cargo preservation is to develop an optimal route from the safety point of view from existing alternatives. The development of methods for transport safety assessment remains a complex scientific task, which depends on the economic efficiency and safety of transportation process.

The developed during research method takes into account disadvantages of mentioned approaches and consists of several steps (it should be also noted that the method was tested on existing system of multimodal transportation):

- reliability assessment of transport hubs on multimodal routes. The evaluation was clearly demonstrated on example of AMS. The results showed the following: readiness coefficient $K_r(t)$ (final probability that the system is operational) is 0.1492; the transition time of the readiness function (dynamic probability that the system is operational at any point of time t) is 44 days; average recovery time is 32 days. In order for estimates to be comparative, a weighting factor was introduced that takes into account the amount of cargo flow handled at airport. Similarly, the reliability of other transport hubs on each multimodal transportation route was evaluated and analysed;
- risk assessment on multimodal routes. The purposed method takes into account both expert and probabilistic assessments of critical failure risk. The practical application was clearly demonstrated during risk assessment of accidents and catastrophes on US NYC → NL RTM transportation route. The obtain risk probability is 0.0018. Similarly, the risk assessments on other multimodal transportation routes were conducted;
- integrated assessment and optimal safe route selection. The purposed method was extended by introducing delivery time and costs parameters. Then criteria of decision-making in conditions of uncertainty were used, namely: Laplace criterion, Wald's criterion, Hurwitz criterion and Savage's criterion. It should be noted that the reliability assessment of transport hub was mirrored, so the optimization function of each system's element was aimed at minimization. Thus, at this stage, a certain assessment of non-safety $(1 - K_r)$ was used. The results showed that MR_1 is the optimal multimodal transportation route from the transport safety point of view: US NYC → NL RTM → AMS → IEV → warehouse. Shipping costs is 4012.69 USD, shipping time is 15.62 days.

Nevertheless, conducted study of transport safety assessment shows the need to further address a number of methodological and methodical issues related to the definition of principles, criteria and rules for improving the safety of integrated transport systems. In this context, it should be emphasized that the development of a system requirements, approaches and methods of transport safety assessment, which are adapted for all modes of transport in integrated transport systems are key steps to ensure the complex safety during transportation, sustainability of transport activities, prevention of harm to people's health and lives, prevention of damage to property and the environment, minimization of economic loss during transport activities.

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