Mathematical formalization of transport safety assessment

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Abstract. Integrated transport systems are a perfect form of transportation organization, because they allow integrated use of competing modes of transport, providing a high level of transportation service at affordable prices and savings in transportation costs. The development of a methodology for assessing the risks of traffic safety violations, adapted for all types of transport in multimodal transport, is substantiated. In this paper the methods of transport safety assessment of the integrated system on the example of multimodal transportations are investigated. According to those methods, the parameters that may affect the security status of the system should be identified, then numerical indicators and dependencies between the parameters should be assessed. The analysis of mathematical models of vulnerability and risk is carried out. Vulnerability models are based on qualimetric assessment models and use the analogy of "quality" and "vulnerability". In the risk model, the term "transport safety" is considered through the term "aviation safety", i.e., through the concept of the risk of emergencies (terrorist act, system failure, accident), in accordance with the recommendations of international standards.

1. Introduction

In the process of technical progress, it becomes increasingly difficult to achieve a high enough level of transport safety, which allows to ensure national security and interests in the field of transport activities. The international community is gradually expanding and modernizing the methods and techniques needed to quantify transport safety, especially over the last 10-15 years. In general, the transport system includes many infrastructures, such as international corridors, roads, transport vehicles and hubs, etc. Since transport safety is the state of the transport system, its assessment includes the safety assessments of various transport infrastructures. In research we focused on transport hub's safety assessment.

Today, there are several main approaches to transport safety assessment, based on the analysis of the transport process by certain factors. According to the approaches, the parameters that may affect the security status of the system should be identified, and then an assessment of their numerical indicators and the relations between them should be conducted [1, 2].

2. Literature review and problem statement

"Transport safety" is the state of protection of transport infrastructure, which allows to ensure national security and national interest in transport activities, sustainability of transport activities, the ability to prevent harm to human health and life, damage to property and the environment, minimize economic damage transport activities.

For research of those indicators it is recommended to carry out an assessment of safety of transport hubs by means of mathematical models taking into account such indicators, as reliability, security [3], sustainability [4], survivability, vulnerability [5, 6], danger [7], risk [8, 9], threat and quality.

3. The aim and objectives of research

The aim of the article is to study contemporary mathematical models of transport safety assessment at transport hubs.

4. Presentation of the main material

4.1. Mathematical model of risks

This model of safety assessment of transport hubs is based on risk assessment in aviation security.

A risk event (R) as a mathematical category is a discrete event with dual properties such as chances and losses. Then the risk assessment (R) as the amount of danger in the system with the predicted risk event $(\tilde{R})$ is set by a set of relevant indicators, and then integrated, for example in points or indicators using risk analysis matrices [10].

The mathematical characteristic that reflects the physical nature of the risk follows from the concept of dividing the space of Ω-results into events ω_0 , ω_1 :

$$\Omega = \omega_0 \cup \omega_1 \cup \emptyset. \tag{1}$$

$$\omega_0 = A \tag{2}$$

$$\omega_1 = \bar{A} \equiv R \tag{3}$$

where ω_0 - a class of events that are safe; $\bar{A}$ - an event that is inverse to ω_0 (dangerous), $R \equiv R_{\sum j} = \cup R_j$ - class of events in the group $R_{\sum j}$, composed of events R_j.

Formulas 1-3 justify the practical application of risk matrices according to ICAO, i.e., the matrix gives the value of randomness (and losses) for only one event - the result $\bar{A} \equiv R = R_{\sum j}$ without a detailed construction of the general set of events. Given the rarity of events of class ω_1, it is necessary to assess the degree of randomness of this event expertly, for example, to "guess" its value without a general set of events. In this case, the matrix will be only one, and the results of the assessment of risks may be several.

With this in mind, it is proposed to consider the risk matrices of «The Boeing Company» as an example (table 1).

Table 1. The Boeing Company Illegal Intervention Risk Matrix

Risk of terrorism	Risk of danger to transport objects		
	High	Medium	Low
High	1	2	3
Medium	4	5	6
Low	7	8	9

It is proposed to find a risk indicator without probability in the form:

$$\hat{R} = f(K, U);\ K = 1,..,5;\ U = A,..,E \quad (4)$$

However, the integral risk R does not coincide with the simplest concept of medium risk, because the probability of a risk event is "almost zero".

Corollary 1. The value of risk according to the concept of risk, is, formally, estimated through a two- or three-dimensional set of indicators in the form of:

$$R = \{\mu_1, H_R | \sum o\} \quad (5)$$

or

$$R = \{\mu_1, \mu_2, \widetilde{H}_R | \sum o\} \quad (6)$$

where μ_1 - expected value of risk of the 1st kind in the form of an indicator of randomness or uncertainty of occurrence of a risk event which can be measured expertly (rarely, often, etc.) without a probabilistic category; $\widetilde{H}_R$ - measure of consequences or damage; μ_2 - measure of risk of the 2nd kind in the system due to system failures; $\sum o$ - conditions of experience during operation of the system, including scenarios of events in case of accident or catastrophe.

Corollary 2. In hazardous situations with a probability of "almost zero" results, it is recommended to assess the risk by relative and conditional indicators only by the amount of possible damage (loss), such as insurance or earthquake impact assessments.

According to international standards, the security of the system in the presence of a threat is defined through risk as the state of the system with an acceptable value of risk assessment ($\tilde{R}_*$) in a possible risk event R, i.e., under the condition $\tilde{R} \leq \tilde{R}_*$. Based on the integrated indicator $\hat{R}$ with the critical value $\hat{R}_*$ according to formulas 5-6, the safety condition will be:

$$\tilde{R} \to \tilde{R}_* \Rightarrow \hat{R}_* = \{\tilde{R}_{*j}\} \quad (7)$$

$$\hat{R}_* = f_R(\tilde{R}_* | \sum o) \equiv f_R(\mu_{1*}, \mu_{2*}, \widetilde{H}_* | \sum o) \quad (8)$$

where f_R - set of elements (formula 5), for example in points or indicators.

The integral value of $\hat{R}$ (level) of risk assessment in formula 8 can also be found by assigning the advantages $\tilde{R} \to \hat{R}(\tilde{R})$ for objects such as terminals, runways, fuel depots, technical services, etc.

4.2. Mathematical model of vulnerability

The proposed concept of the model of "vulnerability" is based on qualimetric evaluation models and uses the analogy of the concepts of "quality" and "vulnerability": both are the degree of correspondence between the requirements and the actual characteristics [11].

The concept of "vulnerability" of the object (f) is defined as the state of the object of civil aviation (CA) and the system of its aviation security (AS), which assumes the possibility of acts of unlawful interference (AUI) in its activities and the threat of the object CA. The "vulnerability" model includes a model of the object of protection, which is formed as a set of models combined into a threat model and a set of models combined into a protection model. Then the parameters of the vulnerability model are quantified and used in the model of integration of airport security for adaptive integration management.

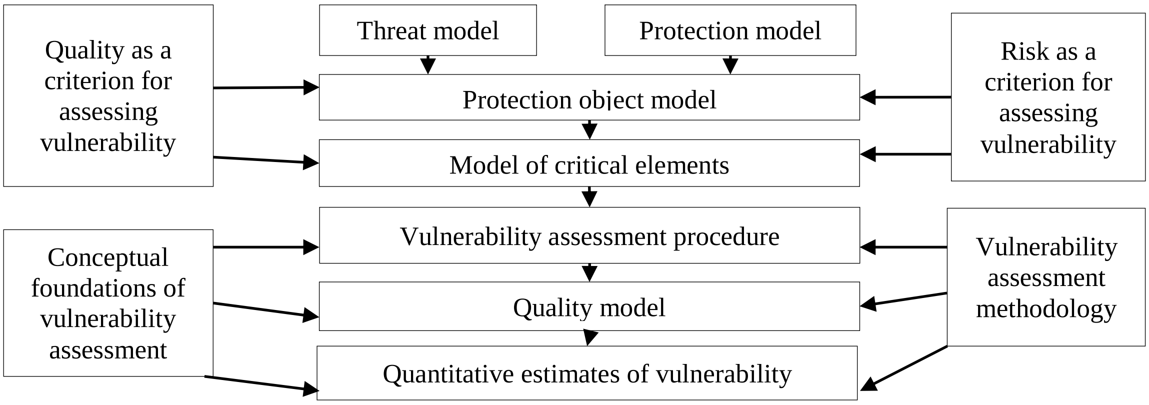

Figure 1. Structural and logical model of "vulnerability"

A critical element (CE) is an element of an object that completely or partially ceases to function because of acts of unlawful interference. A quality indicator QI_{CE} is assigned to each CE. Appropriate requirements can be formulated for each CE – $A_1 \div A_m$. On the other hand, the protection is provided by $B_1 \div AB_m$, which must meet these requirements.

In this procedure, an expert assessment of the degree of compliance of the protection with the requirements is being held. As a result, the quantitative assessments of quality indicators $AB_1 \div AB_m$ are setted. These estimates are complexed, scaled and given in the form of a quantitative value of the quality indicator QI_{CE}, which belongs to the studied critical element. In analytical form, the quality model is described by a convolution scheme that includes weight coefficients:

$$\left\{ \begin{array}{l} QI_{TD} = \mathcal{L}_1 QI_{TD_1} + \cdots + \mathcal{L}_n QI_{CE_n} + \mathcal{L}_m QI_{CE_m} \\ QI_{CE1} = \mathcal{L}_1 QI_{CE_1} + \cdots + \mathcal{L}_{1K} QI_{CE_{1K}} \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ QI_{CEm} = \mathcal{L}_{m1} QI_{CEm_1} + \cdots + \mathcal{L}_{mr} QI_{CE_{mr}} \\ QI_{CEn1} = \mathcal{L}_{n1} QI_{KEn_1} + \cdots + \mathcal{L}_{nb} QI_{CE_{nb}} \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ QI_{CEnp} = \mathcal{L}_{np1} QI_{CEnp1} + \cdots + \mathcal{L}_{npz} QI_{CE_{npz}} \end{array} \right. \quad (9)$$

The hierarchical structure of indicators of quality of protection of critical elements:

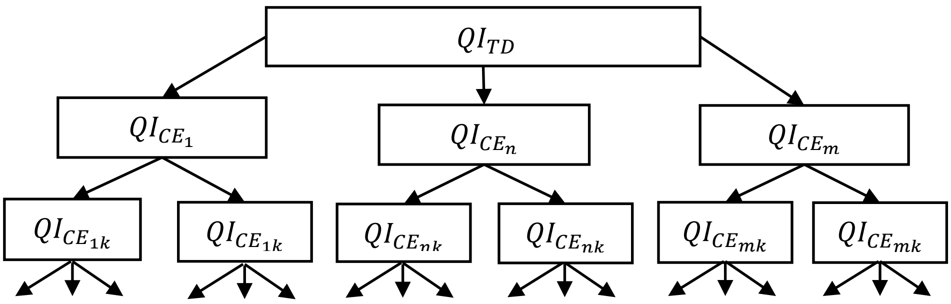

Figure 2. Hierarchical structure of quality protection indicators of critical elements

In the transition to quantitative assessments of vulnerability, it is possible to assert the identity of the concepts of "quality" and "vulnerability" only if the concept of "risk" finds its place in the structure of the concept of "quality".

Today there are many approaches to risk assessment, for example:

$$R = P_i \sum_{i=1}^{n} Q_i S_i \tag{10}$$

where R – quantitative risk assessment; P_i – the probability of a dangerous event; S_i - an indicator of the severity of the i consequences; Q_i – the probability of the consequence i as a result of a dangerous event.

There is also an approach to risk analysis from the view of system vulnerabilities. The mathematical vulnerability V is defined as the conditional probability of the output of the final state of the system with a given region ε_0 of the space of states Ω_m in the event that the event H:

$$V = P[(||KC_n - KC_0||) > \varepsilon_0 | H] \tag{11}$$

In this case, the method of risk assessment should be considered taking into account the production conditions of a particular transport hub. It becomes more important to solve the problem of using risk as one of the criteria for assessing vulnerability, i.e. to solve the problem of embedding quantitative risks in the structure of qualimetric vulnerability assessments. It is proposed to solve this problem through the weight coefficient in the scheme of convolution of indicators:

$$\mu_j = \prod_{i=j}^{p} \beta_i \Big/ \sum_{j=1}^{p} \prod_{i=j}^{p} \beta_i \tag{12}$$

where $B = (\beta_1, \beta_2, .., \beta_p)$ - risk assessment vector; $M = (\mu_1, \mu_2, .., \mu_p)$ - weight coefficient vector.

The algorithm of practical implementation of qualimetric assessment of transport hub's vulnerability is presented in figure 3.

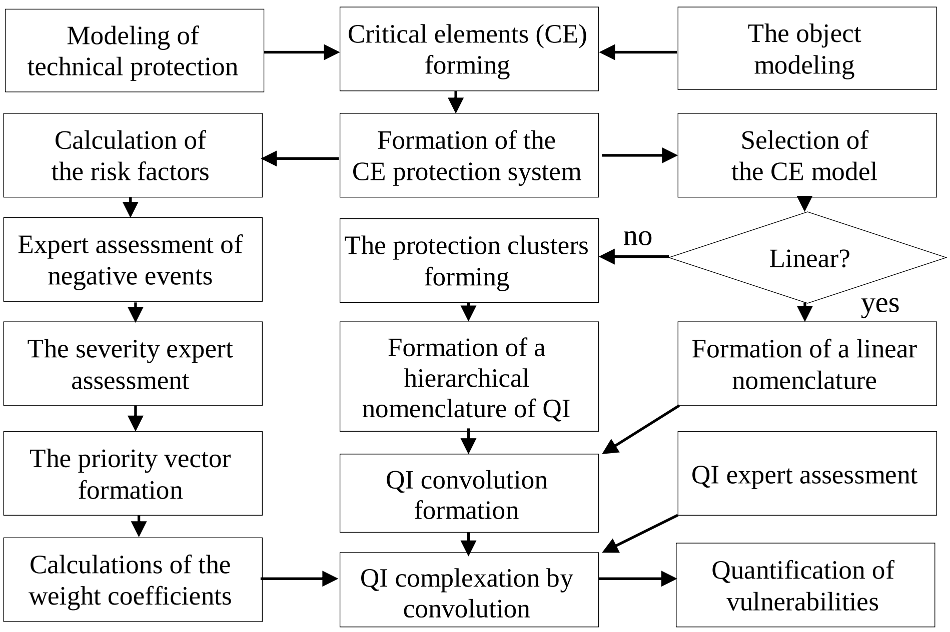

Figure 3. Algorithm for practical implementation of qualimetric vulnerability assessment

Conclusions

Having analyzed most modern models and approaches to determining the level of safety, we can conclude that the assessment of the level of safety of transport nodes is recommended to approach in two ways. On the one hand, it is necessary to first consider the concepts of "reliability", "security", "stability" and "survivability" as synonyms for "security", and then - to assess their relationship with each other. On the other hand, security identification can be carried out not only in its presence, but also in its absence - to assess the negative impact factors. Thus, "security" should also be compared with the concepts of incomplete or partial security, which can be described as "vulnerability", "danger", "risk" and "threat".

Thus, there is some imaginary protection field of the object of transport infrastructure, which provides counteraction to a set of existing or perceived threats.

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