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CONSTRUCTION OF AN INTEGRATED CRITERION FOR ESTIMATING THE CONSEQUENCES OF EMERGENCIES INVOLVING DANGEROUS GOODS

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Запропоновано метод оцінювання наслідків аварійних ситуацій з небезпечними вантажами при перевезенні їх залізничним транспортом. Метод заснований на формуванні комплексного критерію, який враховує фактори впливу на величину ризику, що, в свою чергу, залежить від певної композиції составу вантажного поїзду з небезпечними вантажами.

В якості критерію обрано умовну впевненість виникнення більш значних наслідків в результаті аварійної ситуації. Критерій залежить від: кількості груп вагонів з небезпечними вантажами в составі поїзда, що формується; загальної кількості вагонів з небезпечними вантажами. Також вплив на критерій мають: ступінь небезпеки групи, до якої віднесено вагони з небезпечними вантажами та кількість випадків сумісного розташування вагонів різних груп небезпеки. Встановлено, що значення факторів постійно змінюються, тому їх описано за допомогою апарату нечіткої логіки та нечітких множин. Використання такого апарату дозволило комплексно виявити взаємний вплив цих факторів на більш безпечний варіант формування составу поїзда на сортувальних станціях.

Моделювання можливих ситуацій дозволило зробити висновок про відповідність величини значень вхідних нечітких параметрів величині значення умовної впевненості виникнення більш значних наслідків в результаті аварійної ситуації. Отримані результати логічно свідчать про виникнення більш значних наслідків при наявності в составі поїзда максимальних значень нечітких змінних, середніх – при середніх значеннях, а мінімальних наслідків при найменших значеннях нечітких змінних. Визначено взаємозв'язки нечітких вхідних даних, аналіз яких довів, що при збільшенні значення будь-яких нечітких параметрів (та їх комбінацій) зростає загальне значення величини умовної впевненості виникнення більш значних наслідків в результаті аварійної ситуації

Ключові слова: небезпечні вантажі, умовна впевненість, нечітка логіка, аварійна ситуація, оцінка ризиків

1. Introduction

One of leading places in the world transportation system of cargo delivery, including dangerous goods whose volumes are growing, belongs to railroad transport. In case of an emergency when transporting a dangerous cargo, main consequences are the costs of recovering the infrastructure (rolling stock, tracks, facilities, etc.). Consequences of the emergency involving dangerous goods (DG), in addition to the damage to railroad infrastructure, include socio-economic losses (costs incurred as a result of killing or injuring people), collateral damage. In addition, there may emerge the environmental damages (damages to objects in the environment), losses due to a decrease in labor resources because of death of people or their loss of working capacity [1]. Thus, it is a relevant issue to ensure safe delivery of DG in the domestic and international transportation by reducing the consequences of emergencies through the rational arrangement of wagons at freight trains when they are formed at marshalling stations.

2. Literature review and problem statement

International processes that occur in the transportation sector imply a set of measures for the development of cargo deliveries, including dangerous goods, by rail transport in international traffic [2].

Paper [3] constructed a risk assessment model for the case of rolling stock derailing when transporting DG. The model, reported in [4], uses a probability of train derailing, considering the arrangement of wagons carrying DG relative to each other; it is applied to a simulated transport corridor in order to demonstrate the results obtained. However, stud-

ies [3, 4] do not consider operational costs that would grow as a result of increasing the number of shunting operations.

Paper [5] devised approaches to assess and reduce risks when transporting dangerous goods by rail. Study [6] reported a mathematical model that performs the functions of identification, quantification, and risk management. However, it should be noted that the cited works [5, 6] take into consideration only the presence of wagons with DG in the train, disregarding their classes of danger and compatibility between them.

Article [7] presented methods of risk management during transportation of dangerous goods by road and air transport [8] that points to the relevance of the problem, given the increasing proportion of DG in the total freight transported. The approaches considered in [7, 8] apply standard mathematical modeling methods. The issue on the consequences of emergencies involving DG are more complex and require a comprehensive approach taking into consideration the large number of factors that affect the results obtained. A significant share of such factors is different in its significance and thus a description of processes that occur during modeling requires the use of appropriate mathematical apparatus. Such an apparatus could be the theory of fuzzy sets and fuzzy logic that is used in many cases to describe complex processes, which have a large amount of input information. Thus, paper [9] provides an example of using fuzzy logic for the textile industry, paper [10] – when drilling oil and gas wells for predicting complications, work [11] addresses the application of fuzzy approach in designing and operating distributive electric networks.

The railroad transport also uses the theory of fuzzy sets and fuzzy logic, for example in determining the suitability of rolling stock in terms of commercial utilization at its allocation [12]. When determining a rational way to receive freight trains [13] and to assess transporting vehicles [14], fuzzy input data are also applied.

Thus, given the fact that available studies do not deal with issues related to compatibility among DG from different classes of danger, and to using appropriate mathematical apparatus, a comprehensive approach to estimating the consequences of emergencies must be developed.

3. The aim and objectives of the study

The aim of this study is to construct a comprehensive criterion for estimating the consequences of emergencies involving DG when they are transported by rail.

To accomplish the aim, the following tasks have been set:

– to choose and substantiate a structure of the criteria and to describe by appropriate mathematical methods those parameters that affect it;

– to perform simulation and analyze the obtained results of possible situations that arise during operation when forming freight trains that include wagons carrying DG.

4. Methods of research into the influence of parameters for a conditional confidence in the occurrence of greater consequences as a result of an emergency

One of the main problems when forming the trains with wagons that carry DG is the lack of scientific substantiation for the dependence of magnitude of the consequences of emergencies on arrangement of wagons carrying DG in such trains. Therefore, an important task is to devise a comprehensive criterion for estimating the consequences of emergencies involving dangerous goods taking into consideration the arrangement of compatible wagons carrying DG from different classes when forming a "safe" train. A "safe" train implies the train whose composition would maximally exclude the number of dangerous compatible arrangements of wagons carrying DG from incompatible classes. This, in turn, would make it possible to minimize possible consequences as a result of the occurrence of an emergency.

The total cost of forming a "safe" train depends on the cost of shunting operations and the magnitude of risk. These costs are affected by the following parameters, which most significantly influence operational work when forming and running a "safe" train whose composition contains freight wagons carrying DG [15]:

– the number of group of wagons carrying dangerous goods within a forming train (n);

– the total number of wagons carrying dangerous goods (m_n);

– the degree of danger of the group that consists of wagons carrying dangerous goods (g);

– the number of cases of compatible arrangement of wagons from various groups of danger (b).

The specified parameters depend on operational circumstances that dynamically change over time. Given this, the efficiency of decision making by operational staff is determined based on the calculation of a series of individual criteria and parameters. However, their application does not make it possible to fully evaluate the performance effectiveness of a railroad division in general. Thus, one needs to employ a generalized assessment of changes in the basic indicators of performance of the specified unit and their impact on the ultimate result. The problem relates to the fact that there is a list of restrictions in achieving the ultimate goal, which generally cannot be described clearly and unambiguously. This is due to such factors as operational changes within a railroad unit, diversity in the nature of the investigated parameters, impact of the human factor, etc. Since it is impossible to consider absolutely all restrictions and parameters, there is a need to formalize the ultimate objective by applying a mathematical apparatus of fuzzy sets.

In this study, decisions are made by operational personnel not under conditions of change in the consequences of emergencies, but rather to prevent the occurrence of more serious consequences. Cost assessment of consequences [1] and its dimensions depend on the possible reaction by incompatible DG, which is affected by the arrangement of wagons carrying incompatible DG next to each other within a train.

We shall represent parameters n, m_n, g, b in the form of fuzzy variables with appropriate membership functions. The chosen initial parameter for modeling is the conditional criterion for estimating the consequences of emergencies U.

Thus, according to the set interim task to determine U, it is required to assign four linguistic variables in the form [16]: $\langle \mathrm{n}, H_1, Q\rangle$, $\langle \mathrm{m}_n, H_2, F\rangle$, $\langle g, H_3, J\rangle$, $\langle b, H_4, V\rangle$. Fig. 1 shows a general graphical interpretation for forming four fuzzy variables in the programming environment Matlab using Toolbox Fuzzy Logic.

Directly proceeding to formalization, a linguistic change $\langle \mathrm{n}, H_1, Q\rangle$ can be represented in the following form:

$$\langle n, H_1, Q\rangle \rightarrow \langle \text{"Number of groups"}, H_1, [q_{\min}, q_{\max}]\rangle, \qquad (1)$$

where H_1={"low danger", "high danger"}; q_{min}, q_{max} is the region for determining Q={q} the corresponding fuzzy variable that is responsible for the number of groups of wagons carrying dangerous goods within a train.

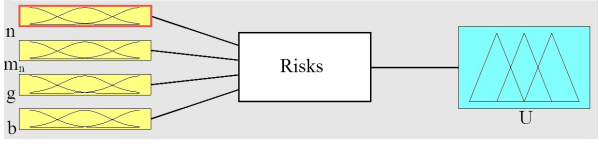

Fig. 1. Graphical interpretation of fuzzy variables formation

The fuzzy subset of set Q can be represented in the following form

$$\tilde{q}_i = \left\{\left\langle \mu_{q_i}(q)/q\right\rangle\right\},\ \ (q \in Q), \tag{2}$$

where $\mu_{q_i}(q)$ is the membership function that describes the fuzzy variable $\tilde{q}_i$.

In a given case, the value for linguistic variable "The number of group" with the term-set Q is described by the membership functions with appropriate names and constraints for possible values. According to this, parameters for fuzzy variables $\tilde{q}_i$ can be reproduced in analytical form as follows:

$$\begin{matrix}\left\langle \text{"low danger"},[q_{\min},q_{\max}],\tilde{q}_1\right\rangle,\\ \left\langle \text{"high danger"},[[q_{\min},q_{\max}]],\tilde{q}_2\right\rangle.\end{matrix} \Rightarrow \begin{matrix}\left\langle \text{"low danger"},[60,0],\tilde{q}_1\right\rangle,\\ \left\langle \text{"high danger"},[0,60],\tilde{q}_2\right\rangle.\end{matrix} \tag{3}$$

In this case, the meaning of values for the term-set "low danger" is the maximum confidence in low danger in case when n=0, and the minimum confidence if n=60. The term-set "high danger" is the maximum confidence in high danger when n=60, and the minimum confidence in high danger at n=0.

Graphical representation of the specified membership functions of fuzzy variable n is shown in Fig. 2.

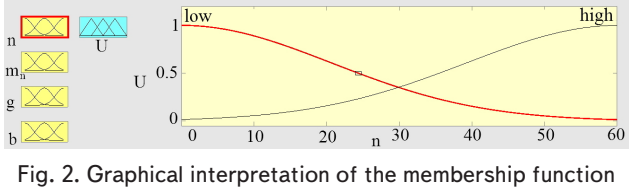

Fig. 2. Graphical interpretation of the membership function formation for fuzzy variable n

Linguistic variable $\langle m_n, H_2, F\rangle$ can be represented in the following form:

$$\langle m_n, H_2, F\rangle \rightarrow \left\langle \text{"Number of wagons"}, H_2, [f_{\min}, f_{\max}]\right\rangle, \tag{4}$$

where H_2={"low danger", "high danger"}; f_{min}, f_{max} is the region for determining F={f} the corresponding fuzzy variable, which is responsible for the number of wagons carrying dangerous goods within a train.

The fuzzy subset of set F can be represented in the following form:

$$\tilde{f}_z = \left\{\left\langle \mu_{f_z}(f)/f\right\rangle\right\},\ \ (f \in F), \tag{5}$$

where $\mu_{f_z}(f)$ is the membership function that describes fuzzy variable $\tilde{f}_z$.

In a given case, the value for linguistic variable "Number of wagons" with the term-set F is described by the membership functions with respective names and constraints for possible values. Given this, the parameters for fuzzy variables $\tilde{f}_z$ can be reproduced in analytical form as follows:

$$\begin{matrix}\left\langle \text{"low danger"},[f_{\min},f_{\max}],\tilde{f}_1\right\rangle,\\ \left\langle \text{"high danger"},[[f_{\min},f_{\max}]],\tilde{f}_2\right\rangle.\end{matrix} \Rightarrow \begin{matrix}\left\langle \text{"low danger"},[60,0],\tilde{f}_1\right\rangle,\\ \left\langle \text{"high danger"},[0,60],\tilde{f}_2\right\rangle.\end{matrix} \tag{6}$$

Similar to the case with a fuzzy variable of the term-set, "low danger" corresponds to the maximum confidence in low danger for the case when m_n=0, and the minimum confidence if m_n=60. The term-set "high danger" is the maximum confidence in high danger at m_n=60, and the minimum confidence in high danger is at m_n=0.

Graphical representation of the specified membership functions of fuzzy variable m_n is shown in Fig. 3.

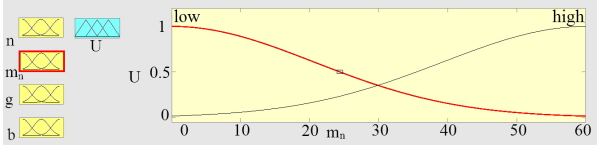

Fig. 3. Graphical interpretation of the membership function formation of variable fuzzy m_n

Linguistic variable $\langle g, H_3, J\rangle$ can be represented in the following form:

$$\langle g, H_3, J\rangle \rightarrow \left\langle \text{"Degree of danger"}, H_3, [j_{\min}, j_{\max}]\right\rangle, \tag{7}$$

where H_1={"first degree", "second degree", "third degree", "fourth degree"}; j_{min}, j_{max} is the region for determining J={j} the respective fuzzy variable that is responsible for the degree of danger of the group to which the wagons carrying dangerous goods are assigned.

The fuzzy subset of set J can be represented in the following form:

$$\tilde{j}_o = \left\{\left\langle \mu_{j_o}(j)/j\right\rangle\right\},\ \ (j \in J), \tag{8}$$

where $\mu_{j_o}(j)$ is the membership function that describes fuzzy variable $\tilde{j}_o$.

In a given case, the value for linguistic variable "Degree of danger" with the term-set J is described by the membership functions with respective names and constraints for possible values. Given this, the parameters for fuzzy variables $\tilde{j}_o$ can be reproduced in analytical form as follows:

$$\begin{matrix}\left\langle \text{"low degree"},[j_{\min},j_{\max}],\tilde{j}_1\right\rangle,\\ \left\langle \text{"medium degree"},[j_{\min},j_{\max}],\tilde{j}_2\right\rangle,\\ \left\langle \text{"high degree"},[j_{\min},j_{\max}],\tilde{j}_3\right\rangle,\\ \left\langle \text{"extremely high degree"},[j_{\min},j_{\max}],\tilde{j}_4\right\rangle.\end{matrix} \Rightarrow \begin{matrix}\left\langle \text{"low degree"},[1,2],\tilde{j}_1\right\rangle,\\ \left\langle \text{"medium degree"},[1,3],\tilde{j}_2\right\rangle,\\ \left\langle \text{"high degree"},[2,4],\tilde{j}_3\right\rangle,\\ \left\langle \text{"extremely high degree"},[3,4],\tilde{j}_4\right\rangle.\end{matrix} \tag{9}$$

In a given case, the term-set "low degree" corresponds to the maximum confidence at a low degree of danger if j=1.

The term-set "medium degree" corresponds to the maximum confidence at a medium degree of danger if j=2. The term-set "high degree" matches the maximum confidence at a high degree of danger if j=3. The term-set "extremely high degree" corresponds to the maximum confidence at an extremely high degree of danger in case j=4. The specified parameters correspond to the graphical dependences when using the Gaussian distribution.

The choice of the number of membership functions and related terms-sets is carried out in accordance with [17], chapter 5.8.3. "The priority of danger", and [18], section 7, Table 5 "Compatible loading of one wagon or container". In the study, we accepted assumptions about the division of all classes of danger into four groups: $\mu_{j_1}(j)$ (class 8; class 9) – "low degree"; $\mu_{j_2}(j)$ – class 4.3; class 5.1 – "medium degree"; $\mu_{j_3}(j)$ – (class 2; class 3; class 4.1; class 4.2; class 5,2; class 6.1; class 6.2; class 7) – "high degree"; $\mu_{j_4}(j)$ – (class 1) – "extremely high degree".

The membership function $\mu_{j_4}(j)$ was chosen according to the requirements defined in [18], concerning the ban on compatible loading of dangerous goods from different classes, and requirements from [17], as those kinds of danger that are inherent to class 1 are always a priority. The membership function $\mu_{j_3}(j)$ was chosen also according to the requirements defined in [18]. DG from such classes can be loaded together with certain dangerous goods from other classes. However, according to [17], the main types of danger that are inherent to DG from such classes are always a priority. The membership function $\mu_{j_2}(j)$ was chosen based on the following: according to [17], classes 4.3 and 5.1 in most cases take precedence over the classes that are included in $\mu_{j_1}(j)$, that is especially true for packaging groups I and II. The membership function $\mu_{j_1}(j)$ was chosen according to [17] as they are of lower priority compared with classes assigned to $\mu_{j_2}(j)$.

Graphical representation of the specified membership functions of fuzzy variable g is shown in Fig. 4.

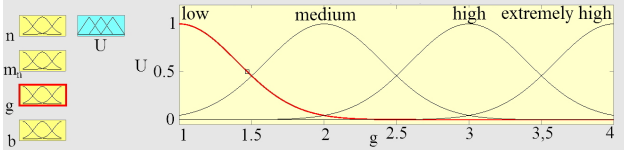

Fig. 4. Graphical interpretation of the membership function formation of variable fuzzy g

Linguistic variable $\langle b, H_4, V\rangle$ can be represented in the following form:

$$\langle b, H_4, V\rangle \rightarrow \langle \text{"Danger combination"}, H_4, [v_{\min}, v_{\max}]\rangle, \quad (10)$$

where H_4={"low danger", "high danger"}; $v_{\min}$, $v_{\max}$ is the region for determining V={v} the corresponding fuzzy variable that is responsible for the number of cases of compatible arrangement of wagons from different groups of danger.

The fuzzy subset of set V can be represented in the following form:

$$\tilde{v}_x = \left\{\langle \mu_{v_x}(v)/v\rangle\right\}, \quad (v \in V), \quad (11)$$

where $\mu_{v_x}(v)$ is the membership function that describes fuzzy variable $\tilde{v}_x$.

In a given case, the value for linguistic variable "dangerous combination" with the term-set V is described by the membership functions with respective names and constraints for possible values. Given this, the parameters for fuzzy variables $\tilde{v}_x$ can be reproduced in analytical form as follows:

$$\begin{matrix}\langle \text{"low danger"}, [v_{\min}, v_{\max}], \tilde{v}_1\rangle, \\ \langle \text{"high danger"}, [v_{\min}, v_{\max}], \tilde{v}_2\rangle.\end{matrix} \Rightarrow \begin{matrix}\langle \text{"low danger"}, [0,10], \tilde{v}_1\rangle, \\ \langle \text{"high danger"}, [10,59], \tilde{v}_2\rangle.\end{matrix} \quad (12)$$

Graphical representation of the specified membership functions of fuzzy variable b is shown in Fig. 5.

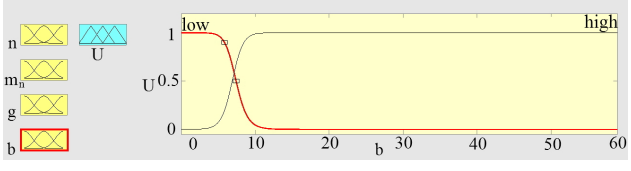

Fig. 5. Graphical interpretation of the membership function formation of variable fuzzy *b*

The term-set "low danger" corresponds to the maximum confidence at a low degree of danger if v=10. The term-set "high danger" corresponds to the maximum confidence at a maximum degree of danger in the range from 10 to 59 combinations, that is $v \in [10, 59]$.

Upon determining dependences U on the investigated parameters n, m_n, g, b, it becomes possible to determine its resulting character. Thus, U is the conditional confidence in the occurrence of greater consequences as a result of an emergency (a criterion for estimating the consequences of emergencies). This assumption is based on logical dependence of values for U on the magnitude for the specified parameters.

In terms of fuzzy logic, the expression for an integrated criterion for estimating the consequences of emergencies involving DG when they are transported by rail takes the following form

$$U = n \cup m_n \cup g \cup b. \quad (13)$$

This expression in the analytical form indicates the necessity to combine the specified parameters into a single system in order to achieve the ultimate goal of minimizing the consequences of an emergency, predetermined by the magnitude of risk.

Known methods for determining the magnitude of risk [19, 20] take into consideration the value for probability and consequences of an adverse event. This approach is general in nature and does not make it possible to fully take into consideration the interdependence among the parameters of the proposed integrated criterion.

Thus, in this study, the magnitude of risk depends on the magnitude of the specified integrated criterion U and consequences from the occurrence of an adverse event

$$R = U \cdot \sum_{a=1}^{l} E(w_a), \quad (14)$$

where U is the conditional confidence in the occurrence of greater consequences as a result of an emergency (the integrated criterion); $E(w_a)$ are the averaged costs reduced per

a single emergency, which consist of: $E(w_1)$ are the averaged reduced costs due to the payment of monetary compensation for damaging a person (death, injury, loss of working capacity); $E(w_2)$ are the averaged reduced costs that arise as a result of damage to the environment; $E(w_3)$ are the averaged reduced costs due to damage to the infrastructure (track, wagons, buildings and facilities); l is the number of components in the averaged costs.

5. Results of modeling possible situations that occur during operational work when forming freight trains that include wagons carrying dangerous goods

We verified the proposed integrated criterion for the boundary and average values for the components of the conditional confidence in the occurrence of greater consequences.

This work reports the results from determining conditional confidence in the occurrence of greater consequences as a result of an emergency.

A combined arrangement implies that goods from various groups of danger are placed next to each other without dividing them by wagons with safe goods or empty wagons (Fig. 6–8).

Thus, it is assumed that the input of the constructed model of fuzzy logical inference receives the parameters that are responsible for the basic critical factors influencing safety during transportation of DG.

Fig. 6 demonstrates a situation when the freight train carrying DG includes one wagon with a dangerous cargo; this is a logical way to indicate that the number of groups that include such wagons is also one. In addition, the input vector of the proposed situation implies that the degree of danger of the group to which the wagon carrying a dangerous cargo is assigned has the lowest level. The number of cases of compatible arrangement of wagons from various groups of danger is the minimum of all possible, that is, given a single wagon and a single group, the number of dangerous arrangements is equal to zero.

The result is the derived fuzzy logical inference with value U=0.146≈0.1, which logically indicates a low level of conditional confidence in the occurrence of greater consequences as a result of an emergency.

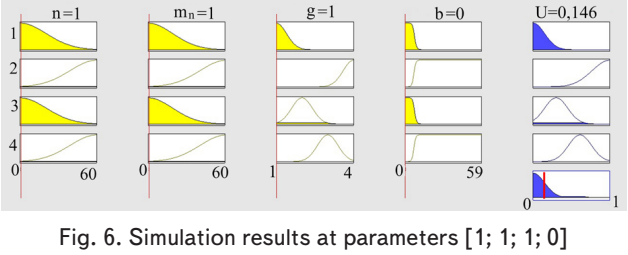

Fig. 6. Simulation results at parameters [1; 1; 1; 0]

Fig. 7 shows the simulated, imaginary, most unfavorable situation, when the freight train carrying DG includes the maximum number of wagons with dangerous cargoes (under conditions of the current model, this value is 60). In this case, it is assumed that the number of groups of wagons carrying DG within a train is also maximal (that is, also 60). The proposed situation implies that the degree of danger for groups to which wagons carrying DG are assigned has the highest level, and the number of compatible arrangements of wagons from various groups of danger accepts the maximum possible value. That is, one position less than the number of wagons carrying DG, specifically 59. The result is the obtained fuzzy logical inference with value U=0.805≈0.8, which logically attests to a high level of conditional confidence in the occurrence of greater consequences as a result of an emergency.

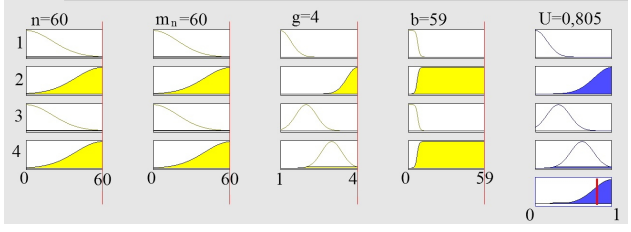

Fig. 7. Simulation results at parameters [60; 60; 4; 59]

To conduct a logical verification of the adequate functioning of the constructed model the following vector of input data was formed from the approximately average values. Thus, Fig. 8 shows the chosen vector, which implies the presence of 20 groups of wagons carrying DG, the number of wagons carrying DG equals 40. The situation under consideration also implies that the degree of danger for groups to which the wagons carrying DG are assigned has a roughly average level, and the number of compatible arrangements of wagons from various groups of danger accepts a value that is equal to 10. The result is the obtained fuzzy logical inference with value U=0.569≈0.6, which in a logical manner indicates a roughly medium level of conditional confidence in the occurrence of greater consequences as a result of an emergency.

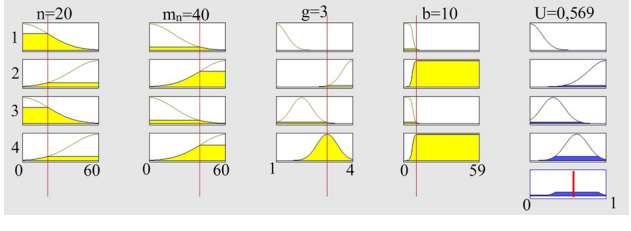

Fig. 8. Simulation results at parameters [20; 40; 3; 10]

Simulation results indicate a direct dependence of the magnitude of values for the input fuzzy parameters on the magnitude of a value for conditional confidence in the occurrence of greater consequences as a result of an emergency.

To visually reproduce the constructed rules, it is appropriate to build appropriate response surfaces based on a pairwise variation of parameters for integrated criterion U. The defined combinations were built in the programming environment MatLab Toolbox Fuzzy Logic (Fig. 9–11). In the computer model, the determined parameters simultaneously affect the graphical representation of the response surface, however, given perception limitations, the parameters, determined in this work, are represented in pairs. Three randomly chosen combinations are used as an example.

Fig. 9–11 show that an increase in the value for any of the fuzzy parameters (and their combinations) points to the growth in the total value for the magnitude of conditional confidence in the occurrence of greater consequences as a result of an emergency.

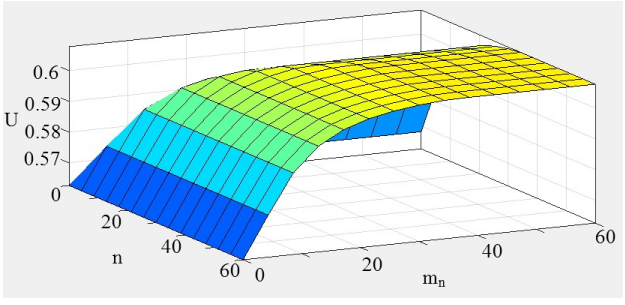

Fig. 9. Response surface at a combination of parameters: the number of wagons carrying dangerous goods within a formed train (n) and the total number of wagons carrying dangerous goods (m_n)

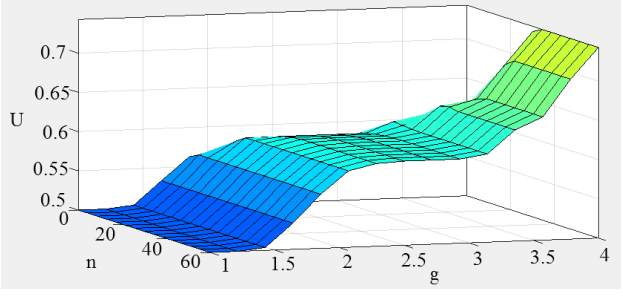

Fig. 10. Response surface at a combination of parameters: the number of group of wagons carrying dangerous goods within a formed train (n) and the degree of danger for the group to which the wagons carrying dangerous goods are assigned (g)

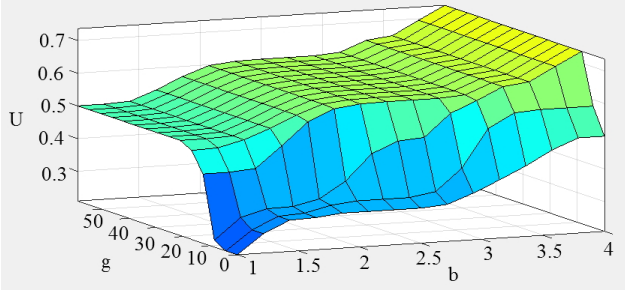

Fig. 11. Response surface at a combination of parameters: the degree of danger for the group to which the wagons carrying dangerous goods are assigned (g) and the number of compatible arrangements of wagons from various groups of danger (b)

6. Discussion of modelling results at different parameters of input variables

In this study, we formed the parameters that influence the magnitude of risk of more significant consequences upon the occurrence of an emergency. These investigated parameters are integrally related when determining the criterion for estimating the consequences of emergency. They were chosen because they exert the most significant influence on operational work when forming and running a "safe" train that includes wagons carrying DG.

When determining the conditional confidence in the occurrence of greater consequences as a result of emergencies, we have obtained the following:

– at variables' parameters [1; 1; 1; 0], the derived magnitude U equals 0.146 (Fig. 6);

– at variables' parameters [60; 60; 4; 59], the derived magnitude U equals 0.805 (Fig. 7);

– at variables' parameters [20; 40; 3; 10], the derived magnitude U equals 0.569 (Fig. 8).

Logical conclusion is the occurrence of more significant consequences if a train has the maximum values for fuzzy variables, medium – at medium values, and the minimal consequences at the lowest values for fuzzy variables. This confirms the proper operation of a given model, as well as its application at any input values under changing operational conditions, which is an unambiguous advantage of the model in comparison with existing models.

The response surfaces with the following combination of parameters are given as an example:

– the number of groups of wagons carrying dangerous goods within a formed train (n) and the total number of wagons carrying dangerous goods (m_n) (Fig. 9);

– the number of groups of wagons carrying dangerous goods within a formed train (n) and the degree of danger of the group to which the wagons carrying dangerous goods are assigned (g) (Fig. 10);

– the degree of danger of the group to which the wagons carrying dangerous goods are assigned (g);

– the number of cases of compatible arrangements of wagons from various groups of danger (b) (Fig. 11).

Of special interest is the interpretation of results from studying the combinations of different parameters that affect the proposed integrated criterion. An analysis of Fig. 9–11 confirms that an increase in the value for any fuzzy parameters (and their combinations) leads to an increase in the overall value for the magnitude of conditional confidence in the occurrence of greater consequences as a result of an emergency. These findings are useful in determining the magnitude of risk during transportation of DG and are applied by operational staff when forming a train.

The approaches reported here can be further advanced when solving a task on selecting the most secure route for trains carrying DG.

7. Conclusions

1. We have defined 4 indicators that influence the criterion of conditional confidence in the occurrence of greater consequences as a result of an emergency. The indicators include: the number of groups of wagons carrying dangerous goods within a formed train; the total number of wagons carrying dangerous goods; the degree of danger of the group to which the wagons carrying dangerous goods are assigned; the number of cases of compatible arrangements of wagons from different groups of danger. The determined components made it possible to comprehensively identify the mutual influence of these factors on a more secure variant of train formation under operational conditions. We have described in the terms of fuzzy logic the components of conditional confidence in the occurrence of greater consequences as a result of an emergency. Such an approach will enable the operational staff, responsible for forming and running trains, to make grounded decisions in a short time, based on the analysis of a large number of possible combinations of input parameters (about 100), to form the maximally "safe" trains carrying DG in real time.

2. We have performed simulation of possible situations that arise in operational work when forming freight trains that include wagons carrying DG. Simulation results at the assigned input parameters are:

– [1; 1; 1; 0] – *U* equals 0.146;

– [60; 60; 4; 59] – *U* equals 0.805;

– [20; 40; 3; 10] – *U* equals 0.569.

An analysis of results obtained in modelling confidently demonstrates correspondence between the magnitude of values for input fuzzy parameters and the magnitude of value for conditional confidence in the occurrence of greater consequences as a result of an emergency. The approach reported here makes it possible for operational staff to continuously process, under changing operating conditions, information about trains that have already arrived to the station and await the disbandment. In addition, it takes into consideration those trains that have not yet arrived at the marshalling station, but the information about their expected arrival is already known. That will make it possible to plan station operations related to forming a train 3–8 hours in advance. In the future, application of the proposed approaches could become possible at integrated determination of operating costs for the formation of trains under condition of economic assessment of the risk of occurrence of greater consequences in emergencies involving DG depending on the local position of transporting vehicles.

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