Intelligent information technology for multi-criteria vulnerability assessment of gas stations to the main types of accidents

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Abstract

The paper considers the creation of intelligent information technology (IT) for multi-criteria vulnerability assessment of gas stations (GSs) to the main types of accidents. The proposed IT consists of 10 consecutive stages. The implementation of the first stages was related to the definition of the main types of accidents for GSs and consideration of GS vulnerability from the point of view of possible adverse consequences, for which 41 criteria were created by experts. It is proposed to apply the analytical hierarchy process for the analysis of expert data in order to obtain a secondary space of vulnerability criteria, without considering the lost lives. On the basis of the secondary space of criteria, data on the GS network was collected and a scheme for their pre-processing and coding was proposed. The GS vulnerability assessment was carried out on the basis of the developed generalized model. To interpret the results of GS vulnerability assessment, the use of fuzzy sets in the form of trapezoidal membership functions is proposed. Intelligent IT for GS vulnerability assessment is implemented in the form of a decision support system (DSS). The decision-maker, based on the entered data according to the vulnerability criteria of a certain GS, will receive a preliminary value of the GS vulnerability and an explanation of how it was obtained. A component of the DSS is a formed knowledge base on pre-evaluated GS with the possibility of editing and expanding it. The use of the proposed intelligent IT of multi-criteria GS vulnerability assessment and DSS based on it provides an opportunity to make informed decisions on the assessment of potentially vulnerable facilities and risk management.

Keywords

Multi-criteria decision-making analysis, analytic hierarchy process, gas station, accidents, intelligent information technology, decision support system, fuzzy logic.

1. Introduction

Ensuring the environmental safety of territories from possible accidents at potentially hazardous facilities (such as large enterprises or warehouses storing hazardous substances, main pipelines, pressure vessels etc.) is one of the state's socially important functions. This process becomes especially important when there are hostilities in the country and such facilities can become a target, causing a man-made disaster comparable to a small earthquake or tsunami (as an example, the Kakhovka Dam destruction in Ukraine in 2023). During the 1st stage of the joint Ukrainian-British research project between the National University of Odesa Polytechnic and the University of Portsmouth (UK) UUT14 "Multiple Criteria Fuzzy Logic Based Methodology for Risk Mapping of Gas Filling Stations and Consequent Decision Optimization" within the framework of the UK-Ukraine Twinning initiative [1], gas stations (GSs) were considered as an example of a complex technological system that can be affected. 4 groups of criteria for the vulnerability of GSs to the main types of accidents were formed, 41 criteria in total. In order to reduce the primary space of GSs vulnerability criteria, a multicriteria decision analysis method was applied, namely analytical hierarchy process (AHP) using a web form for surveying experts, as well as information technology (IT), which allowed to obtain estimates of the importance of criteria in each group [2]. At the 2nd stage of the project, after a reasonable reduction of the primary criteria space, it was proposed to develop IT that would allow, based on the collected data on the GSs' network in a city for all criteria, to conduct a primary assessment of the GS vulnerability, providing recommendations for the assessed GS using fuzzy logic (FL) methods, which will be discussed in this paper.

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A primary assessment of the GSs vulnerability using IT is an integral part of risk assessment and management, which allows government agencies to make informed decisions and take preventive measures to reduce the scale of the negative impact of a possible accident, thereby improving the social and economic well-being of the country, as well as the environmental safety of the territories.

2. Literature overview

The AHP is one of the most popular methods for organising and analysing complex decision-making. It was developed in the 1970s by Thomas Saaty [3]. Let's look at examples of the use of AHP in relation to gas stations in recent publications by researchers. Research [4] used the AHP to assess stakeholder preferences for GS location criteria. The goal of the project is to determine the optimal location of a GS by integrating the preferences of different stakeholders and analysing the seismic area. The top 5 preference criteria are the right land use (with a 31.2% influence), emergency response services (23.6%), protection of the surrounding area from fire and explosion (18.3%), protection of the water supply system from leakage from underground storage tanks (14.2%), and ease of access to the site for any related work (12.7%). In [5], the authors proposed a comprehensive approach that combines the AHP and multi-criteria objective programming for the efficient selection of GS locations. At the first level of the structure, the goal of conducting an AHP is to select the location of GSs. The second level includes the criteria of traffic flow, environment and building characteristics. The third level includes sub-criteria, such as: Average number of cars, motorbikes and waiting time for traffic criteria; Average fuel consumption, number of competitors, average swipe rate and neighbourhood acceptance for environment criteria; and Number of pump islands, number of pumps and lot size for building characteristics. To further improve the method, it is recommended to simplify the process and provide easy-to-use tools for decision-makers. To analyse the risks faced by GSs in Pakistan and their priorities, the research [6] used the AHP and interval pairwise analysis. The results showed that the 5 risk factors that have the greatest impact on the operation of GSs are as follows: transportation and unloading of tanks; fuel distribution; on-site fuel storage; repair, maintenance and modification; and other risk factors. Despite the comprehensive nature of the study, it has two main limitations. First, the data used were collected from only three districts in the Punjab province of Pakistan, which may limit the generalisability of the results to a wider area. Secondly, the statistical methods used in this research, such as fuzzy hierarchical analysis and interval pairwise comparison analysis, also have their limitations and drawbacks. Also, the multicriteria AHP is used to assess the risks of gas compressor station construction and prioritise hazardous factors in the study [7]. Due to the fact that construction sites are one of the most common places where accidents occur, conducting a project safety risk assessment is an important component of effective construction project management. The project is more related to safety during the construction of GSs than to their vulnerability assessment and includes 23 types of activities with corresponding risks arising from them.

FL methods for evaluating GSs from various aspects are used in modern researches. In [8], the authors consider a new method based on FL to determine the choice of a GS. This work is aimed at selecting the optimal GS during the COVID-19 pandemic according to certain criteria. It should be noted that the research conducted by the authors goes beyond traditional approaches by using a new method, AHP-VIKOR, based on FL. An important limitation was the difficulty of gathering expert opinion during the COVID-19 pandemic, which could have affected the efficiency of data collection and consensus building. For example, the pandemic made it difficult to obtain expert opinion on some aspects of choosing a GS location. In addition, the importance of consumers' place of residence was not considered, which could be an important factor in determining the most suitable GS. The paper [9] considers the location of GSs using a fuzzy model in geographic information system (GIS) on a specific example. This research presents a model for decision-makers to determine the location of the optimal GS using a combination of fuzzy and GIS. In [10], a method based on a FL controller using Google Maps was developed to find the nearest GS. For fuzzy modelling, 5 linguistic input variables were taken including distance, gas availability, road congestion metric, gas quantity and number of traffic lights to obtain one output, i.e. time to reach the GS. The system allows the driver to locate GSs with greater accuracy, which requires less time to achieve.

The combined use of multi-criteria decision analysis (MCDA) and GIS is also used for a comprehensive assessment of GSs, in particular in the following researches. The integrated use of environmental impact assessment and AHP with the subsequent visualisation of data in GIS to determine the suitability of a land plot for a GS is discussed in [11]. The study focuses only on the analysis of the location of a GS for the sake of maximum preservation of the natural environment. In other words, the study does not look at the issue from different angles, nor does it define the "sustainability" of the GS as such. The research [12] examines the use of AHP and GIS (ArcGIS) to assess the suitability of GS locations. In the study, a handheld GPS navigator is used to collect primary data. Secondary data includes topographic and soil maps, from which soil types, roads, water bodies, terrain slope and land use features of the territory were extracted. Paper [13] assesses and improves spatial distribution using GIS to avoid environmental risks and achieve safety for GSs. The study aims to improve safety by optimising the location of GSs and reducing potential risks. Using MCDA methods and GIS, the risks of GSs were investigated and a better location for GSs was proposed. The paper [14] analyses the location of retail GSs based on GIS. Attribute information such as the age of the GSs, the number of pumps, petroleum products sold, the functional state of each GS, and the distance of the GSs to other infrastructure were assessed through a field survey and distribution of questionnaires to the owners and employees of each station.

3. Research aim statement

The aim of the research, which is considered in this paper, is to develop an intelligent IT for multi-criteria assessment of the GSs vulnerability to the occurrence of the main types of accidents, the implementation of which will allow for a more rapid preliminary examination of the technogenic safety of GSs.

The main objectives to be performed to achieve the aim:

- Development of the main steps of intelligent IT for multi-criteria assessment of the GSs vulnerability in relation to the main types of accidents, based on a previous study [2];
- Detailed development of the main steps of the proposed intelligent IT, in particular, building a coding scheme for data about GSs, obtaining the weights of GS vulnerability criteria, building a generalized model for obtaining a numerical assessment of GS vulnerability, as well as its interpretation based on FL;
- Implementation of the proposed intelligent IT in the form of a decision support system (DSS) and its approbation based on the data about the GS network in the settlement.

The following methods are used in the study: a MCDA method for assessing the vulnerability of GSs (AHP), a method of intellectual processing and coding of input data according to the criteria of GS vulnerability, a FL method for categorical assessment of GS vulnerability, a gradient scale and coordinate normalisation method for visualising.

4. Intelligent IT for multi-criteria assessing of the GSs vulnerability to the main types of accidents

The development of an intelligent IT that will allow to determine the vulnerability of GS to the main types of accidents discussed in [2] requires the involvement of environmental experts and developers in the field of Data Science. The following list of stages can be proposed for building an intelligent IT to be implemented as a DSS to assess the GSs vulnerability to the occurrence of main types of accidents. The list consists 10 consecutive stages, with the persons performing the respective stage in brackets for each stage:

- Identification of the main types of accidents (expert (E));
- Development of the primary space of economic, environmental and social criteria (EESC) for assessing the vulnerability of GSs to the main types of accidents (E, data scientist (DS));
- Obtaining a vector of weights of EESC based on AHP (DS);
- Development of a secondary space of EESC for assessing the GSs vulnerability (DS);
- Obtaining estimates of the values of EESC of the secondary space for each GS based on public data (E, DS);

- Preliminary processing and coding of the obtained public data in the secondary space (DS);
- Obtaining a vector of weights of EESC based on AHP in the secondary space (DS);
- Improving the general model for assessing the GSs vulnerability, considering stages 1-7 (DS);
- Determination and interpretation of the GSs vulnerability assessment using FL (DS);
- Building a knowledge base for assessing the GSs vulnerability to main types of accidents (DS).

Considering the above stages, Fig. 1 shows the developed intelligent IT assessment of the GSs vulnerability to the main types of accidents in the form of an DSS.

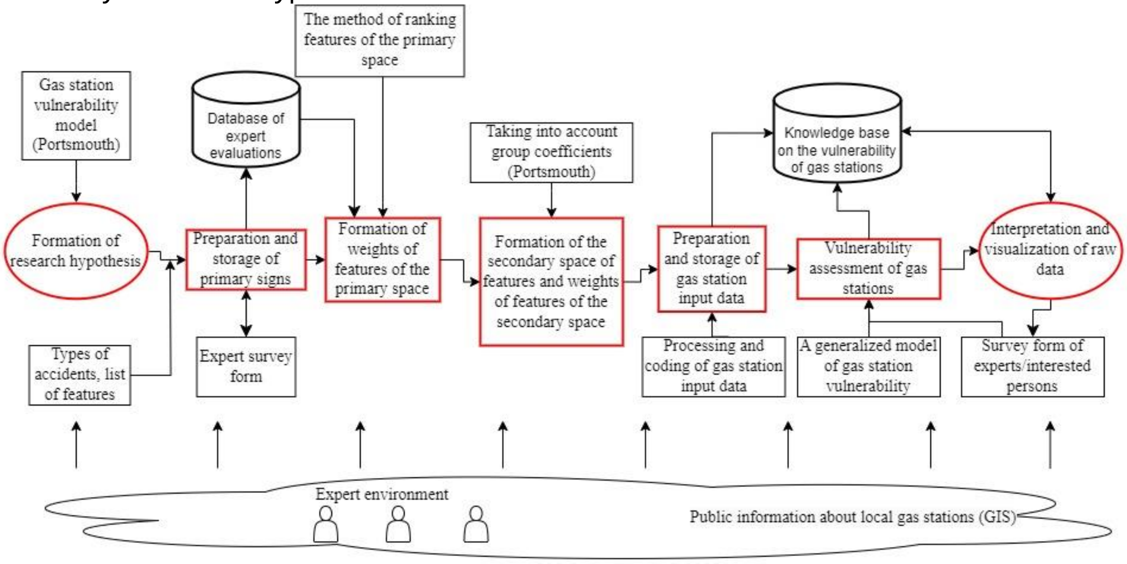

Figure 1: Intelligent IT assessment of the GSs vulnerability to the main types of accidents in the form of an DSS

5. Detailed development of the main steps of the proposed intelligent IT

At the 1st stage of the above-described list, during the development of intelligent IT for assessing the GSs vulnerability with respect to the main types of accidents, the main types of accidents were determined in [2]: explosion of a vapour-air mixture of petroleum products with the formation of a shock wave, fire of petroleum products spill and “fireball”. At the 2nd stage, for the development of the primary space of criteria for assessing the GSs vulnerability, it was proposed to choose 3 groups of criteria regarding the possible consequences of an accident: economic, social and environmental, as well as a separate group of lost lives, that should not be directly compared to other criteria. These groups of criteria form the primary space of criteria Sp_{pf}, described in more detail in [2]:

$$Sp_{pf} = \langle LL, E, S, A \rangle, \tag{1}$$

where lost lives $LL = \{LL_1, LL_2, LL_3, LL_4, LL_5, LL_6, LL_7, LL_8, LL_9\}$;

economical $E = \{E_1, E_2, E_3, E_4, E_5, E_6, E_7, E_8, E_9, E_{10}\}$;

social $S = \{S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}\}$;

environmental $A = \{A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8, A_9, A_{10}, A_{11}\}$.

At the 3rd stage, the evaluation of the criteria was carried out with the help of the AHP, which was implemented using the expert survey web form, as well as the developed algorithm that translated the experts' assessments into a pairwise comparison matrix for the further implementation of the evaluation of the criteria in each group according to the steps of the AHP [2].

At the 4th stage, a secondary space of criteria was developed by reducing the primary space. The selection of criteria that fall from the primary space to the secondary space for each type of accident *j* was made using the threshold processing of the corresponding values of the weights of the criteria w_{ji} in the corresponding group:

$$
\begin{aligned}
w'_{eji} &= \left\{ \forall w_{eij} \geq \lambda_E \right\}; i = \overline{1, N_E}; j = \overline{1,3} \\
w'_{sji} &= \left\{ \forall w_{sij} \geq \lambda_S \right\}; i = \overline{1, N_S}; j = \overline{1,3} \\
w'_{aji} &= \left\{ \forall w_{aij} \geq \lambda_A \right\}; i = \overline{1, N_A}; j = \overline{1,3}
\end{aligned}
\tag{2}
$$

As threshold values, the authors adopted the following values for each group of criteria $\lambda_E = \lambda_S = \lambda_A = 0.1$. At the same time, the group of criteria determining possible lost lives as a result of an accident is not reduced in accordance with the principles of the project [2].

Then the secondary space of GS vulnerability assessment criteria will have the following form:

$$
Sp_{sf} = \left\langle \left\{ \left\langle LL_{ji} \right\rangle \right\}, \left\{ \left\langle w'_{eji}; E^*_{ji} \right\rangle \right\}, \left\{ \left\langle w'_{sji}; S^*_{ji} \right\rangle \right\}, \left\{ \left\langle w'_{aji}; A^*_{ji} \right\rangle \right\} \right\rangle, \tag{3}
$$

where w'_{eji}, w'_{sji}, w'_{aji} – these are the weights of the relevant criteria in the economic E^*_{ji}, social S^*_{ji} and environmental group A^*_{ji} respectively. Therefore, the groups of criteria in the secondary space after the completion of the 4th stage of the method take the following form:

- Lost lives $LL = \{LL_1, LL_2, LL_3, LL_4, LL_5, LL_6, LL_7, LL_8, LL_9\}$;
- Economical $E^* = \{E^*_1, E^*_2, E^*_3, E^*_4, E^*_5, E^*_6\}$;
- Social $S^* = \{S^*_1, S^*_2, S^*_3, S^*_4, S^*_5\}$;
- Environmental $A^* = \{A^*_1, A^*_2, A^*_3, A^*_4, A^*_5, A^*_6\}$.

At the 5th stage, the authors collected data based on the formed secondary space of criteria for the GS network of a certain settlement from public data. Fragments of the received "grey" data are partially shown in Table 1, and for security reasons, we do not assign a coordinate reference to a specific GS. At this stage, we did not collect data on the criteria of lost lives.

When receiving such "grey" data, several problems arise that complicate the collection, processing and analysis of data to obtain a further assessment of the GSs vulnerability:

- The variety of required data: the data required to assess the values of EESC are very diverse, which makes it impossible to find all the data in one source; some data require knowledge of GS features, staff qualifications, etc.;
- The need for manual data collection: most of the time it is necessary to search and analyse data by an interested person, which can lead to the search for a large amount of sometimes redundant information and distortion of data;
- Unstructured data: data obtained during search and analysis is mostly very unstructured and detailed, which complicates data analysis and processing.

Table 1

A fragment of the values of "grey" data about GSs obtained from public sources

GS number		4	5	6	7
E^*_2 value	number of fuel dispensers	1	6	4	2
E^*_3 value	additional enterprises	no	shop	no	no
S^*_2 value	type of the zone	industrial	industrial, recreationa l	industrial, recreationa l	industria l
A^*_1 value	fuel type, standard	gas	5 + gas	3	4
A^*_3 value	forest area	300m	25m	10m	no

At the 6th stage, the received "grey" data on the GS is processed and coded, fragments of which were shown in Table 1 in accordance with the needs of the construction of the subsequent DSS to assess the vulnerability of the gas station to the main types of accidents. According to the defined values of the criterion, the data is given a code value between 0 and 1, where 0 corresponds to the least unfavourable value of the criterion, and 1 to the most dangerous. A fragment of the data coding table for some criteria is presented in Table 2, the full coding table for all criteria of the secondary space, excluding lives lost, can be found in [15].

Table 2
A fragment of the coding scheme of the “grey” database about GSs [15]

Criterion	E_1^* – type of GS construction			
Value	with underground tanks		with above-ground tanks	
Code	0.5		1.0	
Criterion	S_1^* – population density in the area near the GS			
Value	high	medium	low	very low
Code	1.0	0.6	0.2	0
Criterion	A_1^* – type of fuel used, standard			
Value	amount of fuel types $GS_{fueltypes}$ + gas ($GS_{gasfuel}$ is present or no – 0 or 1)			
Code	$a_{f1} = \begin{cases} \frac{GS_{fueltypes}}{6}, GS_{fueltypes} \leq 6 \\ 0.7, GS_{fueltypes} > 6 \end{cases} + 0.3 \cdot GS_{gasfuel}$			

At the 7th stage, for obtaining the vector of weights of the relevant groups of EESC with the help of AHP, the authors proceeded from the following considerations. Since the secondary criteria space had 17 components, to simplify the implementation of the AHP, the data obtained by British colleagues on the project were used, namely, with the help of the classic AHP, they compared the relevant groups of criteria with each other, thus obtaining weight coefficients for the group [16]. The results of this comparison and the corresponding weight coefficients are shown in Table 3.

Table 3
The results of a pairwise comparison of groups of GS vulnerability criteria according to the AHP [16]

Matrix of pairwise comparison of groups of criteria			
	Economic	Environmental	Social
Economic	–	1.5	3
Environmental	0.667	–	1.667
Social	0.333	0.6	–
The values of the weights of the groups of criteria according to the AHP were obtained from the pairwise comparison matrix			
Sustainability Dimension		Initial Weight	
Economic		0.505	
Environmental		0.317	
Social		0.179	

The recalculation of the weights of the criteria obtained at the 4th stage takes place by multiplying the weight of the corresponding criterion by the value of the corresponding weight coefficient of the group obtained from Table 3, which is displayed as *InitialWeight* in the following formulas:

$$w''_{eji} = w'_{eij} \cdot EconomicInitialWeight;$$
$$w''_{sji} = w'_{sij} \cdot SocialInitialWeight; \quad (4)$$
$$w''_{aji} = w'_{aij} \cdot EnvironmentalInitialWeight.$$

Next, we sum up the received weights for each type of accident *j* to obtain the value W_j for the following normalization of the weights of the criteria, which will allow us to obtain a vector of weights for each type of accident with a total value of 1:

$$W_j = \sum_{i=1}^{N_E^*} w_{eji}^{"} + \sum_{i=1}^{N_S^*} w_{sji}^{"} + \sum_{i=1}^{N_A^*} w_{aji}^{"},\ j = \overline{1,3}; \qquad (5)$$

$$w_{eij}^* = \frac{w_{eji}^{"}}{W_j}, w_{sij}^* = \frac{w_{sji}^{"}}{W_j}, w_{aij}^* = \frac{w_{aji}^{"}}{W_j}. \qquad (6)$$

The values of criteria weight vectors obtained at the 7th stage for each type of accident are shown in Table 4. At the 8th stage, considering the previous stages 1-7, we will propose the following general model for assessing the GSs vulnerability:

$$V_f = \frac{\sum_{j=1}^{N_{ac}} \left(\sum_{i=1}^{N_E^*} w_{eji}^* \cdot e_{fi} + \sum_{i=1}^{N_S^*} w_{sji}^* \cdot s_{fi} + \sum_{i=1}^{N_A^*} w_{aji}^* \cdot a_{fi} \right)}{N_{ac}}, \qquad (7)$$

where V_f – assessment of the GS vulnerability with the identifier *f*;

N_{ac} – total number of main types of accidents (in the study – *j* = 3);

N_E^*, N_S^*, N_A^* – total number of EESC respectively;

w_{eji}^*, w_{sji}^*, w_{aji}^* – the weight of the EESC i for j accident scenario respectively (Table 4);

e_{fi}, s_{fi}, a_{fi} – score *i* of EESC for *f* GS for scale from 0 to 1 respectively (Table 2 [18]).

Table 4
Weight vectors of the secondary feature space

Economic criteria	w_{eij}^*	Social criteria	w_{sij}^*	Environmental criteria	w_{aij}^*
		Shockwave			
E_1^*	0.073	S_1^*	0.056	A_1^*	0.061
E_2^*	0.122	S_2^*	0.024	A_2^*	0
E_3^*	0.069	S_3^*	0.048	A_3^*	0.058
E_4^*	0.069	S_4^*	0.029	A_4^*	0
E_5^*	0.116	S_5^*	0.027	A_5^*	0.07
E_6^*	0.106	–	–	A_6^*	0.073
		Oil spill fire			
E_1^*	0.098	S_1^*	0.042	A_1^*	0.058
E_2^*	0.125	S_2^*	0.038	A_2^*	0.058
E_3^*	0	S_3^*	0.052	A_3^*	0.094
E_4^*	0	S_4^*	0.038	A_4^*	0.055
E_5^*	0.138	S_5^*	0.042	A_5^*	0.058
E_6^*	0.103	–	–	A_6^*	0
		"Fireball"			
E_1^*	0.082	S_1^*	0.053	A_1^*	0.062
E_2^*	0.153	S_2^*	0.03	A_2^*	0.056
E_3^*	0	S_3^*	0.055	A_3^*	0.092
E_4^*	0.074	S_4^*	0.032	A_4^*	0
E_5^*	0.109	S_5^*	0.032	A_5^*	0
E_6^*	0.105	–	–	A_6^*	0.065

Since the value of the GS vulnerability assessment obtained using the formula (7) is expressed as a decimal number in the range [0, 1], it is necessary to interpret the value obtained in a form understandable to the user (decision-maker). Since it is a non-trivial task to clearly determine whether a GS belongs to one of the categories for vulnerability assessment, we can use FL and define it using the linguistic variable. At the 9th stage the GS vulnerability assessment is defined as a linguistic variable GV , what is a tuple:

$$\langle GV, T, V \rangle, \tag{8}$$

where: GV – name of the linguistic variable;

T = {"low vulnerability", "medium vulnerability", "high vulnerability"} – the basic term set of a linguistic variable, each value of which represents a fuzzy variable α_i . As a 1st approximation, when choosing the basic term set, it is proposed to use 3 terms, although in the future this number of fuzzy variables can be increased;

V = [0, 1] – the scope of definition of fuzzy variables that are included in the definition of a linguistic variable.

Fuzzy variables from the term set T are also defined as tuples of the form:

$$T = \langle \alpha_i, V_i, A_i \rangle, i = \overline{1,3}, \tag{9}$$

where: α_i – name of the fuzzy variable (α_1 – "low vulnerability", α_2 – "medium vulnerability"; α_3 – "high vulnerability" respectively);

V_i – scope of definition, for all 3 variables V = [0, 1];

$A_i = \{V_f, \mu_{A_i}(V_f)\}$ – fuzzy set on V , describing the possible values that a fuzzy variable α_i can take ($\mu_{A_i}(V_f)$ – the degree to which the value V_f belongs to a given fuzzy variable α_i in the range [0; 1]).

Fuzzy sets A_1 , A_2 and A_3 are proposed to represent in the form of trapezoidal membership functions f_{T_i} as a first approximation due to their simplicity, frequency of use in scientific researches, and the fact that no research was conducted on the spread (Gaussian and others) of the GSs estimations due to the small size of the studied set of objects. Let's define trapezoidal membership functions f_{T_i} for fuzzy variables α_i with the following parameters:

- $f_{T_1}(V_f, 0, 0, 0.3, 0.4)$ – for α_1 "low vulnerability";
- $f_{T_2}(V_f, 0.3, 0.4, 0.6, 0.7)$ – for α_2 "medium vulnerability";
- $f_{T_3}(V_f, 0.6, 0.7, 1, 1)$ – for α_3 "high vulnerability".

The corresponding membership functions f_{T_i} can be displayed graphically in Fig. 2. The fuzzy variable "low vulnerability" is shown in black, "medium vulnerability" in blue, and "high vulnerability" in green.

After substituting the value of V_f the degree to which the vulnerability assessment belongs to one of the 3 fuzzy variables can be calculated (respectively $\mu_{A_i}(V_f)$). Transition values from "low" to "medium" vulnerability in the range [0.3; 0.4] and from "medium" to "high" vulnerability in the range [0.6; 0.7] set the fuzziness in determining whether the assessment of the GS belongs to the relevant variables.

In accordance with the above considerations, at the 10th stage, the knowledge base for assessing the GSs vulnerability to the occurrence of accidents of the main types is formed, which in turn consists of a filled-in database about the GSs network, which will be further filled in accordance with stages 5–6, and will also contain a database rules for deriving the interpreted result of GS vulnerability assessment.

In accordance with the above considerations, we can propose the following rule base for the output of the interpreted result (considering the number of proposed terms, it can be expanded in the future):

- R1: if $f_{T_i} > 0$ – display the message: “The evaluated GS with degree f_{T_i} % belongs to the category “name of the i[th] fuzzy variable””;
- R2: if $f_{T_i} = 0$ – do not display message;
- R3: if $N(f_{T_i} > 0) > 1$ – display the message: “The estimated GS with the degree $f_{T_{i1}}$ % belongs to the category “name of the first i[th] fuzzy variable” and with the degree $f_{T_{i2}}$ % belongs to the category “name of the second i[th] fuzzy variable””.

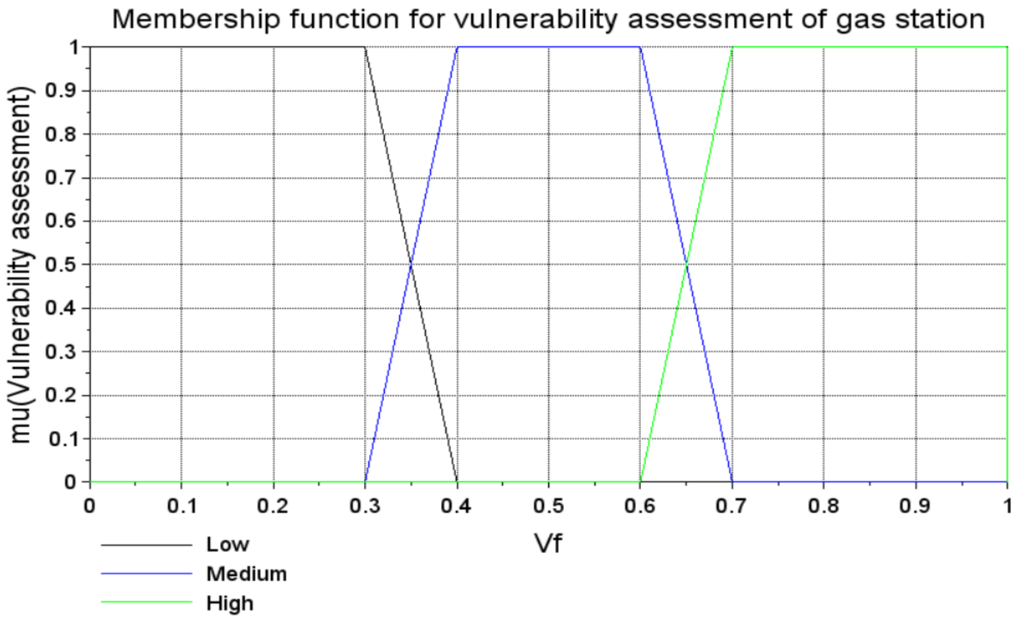

Figure 2: Trapezoidal membership functions of fuzzy variables of GS vulnerability assessment

Below, after deriving the interpreted result of the GS vulnerability assessment to the main types of accidents, the following messages can be issued that characterize the fuzzy variables of the GS vulnerability and can serve as a basis for decision-making by stakeholders:

- “Low vulnerability” means that in the event of a possible accident at the assessed GS, the scale of adverse consequences (economic, social and environmental) may be low and meet a certain acceptable level;
- “Medium vulnerability” means that in the event of a possible accident at the assessed GS, the scale of adverse consequences (economic, social and environmental) may be greater than the average level and may serve as a basis for conducting an examination of the assessed GS for compliance with all necessary regulations by regulatory authorities and taking necessary measures;
- “High vulnerability” means that in the event of a possible accident at the assessed GS, the scale of adverse consequences (economic, social and environmental) may be large, i.e., such that they may cause significant impact, and in this case, inspection of the assessed GS for compliance with all necessary regulations by regulatory authorities is recommended to take measures to reduce threats or close the GS.

An example of the screen form for deriving the interpretation of the vulnerability of a GS, where the assessment of the GS vulnerability belongs to 2 fuzzy variables at once, and therefore is subject to the rule R3 of the output of the interpreted result, is shown in Fig. 3.

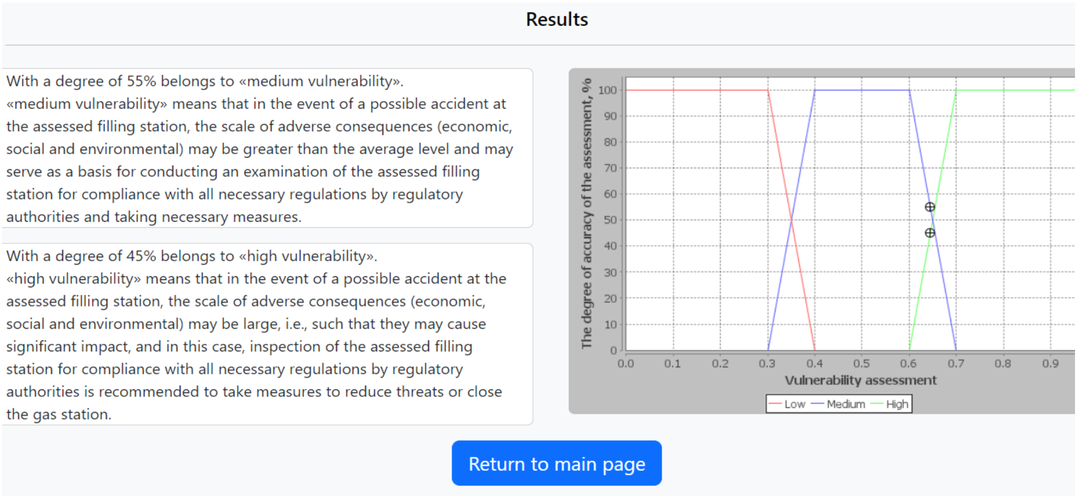

Figure 3: The screen form of the interpretation of the assessment of the GSs vulnerability

6. Implementation of the proposed intelligent IT in the form of a DSS and its approbation based on data about the GS network

As part of the implementation of the project, data on 17 GSs of a certain settlement were collected from open sources. Further, the obtained data were coded according to the coding table in [18]. The result of the received coded values of the GS vulnerability criteria with the help of intelligent IT is shown in Table 5 (full in [15]). After coding the GS data, showed in Table 5, by using model (7), estimates of GS vulnerability to the main accident types were calculated, the value of which is displayed in the last column of the Table 5 (*V*). Based on the results of GS vulnerability assessments, we will plot the distribution of assessment parameters depending on their location in Fig. 4. The parameter x is the normalized value of the latitude (y – the longitude respectively) on which the GS is located. GSs are located on the graph depending on the coordinates and have a colour depending on the vulnerability assessment parameter to the main types of accidents.

From Fig. 4, GSs can be divided into the following classes when comparing each other:

- Dark blue and light blue (4 objects) – has the least vulnerability;

Table 5
A view of the attribute values of coded GS data [15]

№GS	E1	E2	E6	S1	S2	S5	A1	A6	*V*
1	0.5	0.6	0	0.3	0	0.3	0.4	0	*0.403*
2	0.5	0.4	0.7	0.7	1	0.3	0.4	0.3	*0.551*
3	0.5	0.8	1	0.3	1	0.3	0.5	0.3	*0.630*
4	0.5	0.1	0	0.3	0.7	0.3	0.3	0	*0.196*
5	0.5	0.6	0.3	1	1	0.3	0.8	1	*0.716*
6	0.5	0.4	1	0.7	1	0.3	0.3	1	*0.654*
7	1	0.2	1	0.3	0.7	0.3	0.4	0	*0.531*
…	…	…	…	…	…	…	…	…	…
17	1	0.4	0.3	0	0.7	0.3	0.4	0	*0.496*

- Green (3 objects) – has a vulnerability below average;
- Yellow (3 objects) – has medium vulnerability;
- Orange (4 objects) – has an above-average vulnerability;
- Red and brown (3 objects) – has high vulnerability.

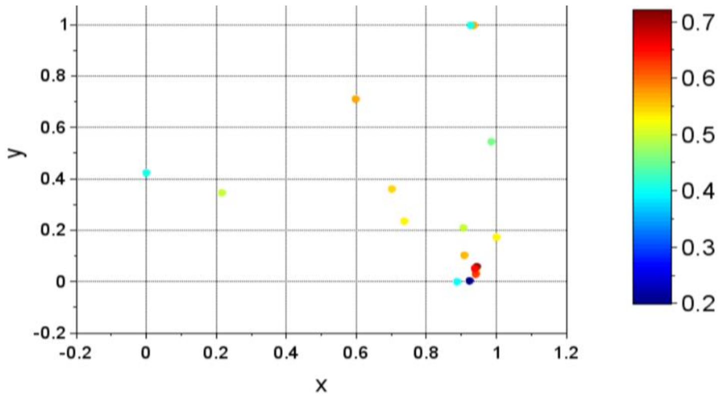

Figure 4: Graph of GS vulnerability assessments according to spatial coordinates

Let's consider the interpretation of the GS assessment, dividing it into the categories using fuzzy variables described in Fig. 2. Let's plot the obtained values of 17 studied GSs on graph in Fig. 5 in the form of point values on the corresponding graphs of membership functions.

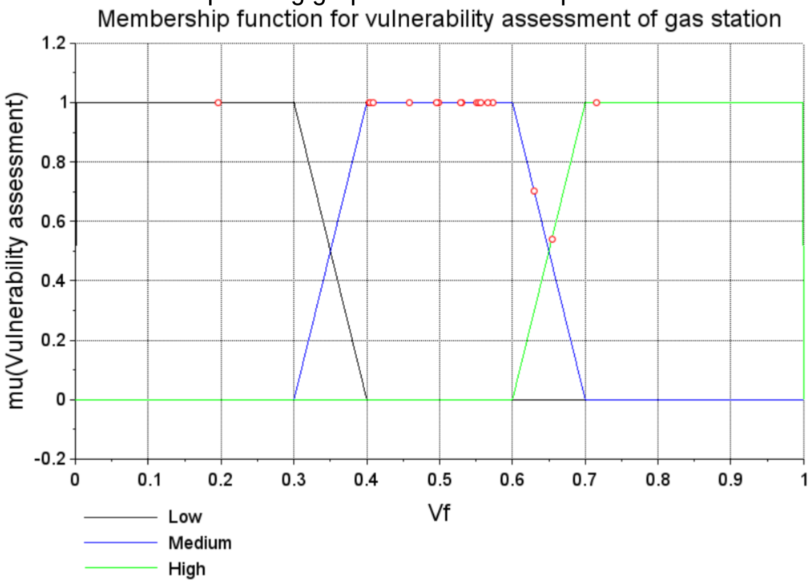

Figure 5: Vulnerability assessments of the studied GS network on graph of fuzzy variables

From Fig. 5 we can see, that studied GSs have the following distribution by fuzzy variables of GS vulnerability assessment: 1 GS has low vulnerability, 13 GSs have medium vulnerability, 2 GSs have medium and high vulnerability with different degrees, 1 GS has high vulnerability.

7. Conclusions

As a result of the research, an intelligent IT was developed for multi-criteria vulnerability assessment of GSs to the main types of accidents. To build it the 10 consecutive stages are proposed and described above, which allows for the creation of a DSS, which will allow numerical assessments of GS vulnerability based on the collected data to be converted into categorical ones using FL for further interpretation by decision-makers.

Among the advantages of using the proposed intelligent IT, it should be noted the increased efficiency of the preliminary analysis of the GSs vulnerability, since the developed IT not only increases the speed of data analysis and data collection, but also provides reasonable assessments of the GSs vulnerability, which gives recommendations for decision-makers. It is also worth noting that the proposed approach with further development and implementation in practice, can serve as a methodological basis for assessing the vulnerability of more complex potentially hazardous facilities, especially in their combination. As a disadvantage of the mentioned approach, its partial non-universality should be noted, since accidents at potentially hazardous facilities and their combinations may be different in nature; the potential complexity of forming an initial model of the vulnerability of a technological object, which may require the involvement of experienced highly specialized specialists, which is a time- and material-consuming task; subjectivity in decision-making, especially when they are based on experts' assessments, which can cause bias and affect the objectivity of the results. Also, due to the limited implementation time and financial capabilities of the project, the group of criteria of lost lives in a possible accident was excluded from the consideration of the GS vulnerability model, but this can serve as a basis for further research and improvement of the considered model.

In general, the developed intelligent IT can serve as a basis for a preliminary review of existing GSs and a preliminary assessment of their vulnerability to the main types of accidents, which can serve as a basis for making decisions about an extended assessment and limitation of their activity or closing the GS. This study may be of interest to a wide range of stakeholders, including regulatory bodies, the population, public organizations, etc.

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