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Fuzzy Analytical Hierarchy Process for Ecological Risk Assessment

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Abstract **– Being able to evaluate risks is an important task in many areas of human activity: economics, ecology, etc. Usually, environmental risk assessment is carried out on the basis of multiple and sometimes conflicting factors. Using multiple criteria decision-making (MCDM) methodology is one of the possible ways to solve the problem. Analytic hierarchy process (AHP) is one of the most commonly used MCDM methods, which combines subjective and personal preferences in the risk assessment process. However, the AHP involves human subjectivity, which introduces vagueness type of uncertainty and requires the use of decision making under those uncertainties. In this paper, work with uncertainty is considered using fuzzy-based techniques. The paper also analyses the ecological risk assessment towards human health in case of gaseous substance escape at a chemical factory using the fuzzy analytical hierarchy process.**

Keywords **– Fuzzy logic, fuzzy representation of knowledge, fuzzy analytical hierarchy process, risk assessment.**

I. Introduction

Risk management is an integral part of environmental risk analysis. This is the process of weighing the alternatives (options), choosing the most appropriate action, integrating engineering, social and economic data into risk assessment results.

Usually, the environmental risk assessment process includes objective data, while the risk management includes the preferences and attitudes that have both objective and subjective elements [1]. Environmental risk assessment, among the other tasks, includes making decisions that involve the choice of alternatives on the basis of multiple and sometimes conflicting factors. The multiple criteria decision-making (MCDM) methodology is one of the possible ways to solve the problem. MCDM has proven to be a promising and growing field of study since the early 1970s and many applications in the fields of engineering, social sciences, and business have been reported. One of the most widely used methods of MCDM group is an Analytic Hierarchy Process (AHP), which was developed and first published in [2], [3]. There is a growing list of publications on the application of AHP method. The AHP provides an ideal platform for complex decision-making problems.

Ecological risk assessment usually takes place in the conditions of lack or absence of valid initial data [4]. Nevertheless, even if the data are available in sufficient amounts, the analysed risk factors often contain linguistic definitions associated with human judgments and subjectivity that in turn introduce uncertainty in decision-making processes. Quite a big number of methods are meant for acquiring and using ambiguous probabilistic assessments, including interval probability, probability of second degree, etc. Difficulty of these methods and a bad interpretation of uncertain results make the methods imperfect.

The main goal of this paper is to quantify the effect of multiple risk factors in the ecological risk assessment process. Aiming at archiving this goal, the fuzzy analytic hierarchy process (FAHP) is applied in the risk assessment towards human health in case of gaseous substance escape at a chemical factory. Using this method as an example, the risk analysis hierarchy model of the gaseous substance escape is established, and then the safety level comprehensively assessed. Also, the weights of various risk factors are defined to find the most influential factors on the total risk level. The present article analyses the ecological risk assessment towards human health in case of gaseous substance escape at a chemical factory using the fuzzy analytical hierarchy process.

II. Fuzzy Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) [5] was first proposed in the 1970s by T. L. Saaty, an American expert in the field of operational analysis.

The AHP method uses special mathematical methods for the processing of personal subjective preferences of the individual or a group of individuals on the pairs of relevant factors assessing and analysing decisions. In most cases, the individuals are the experts in a particular field [6]. The AHP method works on the premise that the process of making a global decision on complex tasks can be performed by separating and structuring complex tasks into many simple tasks, displaying them in the form of hierarchal structure. In its turn, after the hierarchical structure is formed, the pairwise comparison of assessment factors is carried out according to the importance on a lower level of the hierarchy. The results of pairwise comparisons are displayed by numbers ranging from 1 to 9, where "1" means that the two evaluation factors are equally important, while the other extreme rating – "9" reflects the fact that one assessment factor is absolutely more important than the other. Next, the pairwise comparison of alternatives for each of the risk factors is carried out. Then, the obtained estimates are translated to the next level of the hierarchy – the level of the criteria, where the aggregation of previously obtained estimates is performed.

Next, the interim assessments are transferred to the upper level of the hierarchy – the level of objectives. There the final aggregation of previous estimates is made. Thus, the resultant estimation is obtained for each alternative decision. The selection of the optimal solution is made on the basis of comparison of these estimates.

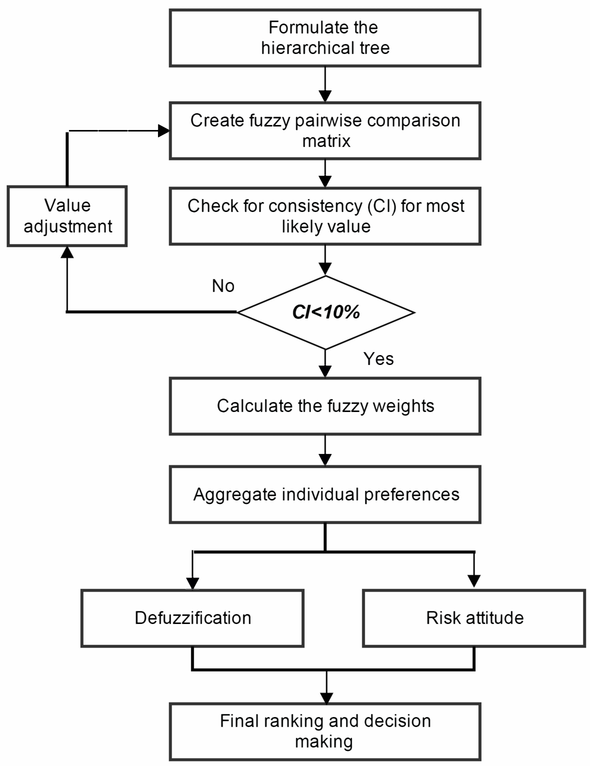

Fig. 1. Fuzzy analytic hierarchy process.

In the risk analysis, the AHP method is upgraded and it can be reduced to three main stages: 1) the creation of a hierarchical model of risk factors; 2) determination of the weights of risk factors; 3) quantitative estimation of the risk level.

S. Lopez and others in their study [7] have proposed a modernised AHP method that produces risk prioritisation according to their threat level.

Currently, there are many studies that combine the AHP methodology with the mechanism of fuzzy logic. Fuzzy logic methodology is used with the analytic hierarchy process to form a model for risk assessment. These models of risk assessment are used in various spheres, for example, risk assessment of floor water invasion in coal mines [8], oil and gas offshore wells [9], information technology projects [10]. In most cases, the fuzzy AHP method assumes that each risk factor is displayed as an element of lower level of the hierarchical structure and is expressed as a fuzzy number, which is the combination of fuzzy evaluation of the probability of a corresponding adverse event and the fuzzy evaluation of potential losses related to the implementation of this event.

The fuzzy analytic hierarchy process (FAHP) described in this paper is based on the interpretation of the decision maker's attitude towards a risk level in the decision-making process and was originally proposed by H. Deng in [11]. In this study, the FAHP methodology is formulated as a series of eight steps and is shown schematically in Fig. 1.

These eight steps are followed through a hierarchical structure example shown in Fig. 2.

III. Hierarchy Model Of Risk Factors

Identification of risk factors is the first step in the environmental risk assessment. In accordance with the features of environmental risk analysis, as well as with the combination of existing data and expertise, 12 factors have been defined. Those factors affect the level of risk in the event of an accident at a chemical plant and a leak of poisonous substances. The factors may also be divided into four categories. All the factors and categories are presented in Fig. 2, where the categories of factors are designated as $F = \{F1, F2, F3, F4\}$, where $F1$ represents a factor category of soil and groundwater vulnerability, $F2$ – hazardousness of substance, $F3$ – preventive and protective measure, $F4$ – human factor.

Each category of the above 4 categories also represents one factor set illustrated as fi, $Fi = \{fi1, fi2, ..., fij\}$, $i = 1, 2, 3$.

In order to support the risk assessment, based on the hierarchy of the risk factors shown in Fig. 2, a comprehensive risk assessment method is established – the FAHP method. The FAHP method includes the important procedures of the determination of weights of various risk factors, the quantitative analysis of risk factors, and the establishment of the comprehensive risk calculation model.

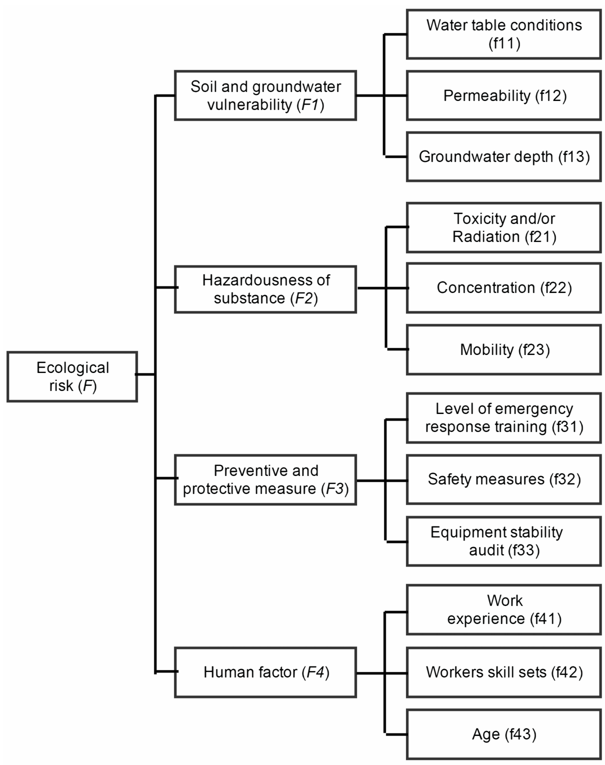

Fig. 2. The hierarchy of the risk factors in case of gaseous substance escape at a chemical factory.

The FAHP method is based on the idea that on the basis of the hierarchical model of risk factors for each factor the risk factor weight is determined. This is achieved by using fuzzy mathematics, performing the operations described below step by step. All mathematical calculations used at all stages and illustrated in the article have been implemented by Microsoft Excel.

A. Step 1: Definition of the Judgment Matrix

The values in the cells of matrix of judgments reflect subjective judgments in relation to importance of each factor in the hierarchical structure towards other factors. Table I presents a fuzzy version of T.L. Saaty's common fuzzy scale [12], in which the result of each comparison is shown as a triangular fuzzy number and its inverse equivalent. A triangular fuzzy number is represented by [lower value, mean value, upper value], i.e., [l, m, u].

TABLE I
LINGUISTIC SCALE OF RELATIVE IMPORTANCE

Linguistic scale for relative importance	Triangular fuzzy scale	Reciprocal of triangular fuzzy scale
Exactly the same	(1, 1, 1)	(1, 1, 1)
The same importance	(1/2, 1, 3/2)	(2/3, 1, 2)
Slightly important	(1, 3/2, 2)	(1/2, 2/3, 1)
Serious importance	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
More serious importance	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolute importance	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

According to the risk factor hierarchy (shown in Fig. 2), through comparison of the importance of each pair of risk factors, the judgment matrix of the 4 categories of risk factors in ecological risk assessment is shown in Table II. For example, an expert has concluded that the risk category "hazardousness of substance" ($F2$) is more important than factor of soil and groundwater vulnerability ($F1$), the result of comparison is displayed by the fuzzy number in the matrix.

TABLE II
JUDGMENT MATRIX OF RISK CATEGORIES

F	F_1	F_2	F_3	F_4
F_1	(1, 1, 1)	(2/5, 1/2, 2/3)	(1/3, 2/5, 1/2)	(2/3, 1, 2)
F_2	(3/2, 2, 5/2)	(1, 1, 1)	(1/3, 2/5, 1/2)	(2/3, 1, 2)
F_3	(2, 5/2, 3)	(2, 5/2, 3)	(1, 1, 1)	(2/3, 1, 2)
F_4	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1, 1, 1)

Similarly, the judgment matrix of risk factors can be obtained respectively as Tables III, IV, V and VI.

TABLE III
JUDGMENT MATRIX OF RISK CATEGORY – SOIL AND GROUNDWATER VULNERABILITY

$F1$	f_{11}	f_{12}	f_{13}
f_{11}	(1, 1, 1)	(1/2, 2/3, 1)	(2/5, 1/2, 2/3)
f_{12}	(1, 3/2, 2)	(1, 1, 1)	(1, 3/2, 2)
f_{13}	(3/2, 2, 5/2)	(1/2, 2/3, 1)	(1, 1, 1)

TABLE IV
JUDGMENT MATRIX OF RISK CATEGORY – HAZARDOUSNESS OF SUBSTANCE

$F2$	f_{21}	f_{22}	f_{23}
f_{21}	(1, 1, 1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)
f_{22}	(2/5, 1/2, 2/3)	(1, 1, 1)	(1/2, 2/3, 1)
f_{23}	(2/5, 1/2, 2/3)	(1, 3/2, 2)	(1, 1, 1)

TABLE V
JUDGMENT MATRIX OF RISK CATEGORY – PREVENTIVE AND PROTECTIVE MEASURE

$F3$	f_{31}	f_{32}	f_{33}
f_{31}	(1, 1, 1)	(1, 3/2, 2)	(3/2, 2, 5/2)
f_{32}	(1/2, 2/3, 1)	(1, 1, 1)	(1/2, 1, 3/2)
f_{33}	(2/5, 1/2, 2/3)	(2/3, 1, 2)	(1, 1, 1)

TABLE VI
JUDGMENT MATRIX OF RISK CATEGORY – HUMAN FACTOR

$F4$	f_{41}	f_{42}	f_{43}
f_{41}	(1, 1, 1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)
f_{42}	(2/5, 1/2, 2/3)	(1, 1, 1)	(2/5, 1/2, 2/3)
f_{43}	(2/5, 1/2, 2/3)	(3/2, 2, 5/2)	(1, 1, 1)

B. Step 2: Consistency Test

Consistency is important in human thinking and enables us to order the world according to dominance [13]. It is significant to ensure pairwise comparisons consistency in experts' evaluations that are defined in Step 1 of the matrix. Results of pairwise comparisons may differ due to the uncertainty of experts' assessments. The AHP method introduces a consistency test and measure to avoid this problem. The same consistency test is used in the Fuzzy AHP methodology. The main idea of this method is the following: once the judgment matrix is populated, the maximum eigenvalue is obtained.

In his works [2], [3] T.L. Saaty described in detail the methodology and formulas necessary for calculating the values and showed that in a consistent judgment matrix, $\lambda_{max} = n$, where, λ_{max} – the maximum eigenvalue and n – the dimension of the judgment matrix. Then using (1) consistency index (CI) is obtained. Consistency index indicates whether a decision maker provides the comparison of consistent values in a set of evaluations.

$$CI = \frac{\lambda_{max} - n}{n-1}. \tag{1}$$

The final possible inconsistency of pairwise comparisons of the results is determined using the consistency ratio CR = CI/RI, where RI is a random index, which is obtained by averaging the CI of a randomly generated reciprocal matrix [3]. Values of RI are shown in Table VII.

According to [3]: the threshold of consistency ratio is 10 %, and in case of exceeding the threshold value to reduce inconsistencies in the pairwise comparisons the following actions are performed: 1) the most controversial judgment in the matrix is determined, 2) the range of admissible values for minor corrections of judgments is determined to achieve reductions in inconsistencies, and 3) the expert is offered to correct some of the results of his/her pairwise comparisons.

TABLE VII
RANDOM INDICES OF N DIMENSIONAL MATRIX [3]

n	1	2	3	4	5	6	…
RI	0	0	0.52	0.89	1.11	1.25	…

The calculation results of consistency of pairwise comparison results for $F1 – F4$ risk factor categories are shown in Table VIII.

TABLE VIII
RESULTS OF CONSISTENCY TEST FOR MATRIX

	λ_{max}	CI	RI	CR
F	4.1818	0.0606	0.89	6.81 %
$F1$	3.0569	0.0284	0.52	5.47 %
$F2$	3.0206	0.0103	0.52	1.98 %
$F3$	3.0099	0.0050	0.52	0.95 %
$F4$	3.0607	0.0304	0.52	5.84 %

For a matrix of pairwise comparisons of the results presented in Table II, the maximum eigenvalue (λ_{max}) = 4.1818, for the $F1$ risk factor category, the dimension of the matrix n = 4, consistency index (CI) from (1) CI = 0.0606, the value of a random index (from Table VII) RI = 0.89. This implies that the value of the consistency ratio CR = 6.81 %. This value does not exceed the maximum admissible value of 10 %; therefore, the matrix results of pairwise comparisons can be correctly used in further calculations.

C. Step 3: Weight Calculation for Risk Factors

There are a number of different methods for calculating weights of factors (for example, [14]). One of the most popular FAHP techniques has been proposed by Chang [15], which uses the Fuzzy Extent Analysis in order to calculate the crisp weights from fuzzy comparison matrices. Applying this theory in the fuzzy comparison matrix, one can calculate the value of fuzzy synthetic extent with respect to the i^{th} object as follows:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1}, \tag{2}$$

where

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right), \tag{3}$$

and

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} = \left(\frac{1}{\sum_{j=1}^{m} u_j}, \frac{1}{\sum_{j=1}^{m} m_j}, \frac{1}{\sum_{j=1}^{m} l_j} \right). \tag{4}$$

The results of computing according to (2) in a matrix of pairwise comparisons, shown in Table II, are presented in the following form:

$S_{F1} = (2.40, 2.90, 4.17)$, $S_{F2} = (3.50, 4.40, 6.00)$,
$S_{F3} = (5.67, 7.00, 9.00)$, $S_{F4} = (2.50, 4.00, 5.50)$.

Next in the decision making process a crisp weight from these fuzzy triangular weights should be determined. D. Chang [15] suggests using the concept of comparison of fuzzy numbers in order to determine crisp weights from the fuzzy weights.

Next, for each fuzzy weight, a pair wise comparison with the other fuzzy weights is performed (using (5)), and the degree of possibility of being greater than these fuzzy weights is obtained. The minimum of these possibilities is used as the overall score for each factor.

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \begin{cases} 1, & \text{if } m_2 \geq m_1 \\ 0, & \text{if } l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise.} \end{cases} \tag{5}$$

Applying (5) to the previous results, we obtain the following values:

$V(S_{F1} \geq S_{F2}) = 0.65$, $V(S_{F1} \geq S_{F3}) = 0.23$,
$V(S_{F1} \geq S_{F4}) = 0.77$, $V(S_{F2} \geq S_{F1}) = 1.00$,
$V(S_{F2} \geq S_{F3}) = 0.58$, $V(S_{F2} \geq S_{F4}) = 1.00$,
$V(S_{F3} \geq S_{F1}) = 1.00$, $V(S_{F3} \geq S_{F2}) = 1.00$,
$V(S_{F3} \geq S_{F4}) = 1.00$, $V(S_{F4} \geq S_{F1}) = 1.00$,
$V(S_{F4} \geq S_{F2}) = 0.92$, $V(S_{F4} \geq S_{F3}) = 0.50$.

Finally, these scores are normalised (they sum up to 1), and the corresponding normalised scores of the 4 categories of risk factors are obtained:

$W_F = (0.10, 0.25, 0.43, 0.22)$

Similarly using the extent analysis method, the weight vectors of the risk factors are obtained as follows:

$W_{F1} = (0.15, 0.45, 0.41)$,
$W_{F2} = (0.73, 0.10, 0.27)$,
$W_{F3} = (0.50, 0.25, 0.25)$,
$W_{F4} = (0.66, 0.05, 0.34)$.

The overall weight of the risk factor equals multiplication of the local weight to weight of its "father factor". The weight importance of the categories and risk factors is shown in Table IX.

TABLE IX
WEIGHT TABLE FOR RISK FACTORS IN ECOLOGICAL RISK ASSESSMENT TOWARDS HUMAN HEALTH IN CASE OF GASEOUS SUBSTANCE ESCAPE AT A CHEMICAL FACTORY

Risk categories	Local weight	Risk factor	Local weight	Overall weight
*F*1	0.10	f_{11}	0.15	0.015
		f_{12}	0.45	0.044
		f_{13}	0.41	0.040
*F*2	0.25	f_{21}	0.73	0.183
		f_{22}	0.10	0.025
		f_{23}	0.27	0.069
*F*3	0.43	f_{31}	0.50	0.217
		f_{32}	0.25	0.108
		f_{33}	0.25	0.109
*F*4	0.22	f_{41}	0.66	0.141
		f_{42}	0.05	0.011
		f_{43}	0.34	0.074

IV. QUANTITATIVE ANALYSIS OF RISK FACTORS

In the previous section, the importance of each risk factor at the general level of risk to the environment in case of leakage of poisonous substances has been identified on the basis of experts' opinions, but that is not enough for the full assessment of the environmental risk. It is also necessary to include in the calculations the value that will display the real situation at the plant for each risk factor. Three risk groups have been defined to assess each risk factor in the study: low, medium and high level, which correspond to the numerical equivalent of 1, 3 and 5 points and are taken into account in the calculations of the ecological risk in case of leakage of poisonous substances at a chemical plant.

Table X demonstrates several risk factors and the description of their values.

V. CASE STUDY

In this article, the environmental risk assessment in relation to human health in the event of leakage of poisonous substances at a chemical plant is regarded as the case study. For visual clarity of display of the FAHP methodology results, it is supposed that a group of experts gave their opinion on the real state of the plant according to the factors presented in Fig. 2 and their values (Table X). For example, the experts after examining the plant have drawn the conclusion that the safety measure levels of the chemical plant (f_{32}) correspond to a medium risk group; therefore, taking into account the importance of this risk factor, the overall risk level of this factor is 0.323 units. The quantitative results of all risk factors are presented in Table XI. The weighed quantity risk and factor results are displayed as a graph in Fig. 3.

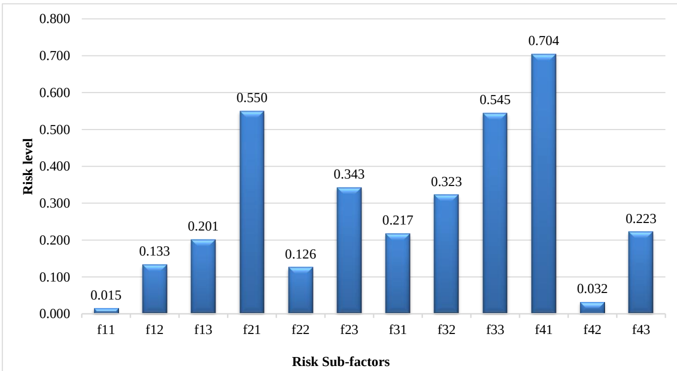

Fig. 3. The histogram of risk level of risk factors in case of gaseous substance escape at a chemical factory.

TABLE X
QUANTITATIVE ASSESSMENT CRITERIA OF RISK FACTORS

	High (5 points)	Medium (3 points)	Low (1 point)
Criteria of emergency response training level (f_{33})	Min.2–4-hour safety training – In emergency they would leave the area, then call for help, and keep others out of the area.	Min. 8-hour safety training – Personnel primary function is to contain the release from a safe distance, keep it from spreading, and prevent exposures. May be involved in decontamination.	Min. 24-hour safety training – Personnel will stop the release by plugging, patching or shutting down the process.
Safety measure levels of the chemical plant (f_{32})	The plant does not correspond to necessary safety requirements.	Generally, the plant corresponds to necessary safety conditions.	The plant fully corresponds to the safety requirements.
Criteria equipment stability audit level (f_{33})	The absence or lack of safety checks, repairs, or in rare cases, replacement of the equipment only after the failure.	Replacement or repair of equipment, if possible after detection of significant deviations from the norms of operability.	Constant automatic and manual security and equipment operability checks conducted by the experts of highest classification. Replacement of the equipment immediately after the detection of the smallest deviations.

TABLE XI
RISK FACTORS TABULAR STATEMENT FOR ECOLOGICAL RISK ASSESSMENT PROCESS

Risk factor	Overall weight	Chemical plant risk level	
		Real plant situation	Risk level
f_{11}	0.015	1	0.015
f_{12}	0.044	3	0.133
f_{13}	0.040	5	0.201
f_{21}	0.183	3	0.550
f_{22}	0.025	5	0.126
f_{23}	0.069	5	0.343
f_{31}	0.217	1	0.217
f_{32}	0.108	3	0.323
f_{33}	0.109	5	0.545
f_{41}	0.141	5	0.704
f_{42}	0.011	3	0.032
f_{43}	0.074	3	0.223

VI. FAHP LIMITATIONS

Notwithstanding a big number of advantages of FAHP methodology in the ecological risks assessments, there are also limitations. The limitations of Chang's FAHP methodology [15] include: 1) the normalisation formula does not take into account constraints derived from the AHP method [16]; 2) the method in very rare cases could lead to a wrong decision, because it might assign zero weights to some items (criteria, sub-criteria or alternatives), excluding them from the decision analysis [17]; 3) crisp values are not fully capable of reflecting a person's vague thoughts [18].

Despite the limitations of Chang's FAHP methodology [15], nowadays it remains one of the most popular FAHP methods for analysis of experts' evaluation.

VII. CONCLUSION AND FUTURE RESEARCH

On the basis of the current conditional situation analysis, 12 risk factors and 4 risk factor categories have been identified, which affect the overall level of risk to human health in case of leakage of gaseous substances at a chemical plant. The hierarchy and patterns among factors have been determined on the basis of the risk factors. Using the comprehensive risk assessment method (FAHP), the weight factors have been determined that represent the importance of each risk factor. The quantitative analysis of risk factors has also been performed. As an example, ecological risk assessment towards human health in case of gaseous substance escape at a chemical factory has been carried out, and the risk factors have comprehensively been assessed. The factors have been ranked according to their effect on the overall level risk.

It has been demonstrated from the application in actual cases that the risk assessment FAHP method is easy and effective in engineering applications, which can provide technical support for the accident risk assessment in the ecological risk assessment process. The application of the FAHP method to the assessment of risk of environment and people's health in case of gaseous substance escape at a chemical allows making a complex algorithm of analysis more affordable in order to obtain risk assessment in case of incomplete and reduced input data.

The use of this model allows for realistic preliminary assessment of the risk of accidental chemical releases. The methodology can be used not only by public authorities but also by plant managers, since it is a method that allows evaluating the risk level of the site and determining whether the safety measurements are suitable. This application can be used as a preliminary risk assessment tool, which can highlight critical situations and the need for more in-depth and complete analysis. It can also be used in case of the necessity to make thoughtful decisions in order to reduce a risk level.

In the future, it is planned to investigate a possibility of using other FAHP methodologies for the ecological risk analysis. The mentioned methods can be the following: Van Laarhoven and Pedrycz's FAHP model (1983); Buckley's FAHP model (1985), etc. It would be possible to consider their differences and analyse the results of identical experts' evaluation (initial data), as well as to make conclusions on the basis of the analysis results concerning positive and negative aspects of each method in case of their usage in the ecological risk analysis.

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