U.P.B. Sci. Bull. Series D, Vol. 72, Iss. 2, 2010 ISSN 1454-2358

ECOLOGICAL RISK ASSESSMENT METHODOLOGY BASED ON EVIDENTIAL REASONING THEORY

Mădălina ARAMĂ[1], Adrian V. GHEORGHE[2], Corneliu V. RADU[3], Radu D. STANCIU[4], Margareta NICOLAU[5]

Articolul prezintă o metodologie privind evaluarea impactului/riscului ecologic bazată pe regula de combinare a evidențelor Dempster din teoria Dempster-Shafer şi algoritmul abordării raționale a evidențelor - Evidential Reasoning, de noutate în România la nivelul anului 2008.Metodologie este capabilă să facă față incertitudinii proprii sistemelor de evaluare subiective.Ea este dedicata să ofere o cuantificare şi un model matematic pentru incertitudine şi răspunde, de asemenea, cerințelor legislației actuale de largă şi transparentă participare democratică a tuturor părților interesate la luarea deciziei în legătură cu impactul/riscul de mediu pentru dezvoltarea proiectelor private, publice sau în parteneriat public-privat.

The paper presents o new methodology to be used in Romania at the level of year 2008 regarding the ecological impact/risk assessment based on Dempster rule of combination from Dempster-Shafer evidence theory and the Evidential Reasoning algorithm. This methodology is able to face uncertainty proper for systems involving subjective assessments. It is able to offer quantification and a mathematical model for the uncertainty. It also respond to the present law requirements regarding large democratic and transparent participation of all stakeholders in the decision making process concerning environmental impact/risk assessment in the development of private, public or public-private partnership projects.

Key words: *environmental impact assessment, environmental risk assessment, Dempster-Shafer theory, Evidential Reasoning algorithm.*

1. Introduction

So far, the ecological impact/risk assessment approach has been based primarily on subjective systems unable to deal with uncertainties specific for such assessments. This comes from the nature of the assessed phenomena, used data, and unavoidable evaluators' subjective judgments. That is why one may submit assessment to subsequent reassessments, strictly dependent on the initial data and experts' panel value-judgments.

[1] Researcher grade III, National Institute for Industrial Ecology-ECOIND Bucharest, Romania
[2] Professor, Economic Engineering Department, University POLITEHNICA of Bucharest, Romania, and Old Dominion University, Norfolk, Virginia, USA
[3] Professor, Economic Engineering Department, University POLITEHNICA of Bucharest, Romania
[4] Professor, Economic Engineering Department, University POLITEHNICA of Bucharest, Romania
[5] Researcher grade I, National Institute for Industrial Ecology-ECOIND Bucharest, Romania

At the level of years 2002, 2004, and 2006 the operational research literature ([1] – [6]) offers practical examples of multi-criteria decision-making support methods for environmental impact/risk assessments based on Dempster – Shafer theory and an evidential reasoning algorithm..

Some of them, representing only a small sample, from a larger number of references that might be put in connection with the presented topic, are part of the cited references in this paper.

This paper, presents the results obtained from three investigated case studies. They have been used to exemplify new ecological impact/risk assessment methodology implementation for extractive, chemical and pharmaceutical industries. This methodology is a support for decision-making process in the environmental impact/risk management. It has a multi-criteria basis, responding to those decisions involving a multitude of interacting factors.

2. Method and instruments used in the current research

The proposed methodology consists of a set of principles, rules and methods able to offer a mathematical model of uncertainty and to consider all opinions during the assessment process even when they are very different in nature. The chosen research method was a case study based, that has the advantage of directly applying the theory in practice investigating the research objects in the real context they occur. It is also a method that includes evidences from multiple sources and uses oriented samples in case studies selection. In ecological impact/risk assessments, this selection type is a plus because, generally speaking, the usual or average cases are not the richest in information.

In case studies selection, we considered, on one side, the uniqueness of each case taking into account the specific pollution, and on the other side the fact that each of them might be a representative case for the prospective sustainable development of Romanian industry. We have also considered that is the most appropriate research method to exemplify the implementation of an ecological impact/risk assessment knowledge based method. We argue that this better emphasizes the causality behind the involved pollution issues.

The instruments of data collection were technical documentation and public surveys. We collected two categories of data for research accomplishment: quantitative data – measurements obtained from INCD-ECOIND Bucharest, and qualitative data from evaluators' value-judgments obtained from conducted public surveys. The evaluators have been selected according to prerequisits of scientific and management interest in their dailly or project-contingent professional activities for environmental protection and ecological risk prediction and based also on knowledge and experience in different areas. The public surveys presented three project alternatives named Project I, II and III, respectively. The entry data about Project I was pollution situations 1 and 2, about Project II was pollution situations 3 and 4 and about Project III was pollution situations 5 and 6. This information presented in a graphical form represents a sum of analytical data and other information that should help the assessors to express their own opinion in relation to the severity of possible pollution consequences.

For data validation we ensured that the used concepts were adequately defined (essentially those of “significant pollution” and “ecological risk”), and the method used in the evaluation process was based on the applicable current environmental legislation.

To assure the internal validity, we used data (physical-chemical and biological) from multiple sources of evidence namely from those three organizations and from INCD-ECOIND Bucharest, Romania laboratories.

By involving a number of 30 persons in the public surveys (grouped in six interest groups based on their specific field of activity), the method assured the external validity. Each group consisted of five members having background and experience in academic, research, hydromechanics engineering, quality management, environment, health and work safety fields, acting as environmental concerned public.

The same person conducted the surveys to assure the coherence of the groups’ instruction. The surveys results were analysed for completeness and usability. The short and explicit form of the survey allowed the checking of the filling data on spot. Next, we present a theoretical summary of the proposed method.

3. Theoretical considerations of the method

There are several possibilities to model mathematically the uncertainty. Dempster-Shafer theory is one of them. Uncertainty is the doubt in relation with the validity of a result. Validity of a result means the confirmation through objective proves that the result might be used for the purpose for which it has been designed. The uncertainty is the state of doubt of a person occurring from the unavoidable randomness of the natural world, and from the incompleteness of our knowledge (i.e. that is all we know at a certain moment in connection with a topic and we do not know what we do not know). The randomness is brought by the disagreement resulted from the attempt to assign the membership of universal set element to one of two or more disjointing sets in partial or total ignorance about the attributes/characteristics of this element.

The merits of the Dempster-Shafer theory come from the fact that it assigns probability mass functions to sets without need to consider the probability of each set elements [2]. This is especially important in a multitude of fields in which experimental results are not singletons but sets. This situation occurs when measurements are rather a set of values then precisely single value (imprecision represents a multitude of alternatives left unspecified in certain conditions) [1].

The theory is especially useful when the inherent uncertainty experts’ value judgments should be brought to a certain common reference. This theory has also the merit to aggregate evidences summing up, simplifying the data, and modelling their conflict [2].

The conflict modelling can be achieved through different rules of aggregation. The original aggregation/combination rule from Dempster-Shafer theory [3] was an AND type rule applied to independent evidences that neglects the conflict degree. This rule emphasizes common points of evidences; is a useful rule when evidence sources are credited as being trust-worthy.

Further modifications have been operated in the technique of using the initial Dempster-Shafer algorithm. The Evidential Reasoning (ER) evolved based on Dempster-Shafer aggregation rule as an algorithm that conforms to four axioms: of independence, of consensus, of completeness and incompleteness [4]. Essentially, it proposes a hierarchical structure of attributes in which an upper level attribute is assessed through a set of lower level attributes.

A summary of ER approach and a decision-making multi-attribute problem in uncertainty conditions is presented further. First, a set of assessment grades/standards are introduced for the assessment process. This assessment/ reference system consists of a number of evaluation grades forming the set $H = \{H_1, H_2, ..., H_N\}$. The five evaluation grades used in the present reference system to assess the pollution consequences represent severity pollution consequences (H_1 – very weak consequences, H_2 – weak consequences, H_3 – average consequences, H_4 – strong consequences, H_5 – very strong consequences). The upper level attribute, Y, represents the severity of pollution consequences in each presented case study. This upper level attribute will be assessed through a hierarchical structure made of its sub-attributes.

One may assess the severity of pollution consequences Y through its basic attributes (the lowest level) e_i for L basic attributes that forms the E set as follows:

$$E = \{e_1, e_2, ..., e_i, ..., e_L\}$$

Each basic attribute e_i has a relative weight w_i previously established through any known method like AHP (Analytical Hierarchy Process) and satisfying the relation $0 \leq w_i \leq 1$.

Generally, a superior hierarchical attribute may have a distributed assessment for the basic attribute e_i as follows:

$$S(e_i) = \{H_n, \beta_{n,i})\} \text{ where } n = 1, ..., N \text{ and } i = 1, ..., L$$

For the proposed Projects I, II and III the distributed assessment takes the forms:

$$y^I = S^I(e_i) = \{(H_n, \beta_{n,i})\}$$

$$y^{II} = S^{II}(e_i) = \{(H_n, \beta_{n,i})\}$$

$$y^{III} = S^{III}(e_i) = \{(H_n, \beta_{n,i})\}$$

where $\beta_{n,i}$ represents the belief degree that satisfies the conditions $\beta_{n,i} \geq 0$, and $\sum_{1}^{N} \beta_{n,i} \leq 1$.

A distributed assessment in the form $S(e_i)$ is complete (respectively incomplete) if $\sum_{1}^{N} \beta_{n,i} = 1$(respectively $\sum_{1}^{N} \beta_{n,i} \leq 1$).

The probability mass function, $m_{n,i}$, represents the measure in which the basic attributes e_i supports the hypothesis that Y attribute is evaluated at the generic grade H_n.

$m_{n,i} = w_i \beta_{n,i}$, $n = 1,...,N$

The probability mass function remaining unassigned to any individual grade after all the evaluation grades N have been used for the evaluation of general attribute Y with reference to generic basic attribute e_i, $m_{H,i}$, is defined as:

$$m_{H,i} = 1 - \sum_{i=1}^{N} m_{n,i} = 1 - w_i \sum_{i=1}^{N} \beta_{n,i} \tag{1}$$

Let $E_{I\ (i)} = \{e_1,\ \ldots,\ e_i)$ be the subset made of the first i basic attributes characterizing the upper level attribute Y, and $m_{n,I(i)}$ the probability mass defined as belief/support that all basic attributes in $E_{I\ (i)}$ support the hypothesis that Y is evaluated to the generic grade of evaluation H_n. The probability mass unassigned to any individual grade after all basic attributes from $E_{I\ (i)}$ have been evaluated, is $m_{H,\ I\ (i)}$. The quantities $m_{n,I(i)}$ and $m_{H,I(i)}$ can be generated through combination of the generic elementary probability mass $m_{n,\ j}$ and $m_{\ H,\ j}$, computed for all assessment grades for the first i basic attributes taken into account where j=1,..i.

Then, the original ER algorithm computes inductively $m_{n,\ I\ (i+1)}$ and $m_{H,I(i\ +1)}$ as follows:

$$m_{n,I(i+1)} = K_{I(i+1)} \cdot (m_{n,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1} + m_{H,I(i)} m_{n,i+1}) \tag{2}$$

$$m_{H,I(i+1)} = K_{I(i+1)} \cdot (m_{H,I(i)} m_{H,i+1}) \tag{3}$$

for $n = 1, ..., N$, and i=1,…L-1.

$K_{\ I(i+1)}$ is a normalisation factor defined by:

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{j=1}^{N} m_{t,I(i)} m_{j,i+1} \right]^{-1} ,\ t \neq j \tag{4}$$

Then we obtain:

$$\beta_n = m_{n,I(L)} \text{ for n=1,..N and } \beta_n = m_{H,I(L)} = 1 - \sum_{n=1}^{N} \beta_n \tag{5}$$

A number of changes have been made also to the original ER algorithm with the purpose to use an aggregation process with a solid scientific theoretical basis. In the ER modified algorithm [5], Yang et all. Considered that the probability remained unassigned to any individual grade, as being split in two parts:

– $m^*_{H,i}$ the part that measures the effect of relative importance of the considered attributes.
– $-m^{**}_{H,i}$ the part that measures the effect of assessment incompleteness of basic attributes e_i for a generic alternative a_k, where $k = 1, \ldots, M$. [5]

The quantity $m^*_{H,i}$ represents how much the other considered attributes/factors can influence the evaluation of Y or, in other words, the proportion of belief that remains to be assigned offering by the frame to solve the conflict in the presence of conflict evidences. The quantity $m^{**}_{H,i}$ represents a measure of evaluation of completeness/incompleteness and is zero when the evaluation is complete i.e. if there is no ignorance in evaluation [6] .

The modified algorithm is used in the selection of the best alternative, from a set of project alternatives with reference to some established relevant criteria. Each of these project alternatives offers different mitigation measures for the possible ecological risk in relation with different environmental factors. The global performance of each alternative/project is evaluated based on relevant criteria that measure the degree of accomplishment of the general objective of the project/alternative selection that is the minimization of total environmental risk for all environmental factors [6].

4. Results and Discussions

In the chosen practical case studies Pr I, Pr II, and Pr III [7], we defined a hierarchical structure on two levels with a top attribute characterized by two basic attributes. The sets of basic attributes are denoted: $\{e_A, e_B\}$, $\{e_A', e_B'\}$, $\{e_{\text{air}}, e_{\text{health}}\}$ and include all factors influencing the evaluation of the top level attribute “Y = the severity of pollution consequences” for: water body I in case study Pr I, water body II in case study Pr II and air pollution in case study Pr III.

1. We defined the above-mentioned sets: $E(I) = \{e_A, e_B\}$, $E(II) = \{e_A', e_B'\}$, $E(III) = \{e_{\text{air}}, e_{\text{health}}\}$
2. We considered the set of relative weights $w = \{w_1, w_2\}$, where $\sum w_i = 1$ and $i = 1{:}2$ in three possible situations in order to analyse the method sensitivity/ robustness: equal weights of those two attributes, one attribute weight is the double of the other, respectively one attribute weight is the triple of the other.
3. We defined five distinct assessment/evaluation grades with semantic values presented in Section 2 (those evaluation/assessment grades represent the multitude of working hypothesis that form the universe of discourse (a complete set of assessment/evaluation standards for each project/alternatives)).
4. The multi-attribute decision problem for each case studies is presented using the distributed assessments:
$S^{I}(e_i) = \{H_n, \beta_{n,i}\}$, where $i = A, B$ with $L = 2$; $n = 1:5$ and $\sum \beta_{n,i} \le 1$
$S^{II}(e_i) = \{H_n, \beta_{n,i}\}$, where $i = A', B'$ with $L = 2$; $n = 1:5$ and $\sum \beta_{n,i} \le 1$

$$S^{III}(e_i) = \{H_n, \beta_{n,i}\}, \text{ where } i = air, health \text{ with } L = 2;\ n = 1:5 \text{ and } \sum \beta_{n,i} \leq 1$$

We made the computations, according to the presented algorithm; the results are presented in the following diagram (see Figure 1). The surveys' information has been presented in four pages graphical doccuments with short comments - a synthesis made by authors after a six months study of the available data [7] considered as the most intutitive manner for quick opinions' formation. The evaluators have at their disposal one day to express their personal subjective probability in relation to the severity of actual or possible pollution consecquences for ecah of the exhaustive set of working hypoteses ranging from from "very low severity" to "very high severity". There were no erroneous answers. The following comments have been presented: suppose we have four polluted water streams representing four pollution situations having the various types of pollutants. As an example, Figure 1 illustrates the pollution situation 1.

The same presentation manner has been used also for the other three pollution situations. Those polluted streams are flowing in other water bodies. Considering the quantitative available data assessment consisting in physical-chemical and biological

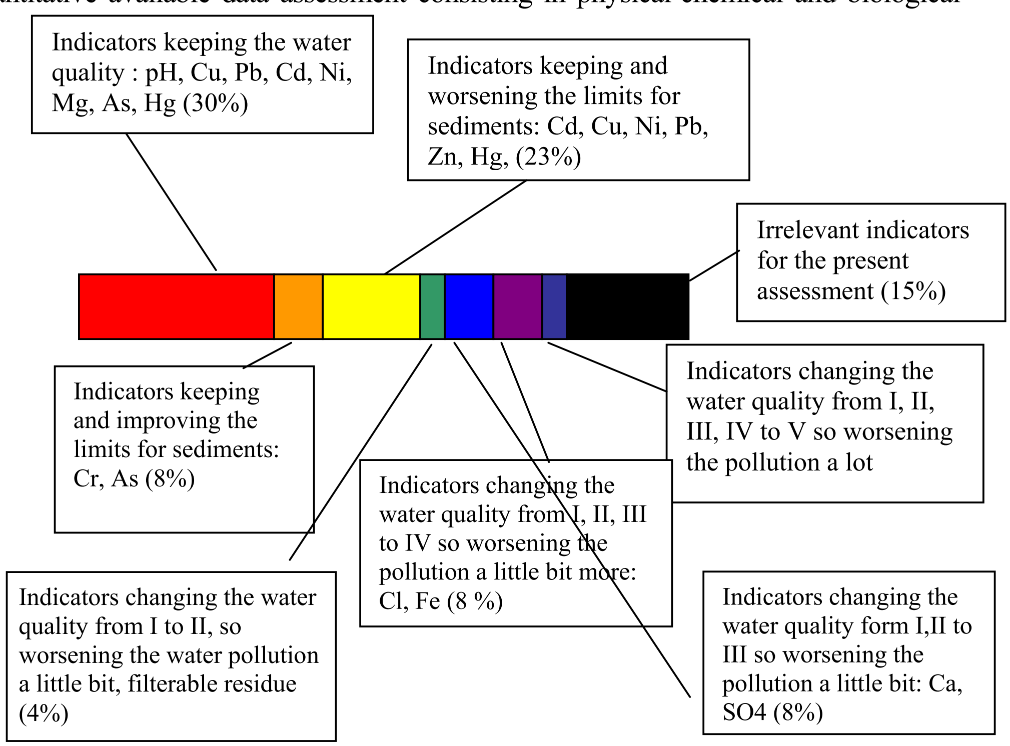

Fig. 1. Pollution situation 1 –small water body flow rate going into big water body flow rate

analysis, we computed the percentage of normally legal pollution indicators for surface water and sediments keeps unchanged the water quality before the confluence with those polluted streams. We determined also the percentage of indicators that generate the deterioration of water quality and how much is this deterioration, knowing that the current legislation considers the following water qualities: I – very good, II – good, III – average, IV- poor and V – very poor. In the assessment, we will consider both the pollutants' nature and toxicity and the fact that water volumes are small in situations 1 and 2, and large in situations 3 and 4. They are going into the same types of water body considered as big rivers. It should be mentioned that the current legislation does not consider Na and Ca indicators as pollutants. However, they are measured and they are discussed contextually in the case of different downstream water usages and in the local pollution context. The presented information received by the evaluators has been summarized in a diagram as the one presented in Fig. 1.

In Figures 2 and 3 we present also the pollution situations 5 and 6 in a different form of that presented for pollution situations 1-4. The information contained in this figure is meant to contribute to the evaluators' value judgments formation about pollution situations exemplified, in those evidences.

After processing the responses from the six evaluators' groups, presented in Figures 4 to 9, the obtained results show the average belief number. The assigned grades as in Figure 10-I,II,III (e_1=e_2) support the classification of the

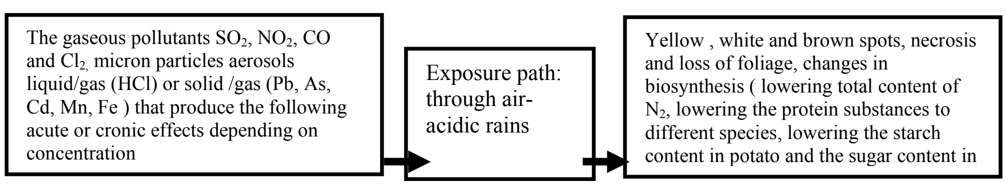

Fig. 2. Pollution Situation 5

projects in the order Project III, Project II, and Project I (from the pollution consequences severity point of view).

The assessment that Project III is the risky one of the three considered projects/alternatives results from the evaluators' perception that the oral exposure by inhalation is much more severe then the oral exposure way by ingestion as in the case of water. In the case presented in Projects I and II, they considered that efficient functionality of water treatment plants reduce the risk for people and their health. This reaction was generated mainly by the perception about the possibility of human health severe consequences and shows that decision in environmental management is one based equally on evidence and emotional motivations.

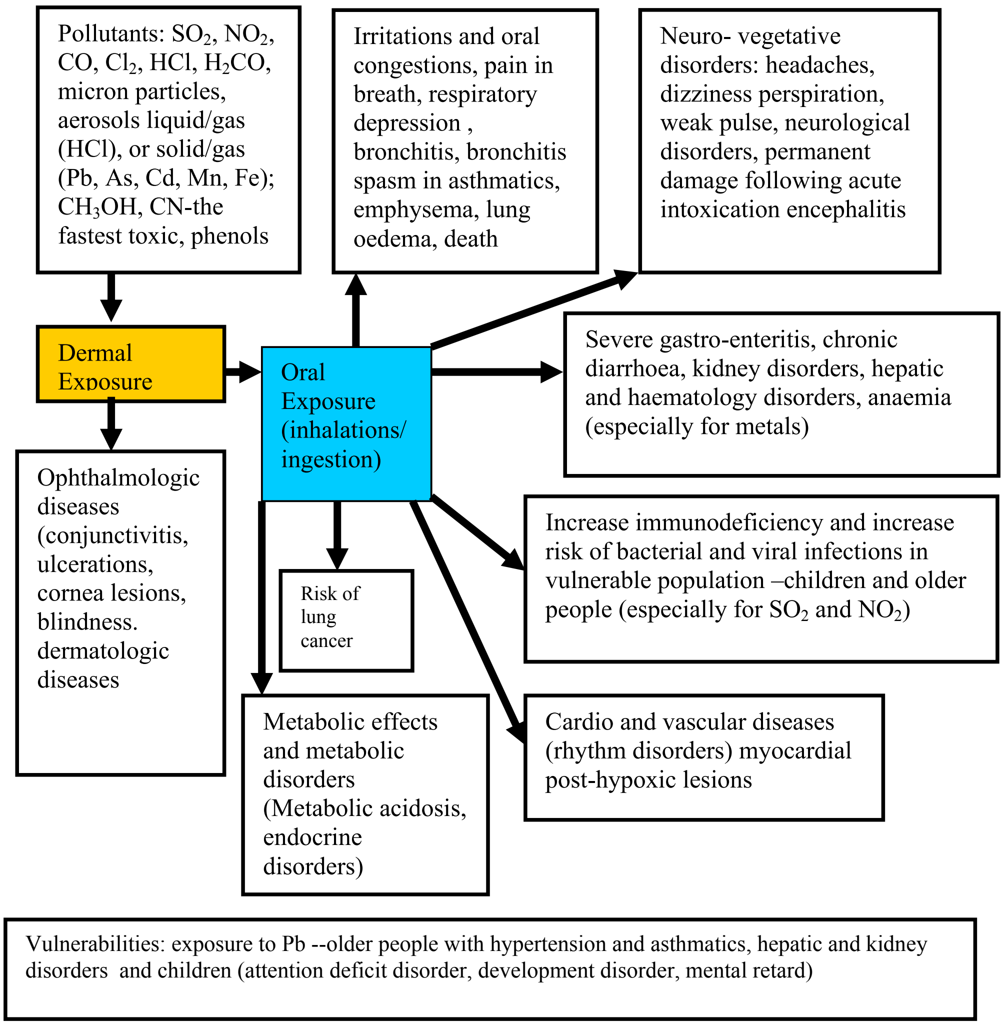

Fig. 3. Pollution situation 6

The method is specifically designed for large consultation including the public, fulfiling the democratic desiderate as the international environmental law requires. It is also a solution oriented method considering all competent experts' opionions when a decision should be made even when divergent oppinions exist. It takes them into account emphasising the assessment comon points.

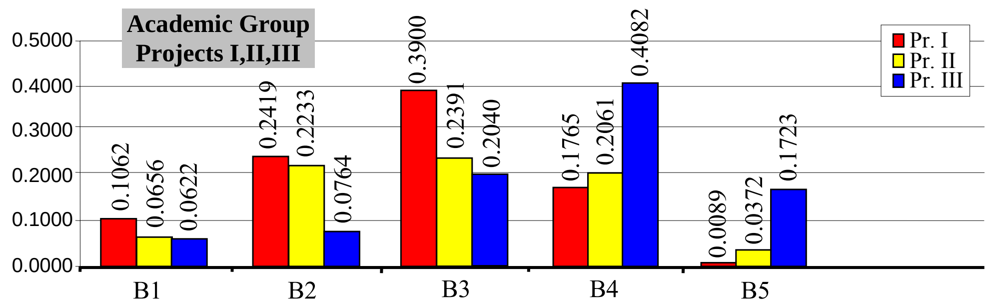

Fig. 4. Academic Group-Distributed Assessment-Average Belief (Group of five members)
B1-very low severity; B2-low severity; B3-average severity; B4-high severity; B5-very high severity

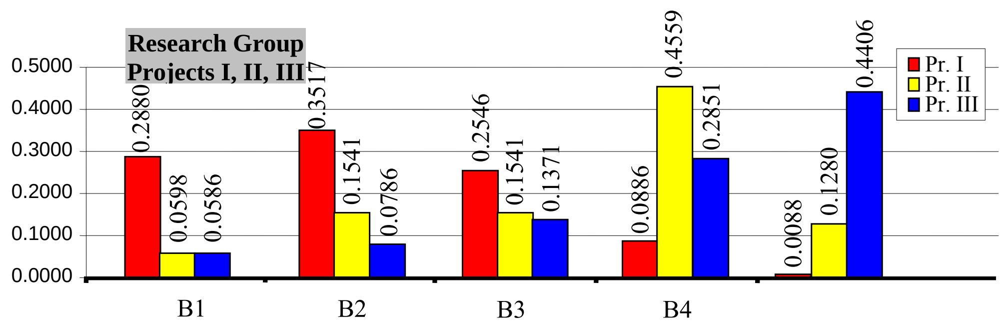

Fig. 5. Research Group-Distributed Assessment Average Belief (Group of five members)
B1-very low severity; B2-low severity; B3-average severity; B4-high severity; B5-very high severity

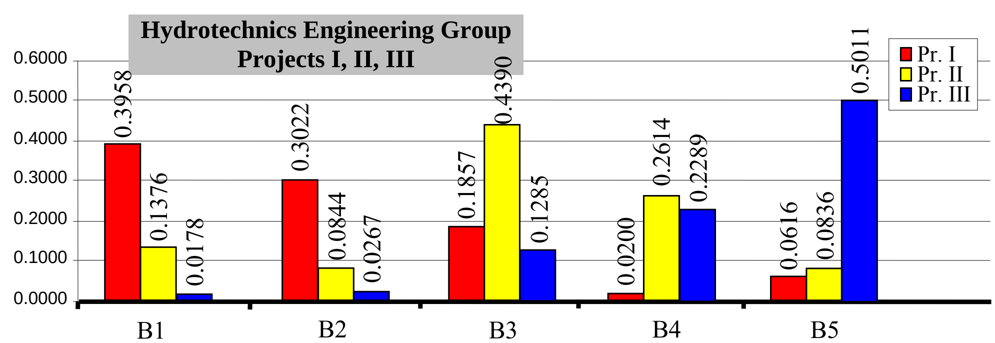

Fig. 6. Hidrotechnics Engineering Group-Distributed Assessment Average Belief (Group of five members)
B1-very low severity; B2-low severity; B3-average severity; B4-high severity; B5-very high severity

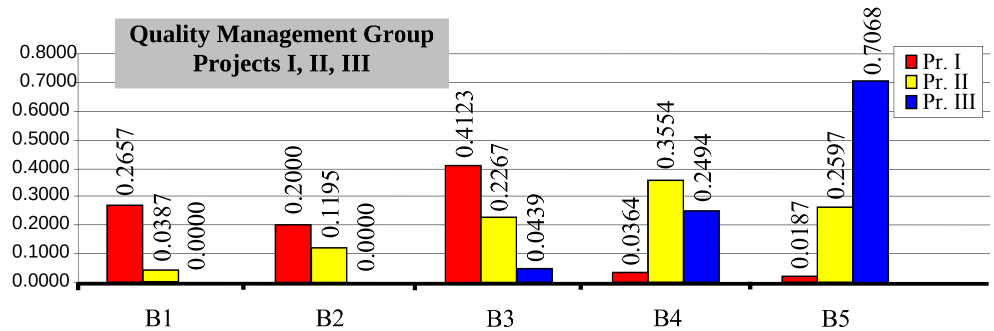

Fig. 7. Quality Management Group-Distributed Assessment-Average Belief (Group of five members)
B1-very low severity; B2-low severity; B3-average severity; B4-high severity; B5-very high severity

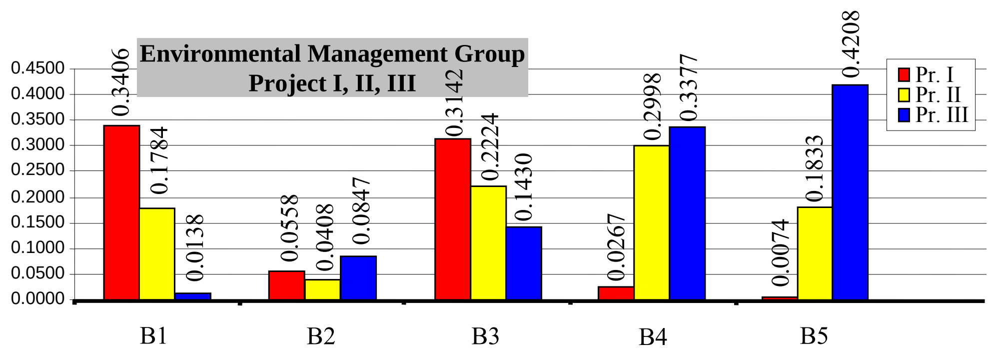

Fig. 8. Environmental Management Group-Distributed Assessment-Average Belief (Group of five members)
B1-very low severity; B2-low severity; B3-average severity; B4-high severity; B5-very high severity

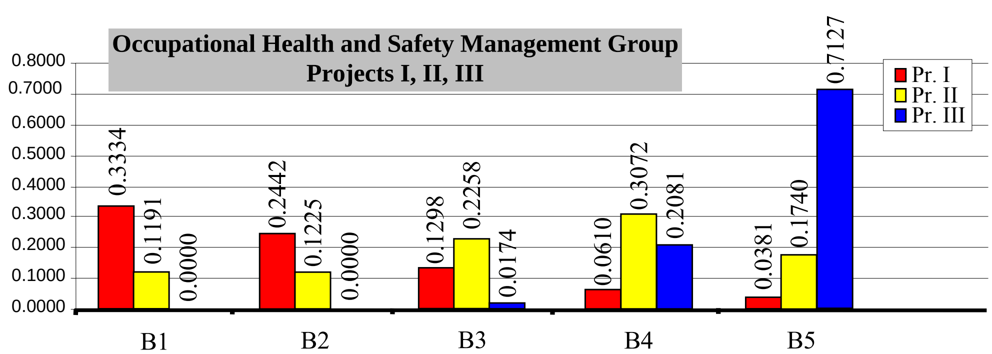

Fig. 9. Occupational Health and Safety Management Group-Distributed Assessment-Average Belief (Group of five members)
B1 -very low severity; B2-low severity; B3-average severity; B4-high severity; B5-very high severity

5. Conclusions

The essential advantage of the working method given in this paper, compared with other aggregation methods is that it supports a transparent and democratic manner of the decision-making process for environmental risk perspective. This assertion was proved by the fact that the ranking order was not changed even when we modified the weight of basic attributes i.e. doubling respectively tripling the weight in aggregation process.

This thing is illustrated in Figures 10-I, II, III, (e_1=e_2), 11-I, II, III, (e_2=2e_1), and 12-I, II, III, (e_2=3e_1). So, even when evaluators may receive information with a possible greater emotional impact, as in the presented case, or when the weight of attributes is very different (see the modification from simple to double and triple of the relative attributes' weights) the ranking of the proposed alternatives is not changed – see the curves' forms and the corresponding values.

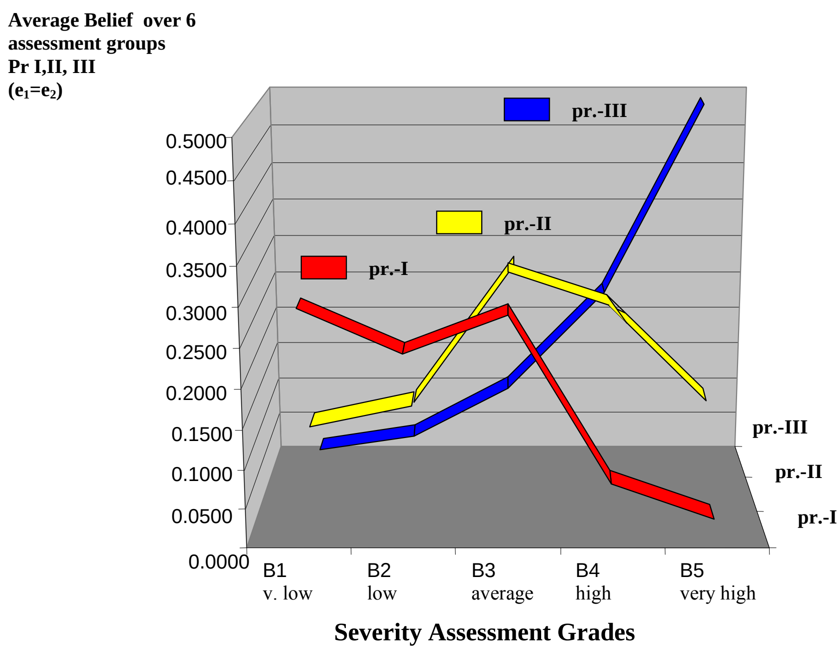

Fig. 10-I, II, III (e_1=e_2) Distributed Assessment Average Belief/Support in each assigned assessment grades -6 professional expert groups-5 members each group assessing the severity of pollution consequences in case study project I, II, and III when attributes weights are equal

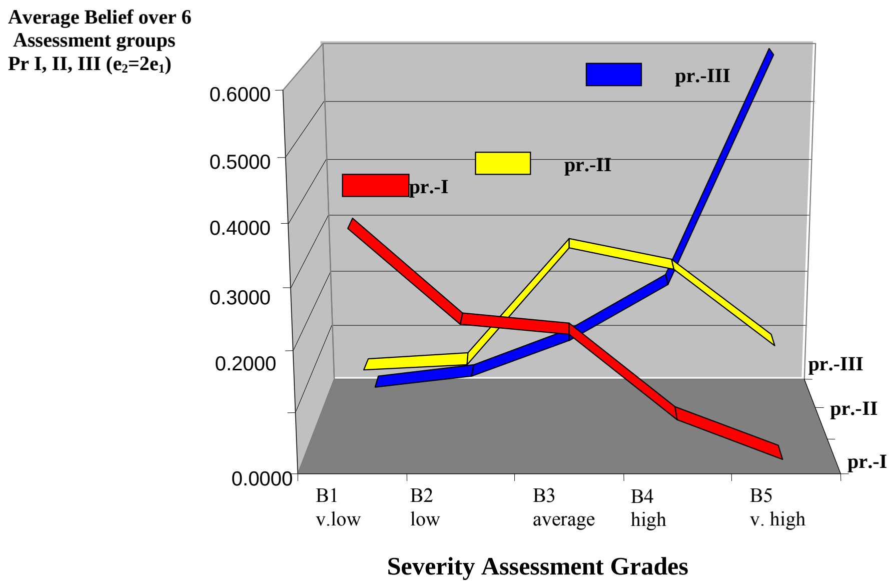

Fig 11-I, II, III, (e_1=2e_2). Distributed Assessment Average Belief/Support in each assigned assessment grades -6 professional expert groups-5 member each group, assessing the severity of pollution consequences in case study project I, II, and III when the weight of one attribute is double of the other.

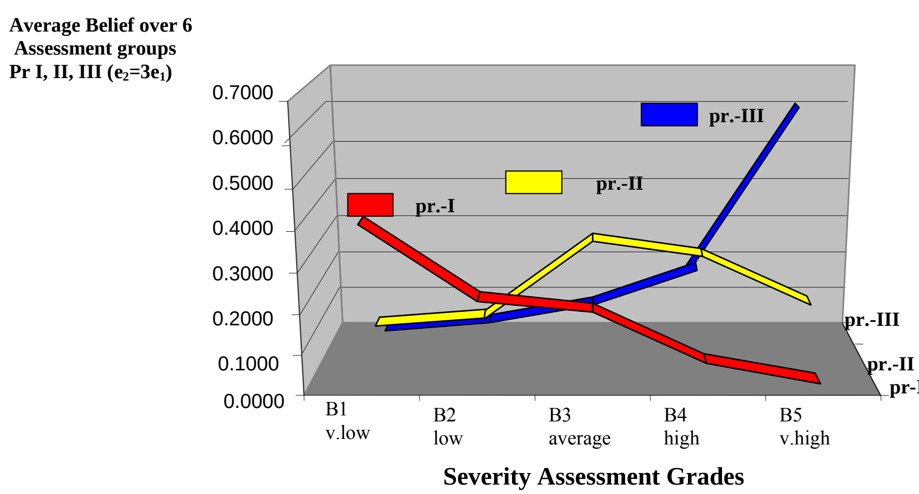

Fig. 12-I, II, III (e_1=3e_2). Distributed Assessment Average Belief/Support in each assigned assessment grades -6 professional expert groups-5 member each group, assessing the severity of pollution consequences in case study project I, II, and III when the weight of one attribute is three times the other

Consequently, we consider that the presented methodology will become a real support for the decisions concerning the pollution impact/risk management, being able to reach the consensus necessary for these kinds of projects in which each interested party can elicit its opinion in a democratic way becoming part of any decision making process.

This method offers the advantage that the evaluation can be submitted to a new scrutiny process and to information updates of the used data. This represents a characteristic that differentiate it very clear from the other used methods existing until now on the consulting market. It is very useful both for evaluators but also for the management that wants to minimize the risk of taken decisions.

REFERENCES

[1] *A. Bernardini, F. Tonon,* "Aggregation of Evidence from random and fuzzy sets", Zamm-Z.Agnew. Math.Mech. **84**, No.10-11, pp 700-709 (2004) www.zamm-journal.org

[2] *K.Sentz, S. Ferson,* Combination of Evidence in Dempster-Shafer Theory. Sandia National Laboratories Report SAND2002-0835 p2

[3] *G. Shafer*, "Perspectives on the Theory and Practice of Belief Functions" 1990 http://www.glennshafer.com/assets/downloads/articles/article40.pdf)

[4] *Van-Nam Huynh, Yoshiteru Nakamori, and Tetsuya Murai,* "Multiple-Attribute Decision Making Under Uncertainty: The Evidential Reasoning Approach Revisited", IEEE Transactions on Systems, Man and Cybernetics –Part A: Systems and Humans, **vol. 36.** No, 4 July 2006, pp. 804-822

[5] *Jian-Bo Yang, Dong-Ling Xu* "On the Evidential Reasoning Algorithm for Multiple Attribute Decision Analysis Under Uncertainty" IEEE Transactions on Systems, Man and Cybernetics – Part A: Systems and Humans, **vol. 32**, No.3, May,2002 pp 289-304

[6] *Ying-Ming Wang, Jian-Bo Yang and Dong-Ling Xu* "Environmental Impact Assessment using the evidential reasoning approach" European Journal of Operational Research **174** 2006 pp 1885-1913

[7] *INCD-ECOIND Bucharest* – Data Bases– Environmental Impact/Risk Studies