

Hazards Identification and Prioritization in Formal Safety Assessment Using Fuzzy Logic Theory

Author Name(s): G. N. Dourmas¹⁾; N. V. Nikitakos²⁾; M. A. Lambrou³⁾

¹⁾ Dept. of Shipping Trade and Transport, University of the Aegean, Chios, Greece, g.dourmas@aegean.gr

²⁾ Dept. of Shipping Trade and Transport, University of the Aegean, Chios, Greece, nnik@aegean.gr

³⁾ Dept. of Shipping Trade and Transport, University of the Aegean, Chios, Greece, mlambrou@aegean.gr

Abstract

Formal safety assessment of ships has attracted great attention over the last few years. This paper, following a brief review of the current status of marine safety assessment is focused on the hazards identification (HAZID) and prioritization process, as the first step in the formal ship safety assessment. A multicriteria decision making framework which is based on experts' estimation is then proposed for hazards evaluation. This paper proposes an innovative methodological approach to evaluate hazards by turning the qualitative judgments to quantitative, where sets of general and domain-specific criteria are used to judge the relative consequences of alternative hazards. The proposed methodology has the innovative feature of embodying techniques of fuzzy logic theory into the classical multicriteria decision analysis. The paper concludes by exploring the potentiality of the above methodology in providing a robust and flexible evaluation framework suitable to the characteristics of a hazard evaluation problem.

Keywords

Decision making; Formal Safety Assessment (FSA); Hazard Identification; Marine safety; Fuzzy logic.

1. Introduction

Hazard Identification (HAZID) is the first and in many ways the most important step in a risk assessment. This paper, following a brief review of the current status of marine safety assessment is focused on the hazards identification and prioritization process. Hazard identification is the process of systematically identifying hazards and associated events that have the potential to result in a significant consequence. The aim of HAZID is first to produce a list of all possible hazards and second to evaluate them in order to prioritize them. In order to support the evaluating procedure we propose as a tool the Multicriteria Decision Analysis (MCDA). The reason is that the final decision depends on criteria which correlate the potential hazardous scenarios with different consequences.

MCDA deals with the problem of ranking various alternatives in the presence of multiple criteria (Zeleny, 1982; Steuer, 1986; Lai and Hwang, 1994). Up to now, there has been a variety of methods that one could choose from in order to solve a multicriteria decision problem (Baas and Kwakernaak, 1977; Wang, 2000;

Nikitakos et. al, 2002). The most famous being the maximin (Dyson, 1980; Leberling, 1981), the weighted average, the multicriteria utility evaluation and the Analytic Hierarchy Process (Saaty, 1980).

All the aforementioned methods assume that the decision maker is able to provide exact assessments on the importance of evaluation criteria on the impact of alternatives. However, owing to the availability and subjectivity of information, it is very difficult to obtain exact assessment data as concerns the fulfilment of the requirements of the criteria or the relative importance of each criterion. Classical decision-making methodologies are thus criticized for over-simplifying the decision-making process by "forcing" the experts to express their views on pure numeric scales. It is common evidence that assessments made by experts are mostly of subjective and qualitative nature.

Fuzzy sets theory, originally proposed by L. A. Zadeh (1965), is an effective means to deal with the "vagueness" of human judgment. This theory offers us tools to handle linguistic terms as the ones mentioned above by converting them to suitable fuzzy sets and numbers. "Fuzzy" multicriteria decision analysis methods allow us to integrate linguistic assessments and weights in a multicriteria decision analysis setting (Liang and Wang, 1991; Prabhu and Vizayakumar, 1996).

After fuzzy sets general methodology presentation this paper proposes an application to evaluate and rank a number of hazards. We assume a multi-criteria decision making framework, where sets of general and domain-specific criteria are used to judge the relative impact of evaluating hazards. The proposed methodology has the innovative feature of embodying techniques of fuzzy logic theory into the classical multicriteria decision analysis. The paper closes with a case study where we apply the methodology in order to evaluate and rank 6 hazards using 16 criteria.

2. Hazard Identification

Hazard identification (HAZID) is the first and in many ways the most important step in a risk assessment. An overlooked hazard is likely to introduce more error into the overall risk estimate than an inaccurate consequence model or frequency estimate.

The aim of the HAZID is to produce, therefore, a comprehensive list of all hazards. The list should include all foreseeable hazards, but it should also avoid double counting by including the same hazard under more than one heading. In order to distinguish between hazards and consequences, it is advisable to start with defining a “hazard”. In formal ship safety assessment, a hazard is defined as “a physical situation with potential for human injury, damage to property, damage to the environment or some combination” (MSA, 1993). Therefore, ship ‘grounding’ is considered as a possible consequence of hazards related, for example, to navigation error/failure, and not as a hazard itself. Similarly, ‘navigation’ ‘ship maneuvering’, etc. are considered as hazardous operations because a component failure could lead to a chain of unwanted outcomes.

HAZID is concerned with using “brainstorming” technique involving trained and experienced personnel to determine the hazards. HAZID is, most of the time a qualitative exercise strongly based on expert judgment. Many different methods are available for hazard identification and some of them have become standard for particular applications. The most important thing is that the HAZID has to be creative in order to obtain comprehensive coverage of hazards skipping as less areas as it could practicably be. Also, it is very important that the conclusions of HAZIDs will be discussed and documented during a final session, so that they represent the views of the group rather than of an individual.

Various scientific safety assessment approaches such as Preliminary Hazards Analysis (Henley and Kumamoto, 1992; Villemeur, 1992; Smith, 1993), Failure Mode Effects and Criticality Analysis (FMECA) and Hazard and Operability (HAZOP) analysis (Henley and Kumamoto, 1992; Villemeur, 1992) can be applied in this step (Kuo, 1998; Wang, 2001).

3. Hazard Analysis

Hazard analysis approach is considered a suitable tool for ship safety assessment. In this approach it is assumed that each specific hazard can be represented by one or several threats that have the potential to lead to an incident or top (initiating) event (THESIS Version 2.02, 1998). A threat can be a specific hazard or a more detailed representation of a specific hazard. Each accidental event may lead to unwanted consequences. If a hazard is released, the accidental event can escalate to one of the several possible consequences. To prevent escalation, the mitigation measures, emergency preparedness and escalation control measures need to be in place to stop chain of events propagation and/or to minimize the consequences of escalation (Trbojevic and Carr, 2000). At Table 1 are described some general hazards which are analyzed in more detailed hazards.

Table 1: List of hazards

General Hazard	Specific Hazard
Impacts and collision	Vessel collision Striking while at berth
Ship related	Flooding Loading/overloading
Navigation	Navigation error Vessel not under command
Maneuvering	Fine maneuvering error Berthing/unberthing error
Fire/explosion	Cargo tank fire/explosion Fire in accommodation Other fires
Loss of containment	Release of flammables Release of toxic material

4. The Building Block

The evaluation setting assumed through out the paper reflects a rather representative situation faced by hazard evaluators. This is mainly characterized by the following:

- There is a number of hazards and the objective is to evaluate the relative impact for each hazard and finally to provide an ordering from the “highest” (highest score) to the “lowest” (lowest score) of the set of the hazards. The highest hazard is that one which causes the worst consequences.
- For the evaluation process a set of criteria is used, which follows a tree-like structure. The depth of the criteria tree, which somehow reflects the depth of the analysis, is usually not constant but varies with the thematic area under consideration. The totality of evaluation criteria is divided in two clusters: the group of *general* and *thematic* criteria. As the name indicates, the criteria of the thematic class vary with the hazard domain, with the general criteria can be naturally applied to general situations according to type of effects (e.g. safety, property damage, mission interruption, environmental effects e.t.c.).
- A panel of experts is used to evaluate hazards by means of the evaluation criteria hierarchy. Generally, both thematic area and evaluation hierarchy are given in advance and experts are asked either to give their opinion using linguistic terms on the relative importance of the criteria to the overall objective or to the degree at which every hazard appeals to the requirements set by each criterion.

5. Methodology Using Fuzzy Logic

5.1 Fuzzy Numbers and Arithmetic

When dealing with numeric evaluation data, finding the weighted average of individual scores and aggregating across the hierarchy is more or less a trivial task.

However, when dealing with fuzzy “quantities” it is not clear at all what is the outcome of certain expressions, such as “very good” or “very important”. One needs an arithmetic that could suitably generalist basic number operations such as addition or multiplication. The theory of fuzzy sets offers a more systematic framework for handling expert linguistic assessments. This scientific area attempts to capture the “vagueness” that is an inherent characteristic of qualitative appraisals (Bellman and Zadel, 1970; Dubois and Prade, 1980; Zimmerman, 1987; Zadel, 1973).

A fuzzy number is considered as a fuzzy set over the set of all real numbers. Generally, there is much freedom in choosing between different shapes for the membership function (refers to the degree of membership for a fuzzy number, varying from no to full membership and takes rates from 0 to 1) of a fuzzy number (Schmucker, 1984; Lee, 1990). However, simple ones, such as a triangular or trapezoidal, are frequently more convenient to handle.

A trapezoidal (triangular) fuzzy number is a fuzzy number whose membership function forms a trapezium (triangle). Throughout this paper, trapezoidal fuzzy numbers are denoted by $(\alpha_1, \alpha_2, \alpha_3, \alpha_4)$, where $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ correspond to the trapezium’s angle points ($\alpha_1 \leq \alpha_2 \leq \alpha_3 \leq \alpha_4$). Note that a triangular fuzzy number is a special case of trapezoidal with $\alpha_2 = \alpha_3$.

Arithmetic similar to that of real numbers can be also developed by fuzzy numbers by extending the basic algebraic operations of addition, subtraction, multiplication and division. The application of the above operations to fuzzy numbers yields always a new fuzzy number (Dubois and Prade, 1978). In the case of trapezoidal fuzzy numbers computations are greatly simplified.

Let $\tilde{A} = (\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ and $\tilde{B} = (b_1, b_2, b_3, b_4)$ be any two strictly positive trapezoidal fuzzy numbers (it is custom in fuzzy sets literature to use ‘~’ above letters to discriminate fuzzy from crisp quantities). Then, it can be proven that corresponding algebraic operators $\{\oplus, \ominus, \otimes, \oslash\}$ for fuzzy sets are as follows (Chen, 1998):

$$\tilde{A} \oplus \tilde{B} = (\alpha_1 + b_1, \alpha_2 + b_2, \alpha_3 + b_3, \alpha_4 + b_4)$$

$$\tilde{A} \ominus \tilde{B} = (\alpha_1 - b_1, \alpha_2 - b_2, \alpha_3 - b_3, \alpha_4 - b_4)$$

$$\tilde{A} \otimes \tilde{B} = (\alpha_1 \times b_1, \alpha_2 \times b_2, \alpha_3 \times b_3, \alpha_4 \times b_4)$$

$$\tilde{A} \oslash \tilde{B} = (\alpha_1 / b_4, \alpha_2 / b_3, \alpha_3 / b_2, \alpha_4 / b_1)$$

where the “circle” is used to notify that the operator applies to fuzzy and not ordinary numbers.

5.2 Defuzzification Procedure

Going back to the problem of ranking hazards, we see that fuzzy numbers and their arithmetic provide us with a convenient tool for reasoning with qualitative linguistic assessments.

In particular, one could easily represent each linguistic term, such as “poor”, “fair”, etc., by a fuzzy number on

a predefined numeric scale (e.g. 0-1, 0-10). In such a way, one gives rise to a set of *fuzzy weights* and *fuzzy rates*, upon which an assessment scheme can be based. Moreover, the algebra of fuzzy numbers, presented above and in particular the extended operations of addition \oplus and multiplication \otimes , provide us with a tool for calculation weighted averages of linguistic data.

As seen, the overall impact of hazards is given in terms of a fuzzy set, which is somehow expected as any algebraic operation on two arbitrary fuzzy numbers yields always a new one. This “vague” picture of the overall impacts generally hinders the task of ranking hazards, since the ordering of fuzzy numbers is not as obvious as that of real numbers. To overcome difficulties of that kind, several approaches have been proposed in the fuzzy literature, the most common being the *defuzzification*.

Defuzzification is the procedure of selecting the most representative among all members of a fuzzy set. By means of defuzzification we attempt to eliminate the “fuzziness” from a fuzzy set, providing thus a “crisp” result. Probably, the simplest defuzzification technique that one can think of is to choose among all members of a fuzzy set the one with the highest degree of membership. However, a more sophisticated method, which takes into account all the information included in the membership function is the center of area or centroid (Yen and Langari, 1999). This is simply the center of area formed under the membership function. The following equation gives the general formula for calculating the centroid \bar{x} of an arbitrarily shaped membership function $\mu(x)$.

$$\bar{x} = \frac{\int_x x \mu(x) dx}{\int_x \mu(x) dx} \quad (1)$$

In the formula above, X denotes the referential of the fuzzy set, which in the case of fuzzy numbers is identified with the real line \mathfrak{R} . For the trapezoidal fuzzy number $(\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ the above formula reduces to (Cheng and Lin, 2002):

$$\bar{x} = (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4) / 4 \quad (2)$$

6. Evaluation Framework

The procedure suggested for the evaluation of hazards is schematically depicted in Fig. 1 and 2 of Annexes A and B. We use two variations of the evaluation process, denoted by V.1 and V.2 whose main difference lies in the way the various rating and importance assessments are aggregated to provide a ranking of the alternative hazards.

The separation of the rating from the importance assessment is a means of making the evaluation of hazards as fair and objective as possible. In order to avoid disagreement or discrepancies among evaluation committee’s members we selected to follow Delphi

method. Generally speaking, the Delphi method is an iterative procedure which aims at the convergence of various subjective opinions into a more widely acceptable view. In general, a set of assumptions form the basis of our evaluation plan:

- All people being involved in the assessment procedure agree to categorization of hazards, evaluation criteria and assessment terms.
- There are a number of hazards which are to be ordered from the highly to the least impact they cause.

6.1 Assessment of Criteria Importance

In our hazards evaluation project a panel of experts has to evaluate the criteria importance by answering a questionnaire. Despite the numerous books and articles that have been written on the subject, questionnaire design lacks until today a coherent theory (Gendall, 1998). For more details about the topic the interested reader could be referred to bibliography (Gendall, 1998; Hague, 1993; Labaw, 1980; Sudman and Bradburn, 1983).

Evaluator's task is to debate on the linguistic weights of the general and thematic criteria which have been predetermined. Each expert is asked to assign weights:

- To every pair of general-thematic trees and
- At each node of the hierarchical structure, moving from the lowest to the highest level criteria.

The importance of every single criterion is evaluated by a closed-format question (or description of the criterion in general), whose answer set includes the five linguistic values: "very low (VL)", "low (L)", "medium (M)", "high (H)", "very high (VH)". From a methodological point of view, those values correspond to a suitably-chosen trapezoidal (and triangular) fuzzy numbers on the numeric scale 0-1 (see Table 2).

Table 2: The linguistic rates of criteria importance

Very Low (VL)	(0.0, 0.0, 0.1, 0.3)
Low (L)	(0.1, 0.3, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.5, 0.7)
High (H)	(0.5, 0.7, 0.7, 0.9)
Very High (VH)	(0.7, 0.9, 1.0, 1.0)

After the assessment has been completed for the totality of thematic areas, a Delphi study is carried out for each thematic area separately, in order that an acceptable level of consensus is achieved. The information that is generated by the Delphi study is stored in a database, which in figures of Appendixes A and B of the implementation plan bears the label "Criteria (linguistic weights)".

6.2 Rating of Hazards

Evaluators are asked to give their opinion on the impact of each hazard with respect to the criteria set by the particular evaluation problem. Rates are only given at the lowest level of the general and thematic hierarchy.

Rating questionnaires could be very similar (or even the same) in design to those described in the previous section. In order to refer in a subjective attribute of hazard impact we use linguistic terms of consequence assignment (Table 3). The impact for every single criterion is assessed by means of closed-format questions with the answer set: "catastrophic (CA)", "critical (CR)", "significant (SI)", "minor (MI)", "negligible (NE)".

Table 3: Linguistic terms of hazard impacts

Linguistic term	Hazard impact
Negligible	Injury not requiring first aid, no cosmetic vessel damage, no environmental impact, no missed voyages
Minor	Injury requiring first aid, cosmetic vessel damage, no environmental impact, no missed voyages
Significant	Injury requiring more than first aid, vessel damage, some environmental damage, a few missed voyages or financial loss
Critical	Severe injury, major vessel damage, major environmental damage, missed voyages
Catastrophic	Loss of life, loss of vessel, extreme environmental impact

Each of the above linguistic terms corresponds to a fuzzy number on the numeric rating scale 0-10. Details of the correspondence are given in Table 4.

Table 4: The linguistic rates of hazards impact

Negligible (NE)	(0, 0, 1, 3)
Minor (MI)	(1, 3, 3, 5)
Significant (SI)	(3, 5, 5, 7)
Critical (CR)	(5, 7, 7, 9)
Catastrophic (CA)	(7, 9, 10, 10)

After the assessment has been completed for the totality of evaluators, a Delphi study is carried out for each hazard separately. After the end of the Delphi study, the various rates obtained for each hazard are stored in a database, which in figures of Appendixes A and B is labeled as "Hazards (linguistic rates)".

The information described above together with the proper criteria weights, provided by the "criteria importance weights" database, is used in the next phase of the evaluation problem: the hierarchy aggregation.

6.3 Hierarchy Aggregation

All have discussed by far refer to the first stage of methodology, the acquisition data. In that part, procedures were less standardized and automated, due to the strong involvement of human expertise. From this stage onwards, tasks tend to be of more algorithmic nature, which definitely calls for the use of specially designed computer programs for performing the required computations.

The steps following the data acquisition could be summarized in two phases:

- Phase I: The evaluation of the aggregate impact of each hazard.
- Phase II: The ranking of hazards with respect to their overall rate.

Those are, according to H. J. Zimmerman, the two typical stages of a multicriteria decision-making problem in which fuzzy sets are used in the assessment process (1987). It is worth mentioning that in most classical (non-fuzzy) multicriteria methods, the results of phase I are numeric scores. Hence, phase II becomes a trivial task, as for the ranking of hazards all that is needed is the pair wise comparison of scores.

However, in fuzzy multicriteria analysis, the situation is more perplexed. Usually, the overall impact of hazards is described by a fuzzy number or a fuzzy set in general, which calls for an additional technique for “removing” the fuzziness and providing a crisp result.

Generally, many approaches have been proposed in the literature that addresses the issues of the overall rating and ranking of alternatives when fuzzy sets are involved in the decision-making process. For an overview of different approaches the reader could refer to several extensive surveys (Ribeiro, 1996). In the proposed methodology is used a technique that is based on the idea of weighted averaging, properly adjusted to fuzzy numbers (Cheng and Lin, 2002; Dong et. al., 1985; Dubois and Prade, 1980; Tseng and Klein, 1992). Is proposed the implementation of two variations of the weighted-average scheme (referred V.1 and V.2), whose difference mainly lies at the stage where defuzzification is applied. Those variations are described below in detail.

Variation V.1

In the first variation, is applied a fuzzy weighted averaging scheme for evaluating the aggregate impact of hazards. For each hazard we compute a weighted average of fuzzy linguistic rates, where each rate is multiplied by a suitable fuzzy linguistic weight. In variation V.1 the aggregate impact of hazards is given in terms of a fuzzy score. Therefore, defuzzification is applied to obtain a single numeric value from each fuzzy score. Those values are then used for ranking hazards.

To give a more concrete presentation of the method, let us assume that for the arbitrary thematic area (say XYZ), the evaluation criteria hierarchy is given, consisting of both the general and the XYZ criteria tree. Let the overall evaluation hierarchy comprise K branches in total, which is also the number of both end-criteria and rates per hazard. Then, the following algorithm is followed:

1. Form the evaluation matrix:

	B_1	B_2	\dots	B_K
H_1	\tilde{r}_{11}	\tilde{r}_{12}	\dots	\tilde{r}_{1K}
H_2	\tilde{r}_{21}	\tilde{r}_{22}	\dots	\tilde{r}_{2K}
\vdots	\vdots	\vdots	\ddots	\vdots
H_m	\tilde{r}_{m1}	\tilde{r}_{m2}	\dots	\tilde{r}_{mK}

Where by $B_k, k=1,2,\dots,K$ we denote the branches of the criteria tree and by $H_i, i=1,2,\dots,m$ the hazards to be evaluated. Every element \tilde{r}_{ik} of the matrix corresponds to the rate achieved by hazard H_i for the particular sub-criterion that lies at the end of branch B_k . The entries of the evaluation matrix are chosen from the set of linguistic rates (“catastrophic (CA)”, “critical (CR)”, “significant (SI)”, “minor (MI)”, “negligible (NE)”) which correspond to the trapezoidal fuzzy numbers presented in Table 4.

2. For obtaining the weight $\tilde{\omega}_k$ that corresponds to rate \tilde{r}_{ik} , trace down the evaluation criteria tree by following the k branch. For every node of the branch that is visited, adjust $\tilde{\omega}_k$ by multiplying with the fuzzy weight assigned to this node.

3. The aggregated fuzzy rates $\tilde{s}_i, i=1,2,\dots,m$ are obtained by multiplying the evaluation matrix with the vector of fuzzy weights:

$$\tilde{S} = \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \vdots \\ \tilde{s}_m \end{pmatrix} = \begin{pmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \dots & \tilde{r}_{1K} \\ \tilde{r}_{21} & \tilde{r}_{22} & \dots & \tilde{r}_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{m1} & \tilde{r}_{m2} & \dots & \tilde{r}_{mK} \end{pmatrix} \otimes \begin{pmatrix} \tilde{\omega}_1 \\ \tilde{\omega}_2 \\ \vdots \\ \tilde{\omega}_K \end{pmatrix}$$

where \otimes denotes the product operation for fuzzy matrices, which works exactly the same as in ordinary matrix algebra. Note that every $\tilde{s}_i, i=1,2,\dots,m$ is a trapezoidal fuzzy number.

4. In order to obtain an ordering on the set of hazards, apply the defuzzification formula for trapezoidal membership functions (Eq. 2). The defuzzification values are used for ranking hazards from the highest to the lowest impacting.

Variation V.2

In the second variation, the various fuzzy linguistic assessments (rates and weights) are a priori defuzzified by using the “center of gravity” technique. The aggregate impact of each hazard is found by computing weighted averages of defuzzified rates. The numeric scores obtained are used for ranking purposes. More precisely, let us again assume that the overall evaluation criteria tree consists of K branches, B_1, B_2, \dots, B_K . Suppose that there are also m hazards, $H_i, i=1,2,\dots,m$ to be evaluated. Then, the procedure followed is:

1. Given the fuzzy rates of each hazard, apply the “center of gravity” defuzzification technique to obtain a

set of numeric rates r_{ik} , $i=1,2,\dots,m$ and $k=1,2,\dots,K$ (\tilde{r}_{ik} denotes the numeric score achieved by hazard H_i for the sub-criterion that lies at the end of branch B_k). Use these rates to form the following evaluation matrix:

	B_1	B_2	\dots	B_K
H_1	r_{11}	r_{12}	\dots	r_{1K}
H_2	r_{21}	r_{22}	\dots	r_{2K}
\vdots	\vdots	\vdots	\ddots	\vdots
H_m	r_{m1}	r_{m2}	\dots	r_{mK}

2. Given the fuzzy weights, applying to the particular evaluation hierarchy, use the “center of gravity” to obtain numeric weights for each node of the evaluation tree. Tracing down each branch $k=1,2,\dots,K$ and multiplying the numeric weights assigned to each node, find the value of ω_k that multiplies each of r_{ik} , $i=1,2,\dots,m$.

3. A crisp aggregate score s_i for each hazard H_i , is obtained by computing the weighted average of r_{ik} , $k=1,2,\dots,K$. In matrix form:

$$s = \begin{pmatrix} s_1 \\ s_2 \\ \vdots \\ s_m \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & \dots & r_{1K} \\ r_{21} & r_{22} & \dots & r_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mK} \end{pmatrix} \bullet \begin{pmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_K \end{pmatrix}$$

4. Hazards H_i , $i=1,2,\dots,m$ are ranked by means of their aggregate score.

7. The Evaluation Setting

For illustrating the proposed methodology, let us assume a decision making problem of evaluation 6 general hazards (H_i , $i=1,2,\dots,6$) of Table 1 (see Table 5). We will follow the whole procedure step by step starting from the responds we received from a questionnaire. Evaluator is asked to give his opinion on the impact of each hazard with respect to the criteria, general and thematic, (which are predefined) set by the particular evaluation problem. Evaluator has to answer some questions which are connected to general and thematic criteria referred to evaluated hazards (at Appendix C you can see the questionnaire).

Table 5: Hazards to be evaluated

H_i	General Hazards
H_1	Impacts and collision
H_2	Ship related
H_3	Navigation
H_4	Maneuvering
H_5	Fire/ explosion
H_6	Loss of containment

The set of general criteria for the evaluation problem are depicted in Fig. 3.

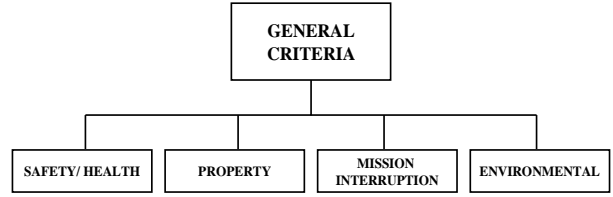


Fig. 3. The set of general criteria

The set of thematic criteria for each hazard is depicted in Fig. 4. Evaluating methodology proposes two parallel procedures:

- Rating the 6 hazards impact accordingly the total 16 criteria (4 general and 12 thematic criteria).
- Rating each criterion importance (for the total 16 criteria).

At the first procedure evaluators use the linguistic terms “negligible (NE)”, “minor (MI)”, “significant (SI)”, “critical (CR)” and “catastrophic (CA)”. Each of the above linguistic terms corresponds to a fuzzy number on the numeric rating scale 0-10 (see section 6.2).

At the second procedure evaluators use the linguistic terms: “very low (VL)”, “low (L)”, “medium (M)”, “high (H)”, “very high (VH)”. Each of the above linguistic terms corresponds to a fuzzy number on the numeric rating scale 0-1 (see section 6.1).

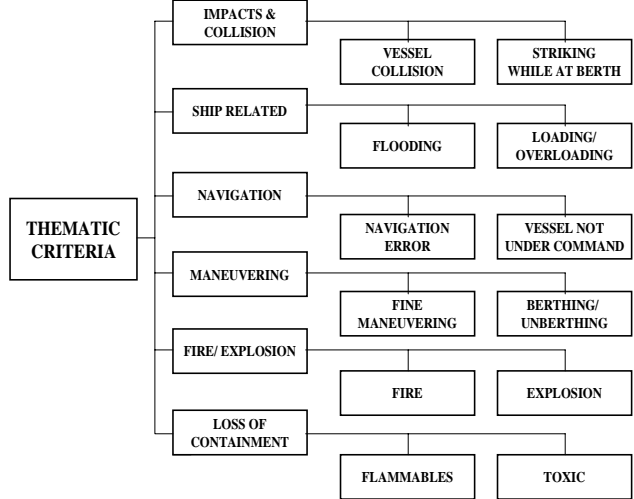


Fig. 4. The set of thematic criteria

Supposing for our case study, an evaluator answered the questionnaire giving hypothetical rates with linguistic terms we get two arrays:

- The array of hazards impact. At this array hazards are denoted H_i , $i=1,2,\dots,6$ (for the 6 hazards) and criteria C_j , $j=1,2,\dots,16$ (for the 16 total, firstly the general and then the thematic criteria serially).

- The array of criteria importance (denoting criteria as above $C_j, j=1,2,\dots,16$).

At Appendix D you can see these two arrays (for a random evaluator response) with linguistic terms and corresponding to fuzzy numbers we take the arrays with numeric rates.

7.1 Defuzzification Using Variation V.1

After the correspondence of linguistic terms with fuzzy numbers the evaluation hazard impact array is a mathematical array 6x16 as follows:

$$\begin{pmatrix} (5,7,7,9) & (7,9,10,10) & \dots & 0 \\ (5,7,7,9) & (7,9,10,10) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ (5,7,7,9) & (7,9,10,10) & \dots & (7,9,10,10) \end{pmatrix}$$

Similarly, the criteria importance array is a mathematical array 16x1 as follows:

$$\begin{pmatrix} (0.5,0.7,0.7,0.9) \\ (0.7,0.9,1.0,1.0) \\ \vdots \\ (0.1,0.3,0.3,0.5) \end{pmatrix}$$

The aggregate fuzzy rates $\tilde{s}_i, i=1,2,\dots,m$ (note that every \tilde{s}_i is a trapezoidal fuzzy number) are obtained by multiplying the evaluation matrix with the vector of fuzzy weights as follows:

$$\tilde{s} = \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \vdots \\ \tilde{s}_m \end{pmatrix} = \begin{pmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \dots & \tilde{r}_{1K} \\ \tilde{r}_{21} & \tilde{r}_{22} & \dots & \tilde{r}_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{m1} & \tilde{r}_{m2} & \dots & \tilde{r}_{mK} \end{pmatrix} \otimes \begin{pmatrix} \tilde{a}_1 \\ \tilde{a}_2 \\ \vdots \\ \tilde{a}_K \end{pmatrix}$$

Using the arrays we obtained in our case we have:

$$\tilde{s} = \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \vdots \\ \tilde{s}_m \end{pmatrix} = \begin{pmatrix} (5,7,7,9) & (7,9,10,10) & \dots & 0 \\ (5,7,7,9) & (7,9,10,10) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ (5,7,7,9) & (7,9,10,10) & \dots & (7,9,10,10) \end{pmatrix} \otimes \begin{pmatrix} (0.5,0.7,0.7,0.9) \\ (0.7,0.9,1.0,1.0) \\ \vdots \\ (0.1,0.3,0.3,0.5) \end{pmatrix}$$

After the above operation we obtain a mathematical array 6x1 where $\tilde{s}_i, i=1,2,\dots,6$ corresponds to a fuzzy number that represents the aggregate score for each of 6 hazards:

\tilde{s}_i	Scoring (fuzzy numbers)
\tilde{s}_1	(14.6, 29, 31.2, 45.6)
\tilde{s}_2	(13.9, 26.3, 28.9, 43.3)
\tilde{s}_3	(15.2, 29.2, 31.8, 45)
\tilde{s}_4	(13.5, 25.9, 29.3, 42.5)
\tilde{s}_5	(14.9, 27.7, 31.3, 44.5)
\tilde{s}_6	(12.1, 24.1, 26.4, 38.4)

In order to obtain an ordering on the set of hazards, apply the defuzzification formula for trapezoidal

membership functions (Eq. 2). After ranking hazards from the highest (highest score) to lowest (lowest score) impacting we take the following table:

\tilde{s}_i	Scoring
\tilde{s}_3	30.3
\tilde{s}_1	30.1
\tilde{s}_5	29.6
\tilde{s}_2	28.1
\tilde{s}_4	27.8
\tilde{s}_6	25.25

7.2 Defuzzification Using Variation V.2

Following the similar procedure and before the following operation \otimes , we implement the defuzzification formula for trapezoidal membership functions (Eq. 2)

$$\tilde{s} = \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \vdots \\ \tilde{s}_m \end{pmatrix} = \begin{pmatrix} (5,7,7,9) & (7,9,10,10) & \dots & 0 \\ (5,7,7,9) & (7,9,10,10) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ (5,7,7,9) & (7,9,10,10) & \dots & (7,9,10,10) \end{pmatrix} \otimes \begin{pmatrix} (0.5,0.7,0.7,0.9) \\ (0.7,0.9,1.0,1.0) \\ \vdots \\ (0.1,0.3,0.3,0.5) \end{pmatrix}$$

and then we have:

$$\tilde{s} = \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \vdots \\ \tilde{s}_m \end{pmatrix} = \begin{pmatrix} 7 & 9 & \dots & 0 \\ 7 & 9 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 7 & 9 & \dots & 9 \end{pmatrix} \bullet \begin{pmatrix} 0.7 \\ 0.9 \\ \vdots \\ 0.3 \end{pmatrix}$$

After the above operation we obtain a mathematical array 6x1 where $\tilde{s}_i, i=1,2,\dots,6$ corresponds to a fuzzy number that represents the aggregate score for each of 6 hazards:

\tilde{s}_i	Scoring
\tilde{s}_1	29
\tilde{s}_2	27
\tilde{s}_3	29.2
\tilde{s}_4	26.8
\tilde{s}_5	28.6
\tilde{s}_6	24.2

After ranking hazards from the highest (highest score) to lowest (lowest score) impacting we take the following table:

\tilde{s}_i	Scoring
\tilde{s}_3	29.2
\tilde{s}_1	29
\tilde{s}_5	28.6
\tilde{s}_2	27
\tilde{s}_4	26.8
\tilde{s}_6	24.2

Although following the procedure with both variations V.1 and V.2 the ranking is the same, the score may differ (depending on the rates). For that reason we have to use both variations in order to ensure the final ranking.

Considering that all above operations depending the number of evaluated hazards and criteria are time-consuming (especially arrays multiplication) we can use Microsoft Excel program (functions AVERAGE, SUMPRODUCT and MMULT).

After all above the final hazards ranking for our case study is:

	HAZARDS RANKING
H_3	Navigation
H_1	Impacts and collision
H_5	Fire/ explosion
H_2	Ship related
H_4	Maneuvering
H_6	Loss of containment

8. Conclusions

In this paper we present an innovative methodological approach to the evaluation, ranking and prioritization of hazards. The proposed methodology introduces a hierarchical analysis of the decision-making problem, in which general and domain specific criteria compose the evaluation structure. The adopted “fuzzy” approach provides us with a suitable tool for modeling and processing linguistic assessments and subjective views in a simple and rather intuitive way.

Apart from methodological issues, this paper also discusses many practical aspects of the evaluation framework and gives multiple guidelines on how such an evaluation procedure could be implemented. Nevertheless, is obvious that the proposed framework is of more general use. Most important it gives enough flexibility in modeling an evaluation problem, since it effectively remains insensitive to changes in many individual components of the methodology.

As an application of our methodology in the hazard identification process of Formal Safety Assessment we follow the procedure in order to evaluate and rank a number of general hazards. As a case study we apply the proposed methodology in order to evaluate 6 hazards using totally 16 criteria.

References

Baas, S. and Kwakernaak, H. (1977). “Rating and ranking of multiple-aspect alternatives using fuzzy sets”, *Automatica* 13, pp 47-58.

- Bellman, R. and Zadel, L. (1970). “Decision-making in a fuzzy environment”, *Management Science* 17, 4, pp 141-164.
- Chen, C. (1998). “A study of fuzzy group decision-making method”, In 1998 6th National Conference on Fuzzy Sets and Its Applications, Vol. 142, pp 174-186.
- Cheng, C. and Lin, Y. (2002). “Evaluating the best main battle tank using fuzzy decision theory with linguistic criteria evaluation”, *European Journal of Operational Research* 142, pp 174-186.
- Dong, W., Shah, H. and Wong, F. (1985). “Fuzzy computations in risk and decision analysis”, *Civil Engineering Systems* 2, pp 201-208.
- Dubois, D. and Prade, H. (1978). “Operations on fuzzy numbers”, *Int. J. Syst. Sci.* 9, 3, pp 613-626.
- Dubois, D. and Prade, H. (1980). “Fuzzy Sets and Systems: Theory and Applications”, Vol.144 of *Mathematics in Science and Engineering*, Academic Press Inc., U.S.
- Dyson, R. G. (1980). “Maxmin programming, fuzzy linear programming and multicriteria decision making”, *J Opl Res Soc* 31, pp. 263-267.
- Gendall, P. (1998). “A framework for questionnaire design: Labaw revisited”, *Marketing Bulletin* 9, pp 28-39.
- Hague, P. (1993). “Questionnaire Design”, Kogan Page, London, England.
- Henley, E. J. and Kumamoto, H. (1992), *Probabilistic risk assessment*, 1002. New York: IEEE Press.
- Kuo, C. (1998), *Managing Ship Safety*, LLP, London: Hong Kong, p. 51.
- Labaw, P. J. (1980). “Advanced Questionnaire Design”, Abt Books, Cambridge, MA.
- Lai, Y. J and Hwang, C. L. (1994). *Fuzzy Multiple Objective Decision Making Methods and Applications*, Springer-Verlag, New York.
- Leberling, H. (1981). “On finding compromise solutions in multicriteria problems using the fuzzy min-operator”, *Fuzzy Sets and Systems* 6, pp. 105-118.
- Lee, C. (1990). “Fuzzy logic in control systems: fuzzy logic parts I, II, *IEEE Transactions on Systems, Man and Cybernetics*, 20, p. 404.
- Liang, G. S. and Wang, M. J. (1991). “A fuzzy multicriteria decision making method for facility site selection”, *International Journal of Production Research*, 29 (11), pp 2313-2330.
- MSA, (1993). “Formal Safety Assessment MSC66/14”, Submitted by the United Kingdom to IMO Maritime Safety Committee.
- Nikitakos, N., Dounias, G. and Thomaidis, N. S. (2002). “D3.1: Evaluation guidelines. Technical report, 2002, contributing to work package III European R&D Results-Assessment and Evaluation of DIAS.net project (project no. IST-2001-35077)”.
- Prabhu, T. S. and Vizayakumar, K. (1996). “Fuzzy hierarchical decision making (FHDM): A methodology for technology choice”, *International Journal of Computer Applications in Technology*, 9(5), pp 322-329.
- Ribeiro, R. (1996). “Fuzzy multiple attribute decision making: A review and new preference elicitation

- techniques”, *Fuzzy Sets and Systems* 78, pp 155-181.
- Saaty, T. L. (1980). *The Analytic Hierarchy Process*, McGraw-Hill, New York.
- Schmucker, K. J. (1984). *Fuzzy Sets, Natural Language Computations and Risk Analysis*, Computer Science Press, Rockville, Maryland.
- Steuer, R. E. (1986). *Multiple Criteria Optimization: Theory, Computation and Application*, John-Wisley and Sons, New York.
- Sudman, S. and Bradburn, N. M. (1983). *Asking Questions: A Practical Guide to Questionnaire Design*, Jossey-Bass, San Francisco, CA.
- THESIS Version 2.02 (1998). “The Health, Environment and Safety Information System, User Guide”, EQE International.
- Trbojevic, V. M. and Carr, B. J., (2000). “Risk based methodology for safety improvements in ports”, *Journal of Hazardous Materials* 71, pp 467-480.
- Tseng, T. Y. and Klein, C. (1992). “A new algorithm for fuzzy multicriteria decision making”, *International Journal of Approximating Reasoning* 6, pp 45-66.
- Villemeur, A. (1992). *Reliability, availability, maintainability and safety assessment*. Chichester: Wiley.
- Wang, H. F. (2000). “Fuzzy multicriteria decision making – an overview”, *Journal of Intelligent and Fuzzy Systems*, Vol. 9, Number 1-2, pp. 61-83.
- Wang, J., (2001). “The current status and future aspects in Formal Ship Safety Assessment”, *Safety Science* 38, pp 19-30.
- Yen, J. and Langari, R. (1999). *Fuzzy Logic Intelligence, Control and Information*, Prentice Hall Publishing Company.
- Zadeh, L. A. (1965). “Fuzzy Sets”, *Information and Control* 8, pp 338-353.
- Zadeh, L. A. (1973). “Outline of a new approach to the analysis of complex systems and decision processes”, *IEEE Trans. Syst. Man Cybern. SMC-3*, 1, pp 28-44.
- Zeleny, M. (1982). *Multiple Criteria Decision Making*, McGraw-Hill Book Company, New York.
- Zimmermann, H. J. (1987). “Fuzzy Sets, Decision Making and Expert Systems”, *International Series in Management Science/Operations Research*, Kluwer Academic.

APPENDIX A

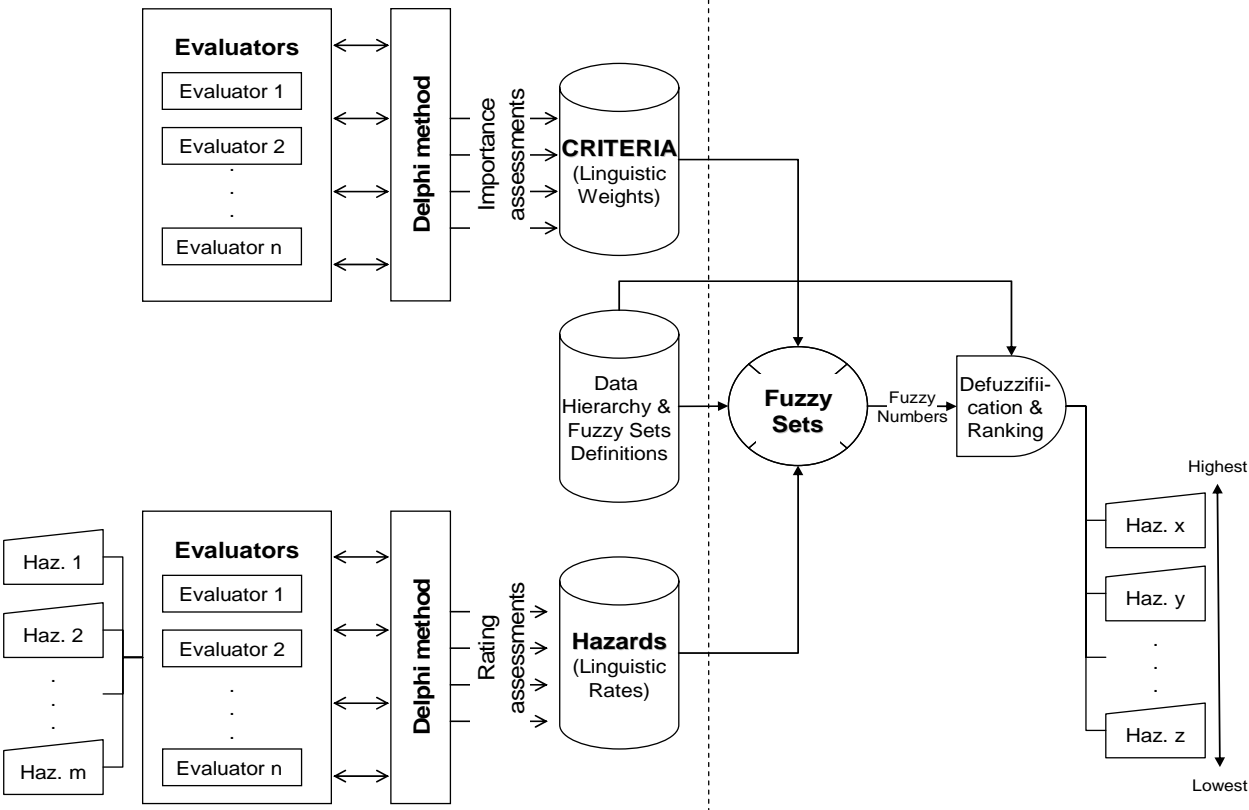


Fig. 1. The first methodological plan for the evaluation and ranking of hazards.

APPENDIX B

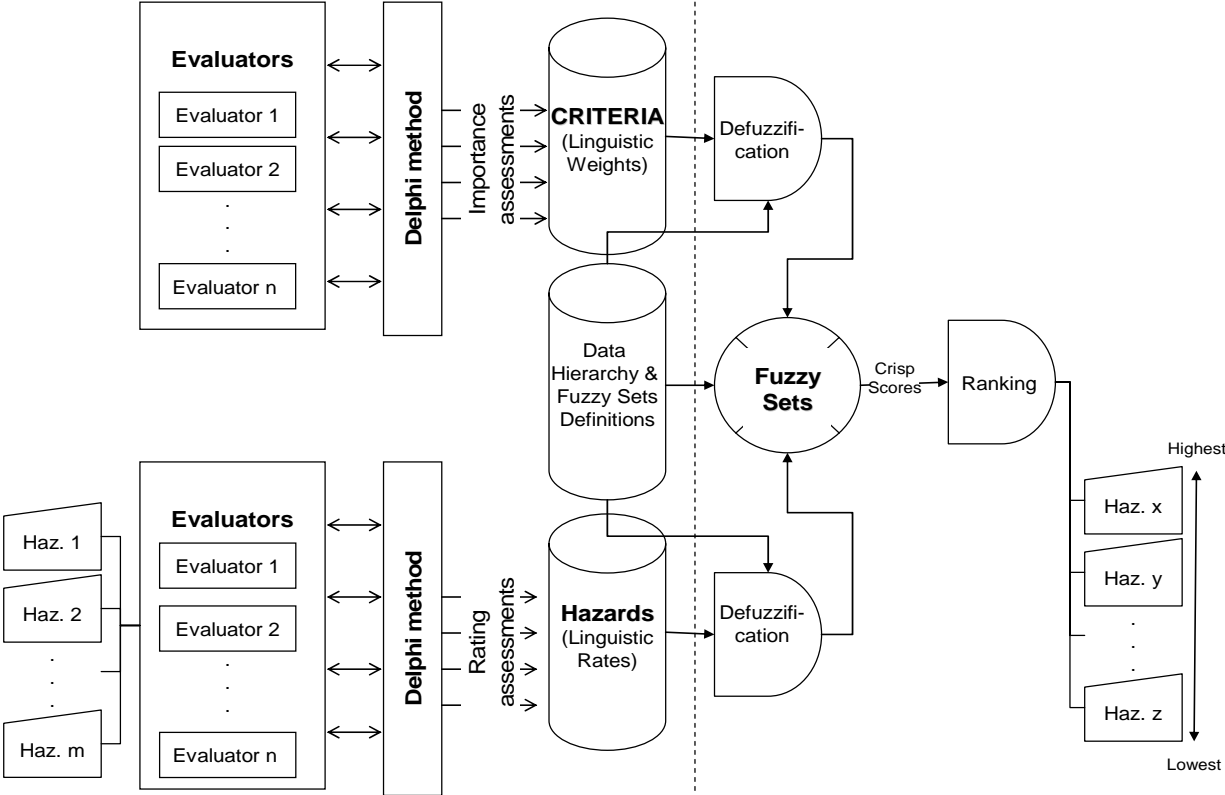


Fig. 2. The second methodological plan for the evaluation and ranking of hazards.

APPENDIX C

C_j	GENERAL CRITERIA	QUESTIONNAIRE
C ₁	Safety/ Health	Which is the level of effects in safety or health (injury or illness results in a fatality or disability)?
C ₂	Property	Which is the level of cost of property damage?
C ₃	Mission interruption	Which are the impacts on ability of vessel to accomplish critical missions?
C ₄	Environmental	To what extend does the impacts in ocean life or offsite health?

	THEMATIC CRITERIA	QUESTIONNAIRE
C ₅	Vessel collision	Which are the impacts of vessel collision (injury, property damage, hull damage, holed and sinkage etc.)?
C ₆	Striking while at berth	Which are the impacts of a striking while vessel is at berth (injury, structural damage etc.)?
C ₇	Flooding	Which are the impacts of flooding (property damage, machinery failure, black out etc.)?
C ₈	Loading/ overloading	Which are the impacts of unsuccessful loading or overloading (cargo shift, reduce vessel stability etc.)?
C ₉	Navigation error	Which are the impacts of navigation error (contact or collision, grounding, route deviation etc.)?
C ₁₀	Vessel not under command	Which are the impacts of vessel not under command (contact or collision, grounding, route deviation etc.)?
C ₁₁	Fine maneuvering	Which are the impacts of failure in maneuvering (time consuming, possibility for contact or collision)?
C ₁₂	Berthing/ unberthing	Which are the impact of an unsuccessful berthing/ unberthing (injury, structural or hull damage etc.)?
C ₁₃	Fire	Which are the impacts of fire (death, injury, property damage, structure or hull damage, sinkage etc.)?
C ₁₄	Explosion	Which are the impacts of explosion (death, injury, property damage, structure or hull damage, sinkage etc.)?
C ₁₅	Flammables	Which are the impacts of flammable releases (fire explosion, death, injury, property damage etc.)?
C ₁₆	Toxic	Which are the impacts of toxic releases (death, injury, damage to the environment etc.)?

APPENDIX D

	GENERAL CRITERIA				THEMATIC CRITERIA											
					H1		H2		H3		H4		H5		H6	
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
H1	CR	CA	CR	CR	CA	CR	-	-	-	-	-	-	-	-	-	-
H2	CR	CA	CR	CR	-	-	CR	NE	-	-	-	-	-	-	-	-
H3	CR	CA	CR	CR	-	-	-	-	SI	CR	-	-	-	-	-	-
H4	CR	CA	CR	CR	-	-	-	-	-	-	NE	CA	-	-	-	-
H5	CR	CA	CR	CR	-	-	-	-	-	-	-	-	NE	CA	-	-
H6	CR	CA	CR	CR	-	-	-	-	-	-	-	-	-	-	NE	CA

GENERAL CRITERIA				THEMATIC CRITERIA											
				H1		H2		H3		H4		H5		H6	
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
H	VH	H	M	L	H	H	H	L	VH	VH	M	VH	H	VL	L