A METHODOLOGY FOR RATING AND RANKING HAZARDS IN MARITIME FORMAL SAFETY ASSESSMENT USING FUZZY LOGIC

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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 prioritisation process. A multicriteria decision making framework, which is based on experts' estimation, is then proposed for hazards evaluation. Additionally in this paper many aspects of the evaluation framework are presented including the synthesis of evaluation teams, the assessment of the importance of criteria, the evaluation of the consequences of the alternative hazards and the final ranking of the 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.

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 prioritisation 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 prioritise 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. Up to now, there are a variety of methods that one can choose from solving a multicriteria decision problem, the most famous being the maximin, the weighted average, the multicriteria utility evaluation and the Analytical Hierarchical Process [13].

All the aforementioned methods assume that the decision maker is able to provide exact assessments on the importance of 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 [22], is an effective means to deal with the "vagueness" of human judgement. 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 [11], [14].

After fuzzy sets general methodology presentation this paper proposes an application to evaluate and rank a number 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.

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" [12].

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 manoeuvring', 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 judgement. Many different methods are available for hazard identification and some of them have become standard for particular applications. Experience proved that there is no need to specify which technique should be used in particular cases. Typically, the system being evaluated is divided into parts and the team leader chooses the methodology, which can be standard technique, a modification of one of these or, usually, a combination of several. In other words, the technique used is not that important since each group can follow a methodology of combined techniques. The most important thing is that the HAZID has to be creative in order to obtain comprehensive coverage of hazards skipping as fewer 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 (PHA), Failure Mode, Effects and Criticality Analysis (FMECA) and Hazard and Operability (HAZOP) study can be applied in this step [21].

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 [18]. 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 [19]. At the table 1 are described some general hazards, which are analysed 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
Manoeuvring	Fine manoeuvring 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 blocks

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 [2], [7], [11], [23].

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. 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 (α_1, α_2, α_3, α_4), where

α_1, α_2, α_3, α_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 α_2=α_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 [6]. In the case of trapezoidal fuzzy numbers computations are greatly simplified.

Let $\widetilde{A} = (\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ and $\widetilde{B} = (b_1, b_2, b_3, b_4)$ 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 $\{\oplus, \ominus, \otimes, \varnothing\}$ for fuzzy sets are as follows [3]:

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

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

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

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

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 e-services, 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 performance of e-services 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 performances generally hinders the task of ranking alternatives, 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 centre of area or centroid. This is simply the centre of area formed under the membership function. The following equation gives the general formula for calculating the centroid $\overline{x}$ of an arbitrarily shaped membership function $\mu(x)$

$$\overline{x} = \frac{\int_X x\mu(x)dx}{\int_X \mu(x)dx}. \tag{1}$$

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 $\Re$. For the trapezoidal fuzzy number (α_1, α_2, α_3, α_4) the above formula reduces to [4]:

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

6. Evaluation framework

We use two variations of the evaluation process, denoted by V.1 and V.2 whose main difference lays 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 recommended.

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 [15]. For more details about the topic the interested reader could be referred to bibliography [8], [9], [10], [17].

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*).

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.

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)

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 (see *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*.

After the assessment has been completed for the totality of evaluators, a Delphi study is carried out for each hazard separately. The information described above together with the proper criteria weights is used in the next phase of the evaluation problem: the hierarchy aggregation.

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)

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 performance 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 [18]. 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 [15]. In the proposed methodology is used a technique that is based on the idea of weighted averaging, properly adjusted to fuzzy numbers [4], [5], [7], [20]. 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:

$$\begin{array}{c|cccc} & B_1 & B_2 & \cdots & B_K \\ \hline H_1 & \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1K} \\ H_2 & \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2K} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ H_m & \tilde{r}_{m1} & \tilde{r}_{m2} & \cdots & \tilde{r}_{mK} \end{array}$$

   Where by B_K, k=1,2,…,K we denote the branches of the criteria tree and by H_i, i=1,2,…,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 ("very poor (VP)", "poor (P)", "fair (F)", "good (G)", "very good (VG)"), which correspond, to the trapezoidal fuzzy numbers presented in Table 2.
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,…,m are obtained by multiplying the evaluation matrix with the vector of fuzzy weights:

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

   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,…,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 "centre 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,..., B_K. Suppose that there are also *m* hazards, H_i, i=1,2,…,m to be evaluated. Then, the procedure followed is:

1. Given the fuzzy rates of each e-service, apply the "centre of gravity" defuzzification technique to obtain a set of numeric rates r_{ik}, i=1,2,…,m and k=1,2,…,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:

$$\begin{array}{c|cccc} & B_1 & B_2 & \cdots & B_K \\ \hline H_1 & r_{11} & r_{12} & \cdots & r_{1K} \\ H_2 & r_{21} & r_{22} & \cdots & r_{2K} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ H_m & r_{m1} & r_{m2} & \cdots & r_{mK} \end{array}$$

2. Given the fuzzy weights, applying to the particular evaluation hierarchy, use the "centre of gravity" to obtain numeric weights for each node of the evaluation tree. Tracing down each branch k=1,2,…,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,…,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,…,K. In matrix form:

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

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

7. Conclusion

In this paper we present an innovative methodological approach to the evaluation, ranking and selection 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 modelling 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 modelling an evaluation problem, since it affectively remains insensitive to changes in many individual components of the methodology.

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