Fuzzy Analytical Hierarchical Process to Assess Weights of Importance in Ship Operation Risk Assessment

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**Abstract.** The evaluation of the safety state of the ship in a generic operative or emergency condition is a very complex issue due to the huge number of attributes involved in the problem, uncertainties of their values and assessment of their mutual importance. The safety of the ship shall be presented in a simple and immediate manner in order to provide a useful decision support to onboard personnel. That is why a hierarchical risk assessment procedure has been developed selecting a set of attributes which are grouped in criteria and sub-criteria. The attributes are fuzzified and combined in order to obtain a risk index for each sub-criterion and criterion. The mutual importance of criteria, sub-criteria and attributes is assessed by means of a Fuzzy Analytical Hierarchical Process (FAHP), which rationally incorporates and treats the experience of masters and officers collected by a survey. This process allows summarizing experience and proficiency into a decision support system devoted to increase ship safety, while providing an interesting representation of the onboard perception about risk and its main causes.

**Keywords.** AHP, Fuzzy AHP, Weight of importance, Operative Risk Assessment, Ship operation.

# Introduction

The assessment of the safety state of a ship in a generic operative condition is not a trivial problem due to the huge amount of attributes that are to be considered simultaneously as well as to the uncertainties that affects them. Nowadays, a continuous development of onboard Decision Support Systems (DSSs) is underway facing a multitude of specific problems, which may could threaten the safety of the ship in navigation. Most of them are based on the concept of risk that is suitable to deal with uncertainties and to present clearly the outcomes of complex assessments to the onboard personnel [1]. The limit of such tools is that they provide only a partial and non-organic risk assessment being limited to their specific topic. The masters and officers has to carry out a synthesis on the base of their experience. Thus, the evaluation of the safety state of the ship is still a subjective process affected to human error or worse by lack or partial information.

In order to overcome this problem, Trincas et al. [1] introduced a risk-based framework capable to assess in an objective way the safety state of the ship. Such a framework is capable to take into account all the aspects connected to ship safety by providing a multi-level risk assessment to make a decision support available to onboard personnel in emergencies as well as during navigation. The framework has a hierarchic structure where the attributes are grouped in sub-criteria and subsequently in criteria at higher level to arrive at assessment of a safety index.

The aggregation of sub-criteria and criteria is the key of the synthesis process. It requires the assessment of the level of importance (weight) of each criterion and sub-criterion. All the weights have to be based on the judgment of experts as well as on the objective assessment of ship safety.

 The Analytical Hierarchical Process (AHP), which was first introduced by Saaty [2], is a very effective method to aggregate experts’ opinions and assessment scores into an elementary system by decomposing a complex problem from higher priorities to lower ones. The problem is decomposed in a hierarchic set of sub-problems subject to the experts’ judgment by means of pairwise comparison. For each couple of criteria, sub-criteria and attributes their relative importance is assigned using a linguistic scale. Among multiattribute decision making techniques, AHP provides the methodology to convert those simple comparisons into weights of importance.

However, since the experts’ opinions are by definition imprecise and vague, the fuzzy set theory developed by Zadeh [3] can be introduced to handle vagueness ad uncertainty into AHP leading to the development of Fuzzy AHP (FAHP). One of the pioneer applications of such a method can be found in Laarhoven & Pedrycz [4]; it has been later improved, among the others, by Buckley [5] and Chang [6].

The FAHP has been applied in many sectors to face Multiple Criteria Decision making (MCDM) problems and has turned out to be the best choice also for ship’s operative risk assessment. After a description of the applied methodology, the risk-based framework is herein briefly depicted. The weight of importance of all criteria and sub-criteria are assessed by means of FAHP considering the judgment of a small set of trained masters and researchers interviewed by a survey.

# Risk-Based Framework

As introduced in Trincas et al. [1], the main goal of a risk-based framework is to integrate into a global risk index all the aspects connected with the ship survivability by means of mathematical modelling for a generic ship condition, characterized by a loading condition, a weather condition, an eventual damage, etc.

This target is reached introducing a hierarchical network composed by three levels, each one contributing to assess the *global risk index*, defined as a number that varies between 1 (no risk) and 0 (utmost risk) which quantifies the safety state of the ship. This assessment is a classical MCDM process based on a very large set of attributes capable to take into account all the aspects which could threaten ship safety.

Attribute values serve as a basis for assessment of sub-criteria. Since they are not generally equally influential or important, it is necessary to apply weighting to reflect their relative importance (*inter-attribute preference*).

In the AHP the decision making process starts with dividing the risk assessment procedure into a hierarchy of a number of criteria and sub-criteria. These hierarchical levels help to simplify the structure of the problem and makes it easy to understand how the final goal, the risk index, is decided. In each hierarchical order the weights of sub-criteria and criteria are calculated, respectively.

Fuzziness in decision making processes stems from complex and imprecise nature of information regarding application of prescriptive rules. As compared to crisp criteria, the fuzzy approach softens the sharp transition from acceptable to unacceptable. It may identify a viable solution which would otherwise be lost by crisp criterion. At the same time, the values of attributes should be normalized in order to make them commensurable in a multidimensional space. To this end, attributes’ scores are subjectto thresholds and fuzzified by means of triangular fuzzy numbers to describe the degree of satisfaction, a number that vary between 1 (safe condition) and 0 (non-compliant).

Then, in the second level, a sub-risk index is determined by aggregating the fuzzified attributes scores belonging to a sub-criterion. At the first level, all the sub-risk indexes are again aggregated to obtain a risk index related to each criterion, which they belong to. Each criterion deals with a main aspect related to ship safety; thus, the overall safety of the ship can be easily monitored through the value of the risk indexes. Anyway, to provide a measurement of the safety state of the ship which allows the simple comparison of different conditions, these indexes are aggregated to obtain the global risk index.

In this framework, the aggregation is one of the most important aspects, and it is performed through corrected weighted average [1] method, which requires the assessment of the weights of importance of all the criteria, sub-criteria and attributes.

# Criteria and Sub-Criteria

As previously stated, the hierarchical risk-based framework takes into account several criteria. Some of them are mandatory to fulfil normative regulations; the others are optional, but can provide a more complete analysis of ship safety. The criteria and their names have been assessed consulting onboard personnel and combining their experience with the international rules. The criteria considered and described herein are the following: dangerous cargo, crew & energy efficiency, essential equipment, evacuation, maneuvering, ship motions, survivability & load line, stability rules and structural strength. The criteria and their sub-criteria are shown in Figure 1.

## Dangerous Cargo

The dangerous cargo criterion is related to the type of cargo defined in IMO IMDG Code [7] and its distribution onboard. In detail is composed by the following sub-criteria: total amount of cargo, type of cargo and cargo layout. The total amount sub-criterion is related to the weight of dangerous cargo versus the allowed amount. The dangerous cargo is classified into classes [7] due to its level of danger providing an intrinsic measure of the risk related to the type of cargo. The cargo layout sub-criterion measures the risk connected to the distance of dangerous cargo from critical spots (essential equipment, heat sources, accommodations, etc.), intervention stations and detection devices.

## Efficiency

The efficiency criterion is related to the crew efficiency and reduction of emissions. Crew efficiency is a crucial aspect in ship safety; all the onboard personnel own a certificate, which grants their competence. Nevertheless, relevant differences in crew competence



**Figure 1.** Structure of the risk assessment including all criteria and sub-criteria

have been spotted by masters, sometimes affecting ship efficiency. It is hard to assess a measure of crew efficiency; the most suitable method is to consider it as a function of the Ship Risk Profile (SRP), as defined in the Paris MoU document [8].

In a given loading condition, weather condition and required ship speed, an optimal floating position should be defined in order to reduce the fuel consumption, i.e. the emissions [9]. The normalized spread between actual and optimal fuel consumption is assumed as a sort of “environmental risk” associated to the condition and included in emissions sub-criterion.

## Essential Equipment

The essential equipment criterion is related to effective operation of the essential systems as defined by Safe Return to Port (SRtP) regulations [10]. The effect of flooding water and heel/trim angles has to be taken into account. The sub-criteria are all the classes of equipment defined by rules (Fig.1) and, in this context, a description of all of them could be tedious. Anyway, it is worth noticing that the evaluation of the risk for each sub-criterion requires a SRtP model where all the essential machinery, switchboard and devices as well as their mutual dependences are defined. The assessment of operation of essential equipment is particularly important in case of fire or flooding and it is required by MSC 1400 [11].

## Evacuation

The evacuation criterion is related to the effect of a casualty on escape routes and the effect of ship’s list on evacuation time as required by MSC 1400 [11]. In detail are considered the number of operative lifesaving appliances, taking into account the effect of fire and/or flooding as well as the dependences from other essential equipment. The time required to complete the evacuation procedure is determined taking into account the effect of heel, trim, fire, and/or flooding. It is compared with the IMO standards or to the time to reach an unsafe condition during transient flooding.

## Maneuvering

Currently no rule prescribes to evaluate actual maneuvering capabilities of the ship. Anyway, this is an important aspect, which can affect ship safety especially in restricted waters and port operations. Therefore, maneuvering shall be included in a risk based frameworks. The sub-criteria deals with the most important mauves defined IMO standards [12]. In detail, the following abilities of the ship shall be evaluated in an actual condition: turning, zig-zag, crash stop.

## Ship Motions

At present, no rule prescribes to take under control seakeeping during navigation and even during ship design. Anyway, seakeeping is one of the most important aspects to consider when designing a ship, especially in the initial design stages [13]. Indeed, as to passenger ships the ship motions along with noise reduction are the most important aspects that determine the comfort onboard. Seakeeping capabilities are also essential for navy ships and offshore vessels, fixing ship’s limits of operation.

All these issues drive to include seakeeping in the risk-based framework considering ship motions’ amplitude and their closeness to resonance frequencies, in order to avoid their magnification. In detail the ship motion criterion is composed by the following sub-criteria: ship motions and accelerations, slamming, green water, propeller emergence, motion sickness index (MSI). Motions and accelerations sub-criterion deals with the maximum value of motions inferred from an observation period of 15 minutes, compared with an acceptable value; the average period of motions is also compared the and the natural periods to evaluate the closeness with resonance phenomena. Slamming, green water, and propeller emergence are well-known undesirable phenomena connected to seakeeping [14]. Therefore, the risk of occurrence shall be added to the framework. The MSI measures the comfort of passengers connected to ship motions and it is the utmost importance in passenger ships.

## Survivability & Load Line

Survivability & load line is related to all the aspects connected to ship floating position (such as freeboard requirements, submersion of the margin line, unprotected openings, load line mark, etc.). In addition, it deals with the most important issues of ship survivability: reserve of buoyancy and risk of capsize due to actual weather condition.

The reserve of buoyancy sub-criterion is function of difference between the laden displacement and the displacement at submersion of unprotected openings in intact condition and bulkhead deck in damaged condition. Nowadays, the dynamic stability of a ship is subject to prescriptive rules, which take into account a standard roll angle and wind speed and are checked at departure and at arrival loading condition. A continuous assessment of risk of capsize based to actual loading and weather condition shall be adopted to increase the safety during navigation. To this end, the data concerning wind speed, wave spectrum and connected ship motions are not statutory but are evaluated from an observation period of 15 minutes. Considering the ship loading condition and heading angle, the probability of capsize can be evaluated with a dynamic stability approach analogous to the one assumed for weather criterion [15], providing reliable stability assessment for the current condition as well as for a generic simulated one.

## Stability Rules

Stability rules criterion is related to compliance with stability rules for intact and damage condition. The compliance with stability criteria impose crisp constraints, making no difference between a requirement fulfilled with a safe margin and another where is only marginally satisfied. That is why, in an operative risk assessment, it is good practice to apply a fuzzy satisfaction introducing for each attribute a safe condition [1]. The safe condition could be defined for each attribute as the value where it provides the highest margin beneath the values corresponding to the loading conditions analyzed in the design process. The sub-criteria of stability rules criterion depend upon the applied stability regulations, thus they vary with the ship’s type and purpose.

## Structural Strength

The structural strength criterion deals with the compliance with longitudinal strength rules in still water and with assessment of the risk of structural failure in developed sea. In detail, it is composed by the following sub-criteria: shear force, bending moment and torque moment in both still water and in a seaway. The class rules, based on statistical formulation results in limit curves for curves of shear force, bending moment and, for special types of ships, torque moment. This approach is used for still water calculations and is not enough reliable for the application in an operative risk assessment which aims to take into account the current weather condition. Since FEM analysis still are not suitable for an onboard direct application, an approach based on the application of a design wave equivalent to the developed sea is under development. The actual stress induced by shear force, bending and torque moment on control points of several sections of the ship shall be used to assess the margin before plastic deformation and the connected risk.

# Determination of Weight of Importance

To assess the weight of importance of all the criteria and sub-criteria a survey has been prepared and submitted for testing to a small set of experts (captains and researchers). The weight of importance of attributes are not considered because they are still under definition as well as other techniques such as fuzzy entropy method could provide better results in their determination compared with FAHP.

All experts provided the mutual importance of each criterion compared to all the others by means of the linguistic scale (Tab.1). In addition, they have been required to comment the structure of the framework and check if the adopted nomenclature is suitable for an onboard DSS in order to facilitate comprehension of outcomes.

**Table 1.** Adopted linguistic scale for pairwise comparison

|  |  |  |
| --- | --- | --- |
| **Item** | **Importance** | **First item fuzzy number** |
| First item | Extreme | (9,9,9) |
| Strong | (6,7,8) |
| Fair | (4,5,6) |
| Moderate | (2,3,4) |
| vs | Equal | (1,1,1) |
| Second item | Moderate | (1/4,1/3,1/2) |
| Fair | (1/6,1/5,1/4) |
| Strong | (1/8,1/7,1/6) |
| Extreme | (1/9,1/9,1/9) |

The data collected have been treated via FAHP obtaining the weights of importance as summarized in Table 2.

Concerning criteria, Crew and energy efficiency was judged of the utmost importance. Analyzing its sub-criteria, crew efficiency results the crucial aspect. Captains, in particular, consider the human factor crucial to assure ship safety, asserting that e good crew can safely conduct the most unsafe ship, whereas an incompetent crew can lead to a disaster even the safest ship. Recent casualties and accidents statistics [16] confirm the rightness of the assertion and, thus, the importance of lowering the probability of occurrence of human errors during navigation and in port operations. A viable solution, is a wide application of DSSs capable to provide complete information presented in a clear manner, which is exactly the purpose of the present research.

The second criteria per importance was maneuvering, mainly connected to the stopping ability. Then, seakeeping, essential equipment and survivability had a comparable importance. It is worth to notice that rules connected to structural strength,

**Table 2.** Normalized weights of importance of all criteria and sub-criteria

|  |  |  |  |
| --- | --- | --- | --- |
| **Criterion or sub-criterion** | **Weight** | **Criterion or sub-criterion** | **Weight** |
| **Dangerous cargo** | **0.087** | **Ship motions** | **0.120** |
| Total amount | 0.264 | Motions and accelerations | 0.310 |
| Type of cargo | 0.093 | Slamming | 0.314 |
| Cargo layout | 0.643 | Green water | 0.044 |
| **Crew & energy efficiency** | **0.187** | Propeller emergence | 0.265 |
| Crew efficiency | 0.892 | MSI | 0.068 |
| Reduction of emissions | 0.108 | **Survivability & load line** | **0.117** |
| **Essential equipment** | **0.118** | Risk of capsize | 0.222 |
| Propulsion | 0.131 | Buoyancy reserve | 0.217 |
| Electric generation | 0.260 | Heel angle | 0.147 |
| Steering | 0.166 | Trim angle | 0.103 |
| Total fuel handling | 1.100 | Load line mark | 0.034 |
| Communication devices | 1.042 | Margin line | 0.037 |
| Fire fighting | 0.121 | Progressive flooding openings | 0.088 |
| Bilge and Ballast | 0.062 | Unprotected openings | 0.105 |
| Navigation devices | 0.035 | Shell doors | 0.047 |
| Detection devices | 0.047 | **Stability rules** | **0.059** |
| Safety areas | 0.036 | GZ curve criteria | 0.389 |
| **Evacuation** | **0.088** | Weather criterion | 0.258 |
| Operation of LSA | 0.616 | Limit curves on KG/GM | 0.353 |
| Time to complete evacuation | 0.384 | **Structural strength** | **0.094** |
| **Maneuvering** | **0.130** | Stress in developed sea | 0.601 |
| Turning | 0.237 | Shear force in flat sea | 0.172 |
| Zig-zag | 0.332 | Bending moment in flat sea | 0.094 |
| Crash stop | 0.431 | Torque moment in flat sea | 0.133 |

evacuation, dangerous cargo, and especially stability were considered less important. In general, the attention was more concentrated on actual capabilities of the ship rather than on rule requirements. The same situation was found also in sub-criteria: structural stress associated to current weather condition is preferred to rules requirements on shear force, bending and torque moment; risk of capsize and buoyancy reserve are preferred on rules on load line and the (old) requirements on margin line.

Hydrodynamics, in particular, resulted an important aspect to assure safety, highlighting the lack of mandatory rule requirements on this field. Maneuvering abilities are the primary concern (the fact is also confirmed by essential equipment sub-criteria: steering gears are considered the second per importance, preceded only by electric generation). Then, concerning seakeeping, slamming and magnification of motions were judged the most dangerous phenomena.

# Conclusions

The application of FAHP into an operative risk assessment proved to be satisfactory to evaluate the weight of importance of criteria and sub-criteria. The results obtained proof how FAHP can be used to convert subjective experience and proficiency into an objective framework devoted to assess the safety state of the ship. In order to obtain more reliable results in weights’ assessment, the survey should be submitted to a wider set of masters and officers and eventually analyzed per type of ship.

Nevertheless, a flexible and complete way to assess the overall safety of the ship has been presented. The introduction of more criteria, sub-criteria and attributes to follow the evolution of the international and class rules or the introductions of new techniques will be possible, subject to partial re-assessment of weights of importance. In conclusion, the risk-based framework is capable to deal with a huge number of attributes, so providing an efficacious representation of the safety state of the ship, suitable for application to a DSS.

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