Giorgio Trincas
Luca Braidotti
Lorenzo De Francesco

Open access paper

http://dx.doi.org/10.21278/brod68103

ISSN 0007-215X
eISSN 1845-5859

RISK-BASED SYSTEM TO CONTROL SAFETY LEVEL OF FLOODED PASSENGER SHIPS

UDC 629.5.016.8:629.541.4
Professional Paper

Summary

Predicting the consequences of flooding is a key issue that may help the ship master of a large passenger ship to make rational decisions in emergency situations. To this end, the Delphi Emergency Decision Support System (Delphi EDSS) has been designed and is under implementation to continuously assess ship's state of survivability. Analyses are performed by means of a time-domain simulation program, where transient stages of flooding are investigated and stored off-line for all the potential damage scenarios. The Delphi EDSS evaluates the ship risk level including the most important aspects related to safety state while establishing the time-to-capsize which is of primary concern for the safe evacuation of the damaged ship.

The methodology is based on a scientific approach, setting an overall platform for rational assessment of non-survivability risk. Determination of the global risk level and its components requires solution of a multicriterial problem, where the level of importance of each criterion contributing to determination of a global risk index is combined with fuzzified contributors to risk calculated at lower levels.

Key words: *Passenger ships; damage stability; safety control; risk indexes*

1. Introduction

Although continuous efforts are being made to prevent their frequency, unfortunately it is possible that grounding and collisions between ships will continue to occur. Therefore, it is important to find out some rational methodology to immediately recognize and minimize the adverse consequences of grounding or collision through a comprehensive and reliable decision-making tool.

A ship is a very complex system composed of various subsystems with a large number of connections and dependences to each other. Therefore, it is difficult to take ship safety under control since all the critical aspects are to be considered simultaneously. In fact, the master and officers are compelled to manage data from different on board systems, to weigh their importance and infer a conclusion also based on their experience and sensibility. This undertaking seems to be a completely subjective process depending on human errors and possible omissions of some important aspects which should be included in a risk evaluation. The consequences of subjective errors or, what is worse, the complete or partial lack of information as well as officers' difficulty about consulting on board mandatory documents could lead to catastrophic consequences in case of a hazardous event such a damage. Moreover, because the problem of safety of a damaged ship is quite complex, it is unrealistic to expect that simple, even probabilistic rules or formulae will be adequate to provide reliable measures of survivability in ship operation. That is why a decision support system is welcome, which has to facilitate recognition of the damage location and extension even in absence of flooding sensors as well as to provide simultaneous measures of the risk levels in a user-friendly way.

After the disaster of "Concordia" in 2012, requirements for safety control of damaged cruise ships are going to become more stringent. The cruise shipping community is committed to reconsider the way the ship status is monitored and governed in pre-casualty and post-casualty situations. It should be mandatory to develop and release an on board tool capable to continuously assess the degree of ship safety, e.g. overall risk level, in both intact and damage condition.

Because of vulnerability of ro-ro ships to stability losses, once they are damaged, a joint European research and development programme on "Safety of Passenger/Ro-Ro Vessels" led to a proposal for new probabilistic rules. Intensive research projects (SAFEREURORO I & II, ROROPROB, HARDER, etc.) and many experimental analyses [1] were carried out to test the accuracy of different mathematical models and numerical tools to look into the effect of dynamic behaviour of damaged ro-ro ships even in waves. Sorrowfully, nothing similar has been even planned for cruise ships so far. Several investigations suggest that flooding scenarios on passenger ships comprise over 70 percent of the risk regarding loss of life generally leading to decisions to abandon the ship [2]. Some studies have been devoted to large passenger ships [3, 4], but the intermediate stages of flooding were not taken into consideration. This is a relevant drawback since the intermediate stages of flooding can sometimes be more severe than the final one due to large free surface and inertial effects on the roll motion.

Although the necessity of preparing damage information to the master in a concise and user's friendly form has been recognized at international level in terms of guidelines with emphasis on all watertight means of the ship, this information is not intended to deliver to the master a ready answer to whether the damaged ship will remain afloat in a safe position or the passengers and personnel shall have to abandon the ship.

Some commercial support tool is available, that can yield damage consequence diagrams (DCD) or loading computers (LC) with lost buoyancy approach. However, all of them are just partial and inadequate to help the ship master to go over heuristic responses in case of damage since these tools do not consider the transient stages and progressive flooding, whilst it should be mandatory to analyse the damaged ship's behaviour because she might capsize well before the final stage is reached. Anyway, these support tools do represent an improvement with respect to the prescriptive documents about damage stability, which are incomplete and difficult to consult because they are more devoted to fulfil IMO and SOLAS rules in the design process than to support decision making in emergency situations.

In recent years, many studies were devoted to simulate the flooding process and analyse the related consequences [5, 6]. In this respect, a significant enhancement was provided by the FLOODSTAND project [7] where, among the others, a simple hydraulic model feeding a time-domain simulation was developed and validated experimentally. Since evacuation time is presently regulated by MSC/Circ.1033 [8], such a strategy was rightly considered the best way to handle this critical topic.

Nonetheless, the FLOODSTAND project, although providing good results, has some deficiencies. The most critical point is its dependence on flooding level detection sensors: a failure on a sensor or a small amount of ingress water may cause an incorrect detection of the hull breach location and size, thus incorrectly affecting the numerical simulation predictions. In addition, even though flooding sensors are mandatory on new buildings, retrofitting of cruise ships built before 2010 with a level sensor-based emergency system would oblige shipping companies to anticipate dry-docking with extra cost for relevant hardware and wiring improvement

There are many commercial products to simulate evacuation of passenger ships through optimal escape routes in case of flooding. Nonetheless, no system is still capable to predict the relation between time-to-evacuation and time-to-capsize in an emergency situation and/or to assess the risk level in order to support the ship master in making rational decision as regards abandoning the ship or mustering to safer places on board.

The Delphi EDSS, which is the most innovative module of the Delphi suite (see Section 2), is under development to overcome all aforementioned limitations, while providing a smart platform for rational decision making process which has to yield more rational guidelines than those suggested by MSC.1/Circ. 1400 [9] as regards operations for safe return to port. It is an integrated system that can perform objective evaluations to assess the ship's risk to capsize, including all most important aspects connected to ship's survivability.

The rest of the paper is summarized as follows. Section 2 presents the Delphi Suite. Section 3 outlines the most original innovation of the system, that is, the continuous assessment of risk level in both intact and damage condition. Section 4 illustrates how the Delphi EDSS performs the operating control on board in real time. Section 5 describes the Delphi EDSS layout. Section 6 discusses the basic concepts of the damage motion tracking as an innovative tool to detect damage location and size. Finally, some concluding remarks are presented in Section 7.

It has to be underlined that this paper is just a description of the structure of the Delphi Suite. In the near future other contributions will deal with the mathematical modelling of flooding, basics of the damage motion tracking, application of the risk level determination procedure while describing a set of case studies.

2. Delphi Suite

The Delphi suite has been developed and is maintained by Navium with the technical contribution of experts from the University of Trieste and Nasdis PDS d.o.o. together with the commercial support of MarineLab d.o.o.. The project started in 2014; the partnership with Seastema S.p.A. (Fincantieri group) has led to the installation of a pilot project on Costa Diadema cruise ship in February 2016 [10].

The conceptual basis of the Delphi Suite is to be a decision support system (DSS). It is a smart and flexible decision-making tool under full control of the officers, which helps to improve their effectiveness in a hazardous situation as well as during navigation. The main innovation of the proposed integrated system is capability to recognise location and size of the hull breach, even in absence of flooding sensors, by means of motion tracking of the ship floating position, so following evolution of the damage event step-by-step via a time-domain simulation. The motion tracking system does not need flooding sensors and this makes the Delphi system particularly attractive for existing ships as it makes unnecessary the costly installation of flooding sensors while still providing a decision support in case of damage. By the way, flooding sensors (mandatory for all ships built after 1st January 2010), can be used by the system in order to be more accurate and faster in damage detection.

The Delphi EDSS, which constitutes the core of the Delphi Suite, predicts the final outcome of the damage event (capsize, new afloat position) as well as the time available for abandonment of the ship. An advanced data analysis technique is implemented to easily estimate and manage the overall risk of a cruise ship. The analysis of damage capsizing will rely on the numerical model which represents ship motions as affected by the water flow outside the hull, flooding of the hull through the damage opening(s), flooding through openings above waterline, sea waves and beam wind forces. For the time being, hull flooding is modelled simply by hydraulic formulas dependent on water head and corrected by calibration coefficients.

The Delphi EDSS is designed to guarantee a real time operating control over the whole ship and to aid the master and officers on board damaged ship in the final decision making whether to immediately evacuate the ship or to proceed safely to the nearest port. At the same time it continuously monitors the risk also in intact condition. This feature makes it a permanently operating tool, which can be used to prevent critical emergencies before their occurrence. To this end, already in intact condition the Live Floatability Assessment (LFA) tool spots the most severe flooding scenario that might occur taking into account the watertight doors left open. This is an important problem especially on cruise ships, where rules allow letting open the watertight doors even during navigation; hence necessity of making the officers aware of the risk related to dangerous behaviour by highlighting the most dangerous one.

Finally, the Delphi EDSS can evaluate the safety state of the ship related to possible counter actions in emergency situations by allowing the master to evaluate and compare possible solutions (like ballasting or deballasting) that can increase safety of the ship.

2.1. Modules of the Delphi EDSS

A complete overview of the Delphi Suite is provided in Figure 1. It includes a number of modules aimed at exercising control over ship safety with a growing degree of complexity and completeness. Each module includes facilities to be integrated with on board automation or other applications inside ship net. In addition, it is possible to remote all the on board modules inside an onshore fleet operation centre where personnel, through the dedicated module, can continuously monitor the whole fleet, view what actions are performed on each ship and perform their own evaluations in order to assist at best the officers during navigation.

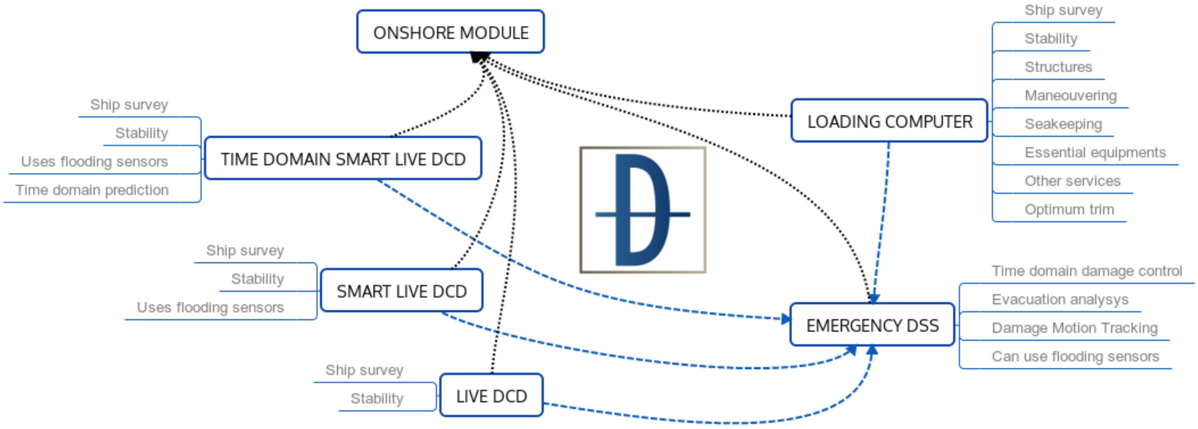


Fig. 1 Structure of the Delphi Suite

All Delphi Suite modules are based on an innovative risk-based framework in order to simplify officers' comprehension and reduce human errors caused by misunderstanding or lack of information. Among the others, it facilitates communication between on board and onshore personnel with time saving (essential aspect during flooding casualties).

The on board modules are covered under the following headings:

- Delphi Live Damage Consequence Diagram (LDCD). It is the entry level solution which provides a smart decision support in intact and damage condition. It needs a very simple and small set of input data in order to perform stability calculation and floatability assessment.
- Delphi Smart Live Damage Consequence Diagram (LDCD-S). This module is dedicated to cruise ships with flooding sensors installed. It has the same features of LDCD but allows automatic recognition of the damage case thanks to alarm from flooding sensors.
- Delphi Time-Domain Smart Live Damage Consequence Diagrams (LDCD-ST). This module offers the same features of LDCD-S but includes a time-domain simulation for progressive flooding (the initially damaged compartments are identified by flooding sensors and considered lost).
- Delphi Loading Computer (LC). This is a new generation loading computer certified for intact and damage stability, which includes a great set of innovative features and tools in order to manage risk beyond complying with rules.
- Delphi Emergency Decision Support System (EDSS). It is the most complete module, which contains all the features of the LC and includes the Damage Motion Tracking (DMT) system to automatically perform hull breach recognition (even without flooding sensors). In addition, it includes advisory cards to recommend the best counter actions during a flooding casualty.

2.1.1. Main Features

The Delphi Suite modules include a large number of features to help the officers in making rational decisions. For this reason, the risk-based framework as well as the possibility to compare more loading and/or flooded conditions are the key features of the whole suite. Through this framework, various aspects connected to ship safety are made available to officers as follows.

All the LDCDs modules are devoted to determine the consequences of flooding on ship's stability and floating position. They present an increasing degree of complexity and integration with other systems on board: the LDCD applies a lost buoyancy method, whereas the LDCD-ST can evaluate the progressive flooding by means of a hydraulic simulation model.

The LC module introduces more criteria in the risk-based framework, beginning from the structural integrity check. In addition, it provides a complete set of tools in order to define and manage the intact loading condition of the ship (tank levels, dry cargo, cranes, unknown deadweight, etc.). In addition, it includes some tools in order to simulate and check loading conditions other than the current one, assess water ballast or cargo distribution and compare the result with current data.

All these features are included in the EDSS, which embeds both LC and DMT systems. The DMT is an emergency system to provide a decision support on board with real-time information in case of flooding, thus predicting how the damage evolves in time, based on macroscopic effects, e.g., slow changing of the ship's floating position due to flooding water ingress).

This goal is pursued by comparing the real-time evolution of damage effects with the evolution of simulated damage scenarios stored in a database. At an intermediate stage of flooding, the simulated damage which yields the ship's spatial position most similar to the actual floating position recorded by the external instruments is considered the most probable. The evolution of the most probable damage is taken as a prediction of the time evolution of the flooding. Therefore, it is possible to predict the final outcome of the damage event (new equilibrium position or capsize), the time to final stage and the time to lose essential equipment operation.

The DMT system is designed to work without flooding sensors; therefore, the sensors are not necessary for the EDSS. The other modules, which do not consider damage evolution in time domain, call for flooding sensors integration.

2.1.2. Tools

The Delphi Suite modules can include a large number of tools to improve ship safety, manage properly loading and unloading, and perform not common calculation such as estimate of squat.

A multi-step damage tool, that is included in all the modules, has been developed. It evaluates the final stage of a flooded ship using the lost buoyancy method. Then, if progressive flooding is pointed out by checking submersion of any internal opening, a new evaluation is performed considering lost also the compartments interested by floodwater pouring. This process is repeated until the ship reaches a safe equilibrium position or capsizes. At each step a risk assessment is performed.

Another important tool, which is included in all the modules, is the Live Floatability Assessment (LFA). This is the core of the flooding prevention system in intact condition: by applying the IMO guidelines [11] to the current loading condition, LFA spots the most severe damage scenario which may occur to the ship taking into account the watertight doors left open during navigation, thus making the officers aware of the worst consequences of their behaviour. For the actual loading condition a ranking is also provided for the risk connected to each open watertight door in order to help the officers in taking the most effective counter actions to reduce risk.

2.2. Onshore Module

An onshore module is recommended in order to perform remote monitoring of the ship condition. The onshore module shall be installed in a fleet operation centre guarded 24 hours a day to take under control the ships' safety level during navigation. Furthermore, in emergency situations, it allows monitoring of the master's counter actions and supports on board decisions by performing additional simulations using the same input data recorded on board.

The Delphi onshore module is based on a SQL database devoted to store all data transmitted from the ships equipped with the same modules as the Delphi system installed on board. In addition, the database contains the overall geometric model of all the monitored ships.

Two or more client computers query this database and show data collected from all the ships in compliance with IMO guidelines [11]. Furthermore, they can process those data in order to mimic the technical results shown by the Delphi on board modules.

3. Risk-Based Control

The main goal of the risk-based framework is to provide the ship master and officers with a simple and efficient tool to mitigate consequences related to a hull breach by advising them in the decision making process for any feasible counter action. To get a fast, accurate and deterministic assessment of the overall safety of the ship in both intact and damage condition is impossible because there are too many items to manage simultaneously. That is why a risk-based control tool has been developed where all the primary endogenous and exogenous factors involved in ship safety are taken into account.

To control the overall safety level, the risk-based framework simultaneously takes into account several criteria and attributes of ship performance. Assessing a global risk index is a classical multicriteria decision making (MCDM) process. This estimate combines the risk indexes at lower levels: first, involving ship properties and their objective degrees of satisfaction with respect to given prescriptive rules; then safety subcriteria and criteria merged with subjective preferences. To handle uncertainties and imprecision in estimating some ship properties as well as differences in group opinions as regards subcriteria and criteria, a fuzzy set approach is introduced.

The risk assessment evaluation process evolves from assessment of ship properties up to the global risk index. Through this cognitive process particular attention is paid to prescriptive rules and how the ship complies with these rules. In addition, innovative methods have been introduced to face problems not currently included in IMO and/or SOLAS norms but anyhow important to assess the ship's safety state.

3.1. Risk Assessment Philosophy

Creating a risk-based framework for an intact or damaged ship means to integrate into a global risk index all the aspects connected with the ship survivability by means of mathematical modelling. The global risk index is a number that varies between 1 (no risk) and 0 (utmost risk) which summarizes the single risk indexes of a set of modules using a multi-level approach.

The decomposition principle is used to construct a hierarchical network (see Figure 2), with the top representing the global risk index and the lower levels representing criteria, subcriteria and properties in descending order.

The criteria that are taken into account in the risk-based framework of the Delphi EDSS are the following:

- Ship survey, related to all the aspects connected to ship floating position such as freeboard requirements, submersion of the margin line, shell doors. In addition, it deals with the most important issues of ship survivability such as reserve of buoyancy and risk of capsize due to actual weather condition.
- Structural integrity, related to the risk of structural failure caused by critical combination of current loading or flooded condition together with weather condition. The IACS UR S1 requirements [12] and MSC.1/Circ.1400 item 16.10 [9] are taken into account.
- Evacuation, related to the effect of flooding on escape routes and the effect of ship's list on evacuation time. The MSC.1/Circ.1400 Item 16.8 requirements [9] are to be complied with.
- Stability rules, related to compliance with stability rules for intact [13] and damaged [14] ship; it deals with IACS UR L5 [16] requirements.
- Essential equipment, related to effective operation of the essential systems as defined by SRtP regulations [16]. The effect of flooding water and heel/trim angles

should be taken into account. The MSC.1/Circ.1400 Item 16.8 [11] requirements are dealt with.

– Ship motions (optional), related to consideration of ship motions' amplitude and their closeness to resonance frequencies, in order to avoid their magnification.

Manoeuvring rules (optional), related to simulation of the most important ship manoeuvres in accordance with IMO standards [17].

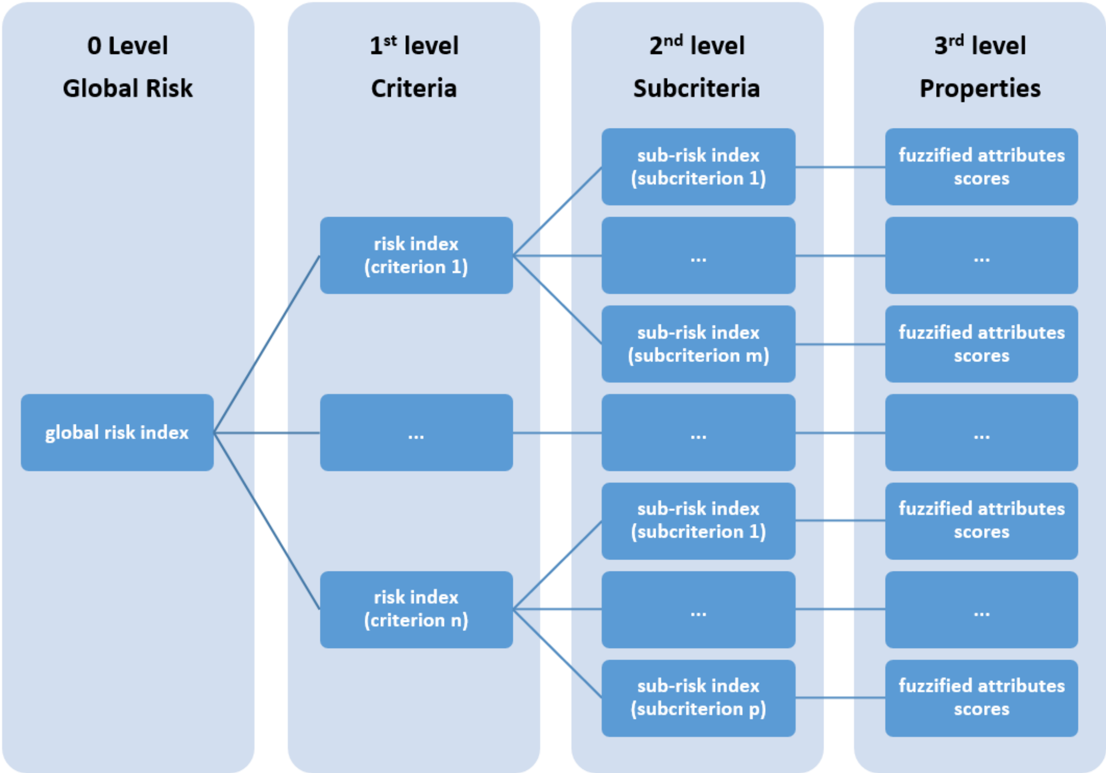


Fig. 2 Structure of the risk evaluation model

The classification of criteria and subcriteria is listed in Figure 3: Distinction is made between primary and secondary level of importance. The first term (blue colour) refers to criteria which the authors consider of utmost influence on ship survivability as well as to subcriteria highly contributing to assessment of criteria risk indexes. On the contrary, the term secondary (green colour) means that a lower impact on the global risk index and criteria is expected from corresponding information available. In the near future, masters' and officers' preferences are planned to substitute authors' opinions as regards levels of importance of criteria and subcriteria.

The process to arrive at the global risk index stems from the bottom (evaluation of ship properties) through sequential determination of risk indexes for subcriteria and criteria, up to the global risk index, as follows:

1. The third level deals with assessment of attributes' scores. The attributes are subject to prescriptive norms and operating constraints, which are introduced as thresholds. In standard codes, there is only a Boolean approach to rules and constraints, e.g., complying or non-complying with: the "border" between these two conditions is the threshold value. There is no difference between a situation where the rule is fulfilled with a safe margin and another one where it is just marginally fulfilled. To overcome this crisp approach, a softer strategy is applied where the scores are normalized and weighted via a fuzzy entropy method.

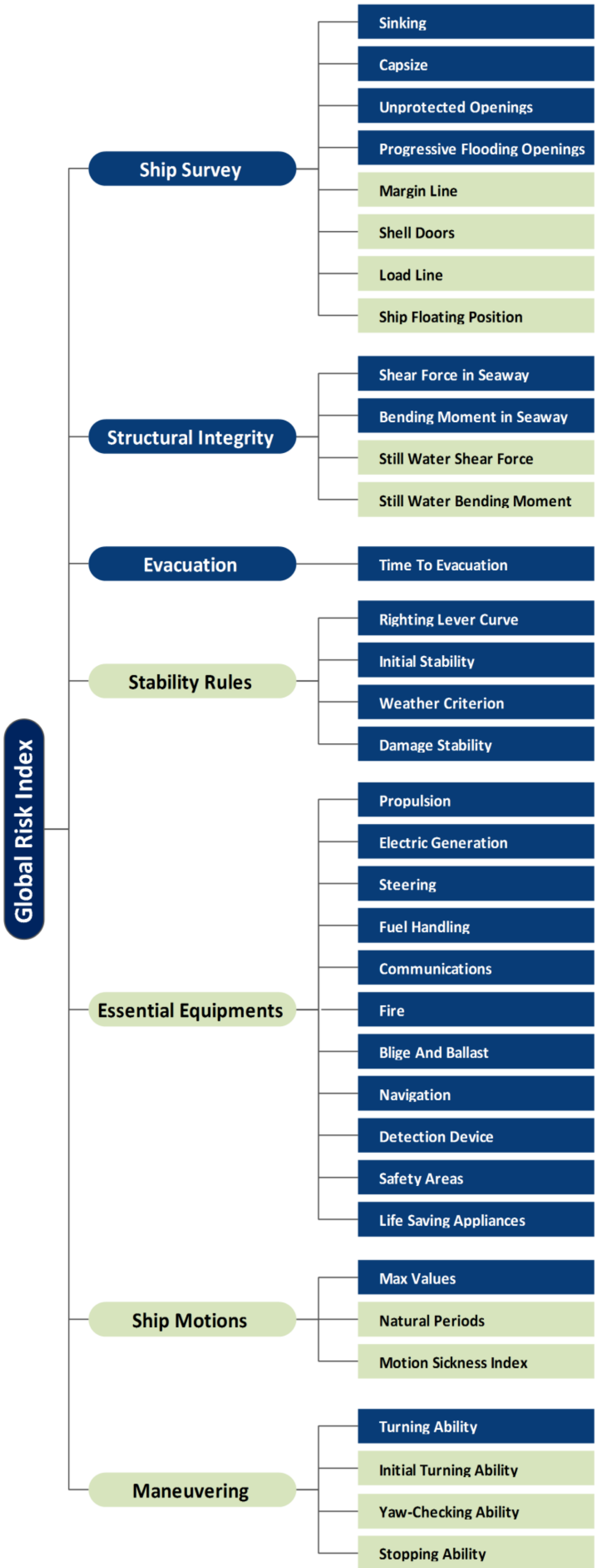


Fig. 3 Subcriteria and criteria leading to the global risk index

2. At the second level, each sub-risk index is inferred by aggregating the weighted fuzzified scores of the attributes as derived from the previous step.
3. The first level of the risk framework aims at calculating the risk indexes for the criteria included in the process. To this end, as stated above, an interview module is being prepared to ascertain subjective judgments of personnel about their feeling over the subcriteria. This group definition of levels of importance of the subcriteria is treated by means of a fuzzified analytical hierarchy process (AHP). These subjective weights combined with the sub-risk indexes as from the second level provide the risk index for each corresponding criterion.
4. The same approach used in the previous step is followed in moving from criteria indexes to the global risk index in order to obtain a higher degree of synthesis.

To summarize, a risk evaluation is obtained at each level of safety problem decomposition: fuzzified scores for each attribute value (third level), sub-risk indexes for each subcriterion (second level), risk indexes for each criterion (first level) and a global risk index to define the safety state of the ship (zero level).

3.2. Fuzzy Comprehensive Evaluation for Safety Risk

It is difficult to assign precise values to performance parameters (attributes), subcriteria and criteria since vagueness, inaccuracy and imprecision are common characteristics at whichever level of risk assessment. This uncertainty is handled by means of fuzzy logic (see Appendix A). At the same time, the comprehensive decision-making process to assess the global risk index requires determination of subjective and objective weight sets. The global risk index is thus determined by a new method for the comprehensive assessment of the elements of the structure illustrated in Figure 3 through the combined use of weighting decision-making methods and fuzzy comprehensive evaluation.

From various surveys it has been observed that attributes, sub-criteria and criteria are not equally influential or important in determining values at a higher level. To reflect the role of their relative importance, e.g. the appropriate weights associated to each of them, a multiple attribute decision making approach (MADM) was found suitable. Several methods to determine weights have been proposed and most of them can be classified as subjective or objective weights according to the type of information acquisition. The subjective weights methods (inter-attribute preference) are supposed to express the relative importance of different criteria and subcriteria as perceived by the ship personnel. The objective methods (intra-attribute preference) determine weights without any consideration of the officers' preferences about ship properties; they reflect the intrinsic importance of the different scores of the same attribute.

In the Delphi risk-based framework the intra-attribute preferences are determined by a fuzzified entropy method (see Appendix C), while as to the inter-attribute preferences a fuzzy group AHP method is deemed particularly suitable (see Appendix D). Once all the relative weights are calculated, a composite weight for each decision criterion is determined by aggregating the weights over the hierarchy for each risk criterion. To do this, the weights are summed up along the paths from the bottom, i.e., the attributes, up to risk sub-criteria; afterwards those sums are multiplied over all the different pathways to the risk indexes of criteria.

3.2.1. Fuzzy Entropy Method

The entropy measure of importance, introduced into the information theory by Shannon [18], can be used as a measure of compliance with rules and constraints in assessing uncertain effects of damage scenarios. Based on the basic principle of information theory, the entropy is a measure of the randomness, disorder, or chaos degree of a system. It is a simple but empowering way for weight determination from information conveyed by the information source, e.g., damage simulations. The main steps of the entropy weight method include the formation of the evaluation matrix, the normalisation of this matrix, the calculation of the entropy, and finally the entropy weight.

When the responses of damage simulations have quite a large difference between each other on the same attribute, the entropy is smaller and the weight of the corresponding ship property will be larger. On the contrary, if the difference is smaller, the entropy is higher and the corresponding entropy weight will be smaller. In other words, when the values of any attribute for every evaluated damage scenario are almost all the same, the entropy reaches the maximum, which means that the corresponding ship property plays little role in the comprehensive assessment of the sub-criterion risk index and may even be removed from the overall evaluation.

In order to establish how much an attribute score complies with the corresponding prescriptive rule or constraint, the level of satisfaction to the associated crisp (Boolean) constraint will be transformed into a fuzzy number to be multiplied to the weight as determined by the entropy method. Assume the scores of the i-th attribute with respect to m damage simulations are viewed as a fuzzy set, defined as the following set of ordered pairs:

$$\{x_i^k, \mu_i^k\} \quad i = 1, 2, \dots, n; \quad k = 1, 2, \dots, m$$

where μ_i^k is the membership grade function mapping the values of the i-th attribute into the interval [0, 1] (fuzzified score), which reflects decision makers' intention as regards the level of importance of the specific attribute.

The main steps of the developed method for the fuzzy entropy weighting are as follows:

1. evaluation of the set of attributes' scores;
2. establishment of the fuzzy evaluation matrix;
3. determination of the weight of each attribute using the entropy weight method;
4. calculation of the risk sub-indexes.

After the fuzzy evaluation matrix $\tilde{\boldsymbol{D}}$ of μ_i^k and the weight vector $\boldsymbol{w}$ are obtained, the comprehensive evaluation of risk sub-indexes at the second level can be determined through fuzzy arithmetic operations by a stepwise computation, as formulated below

$$\widetilde{\boldsymbol{RI}} = \tilde{\boldsymbol{D}} \circ \boldsymbol{w}$$

where "∘" is the fuzzy operator.

Basics of the entropy weight method and its fuzzification are summarized in Appendix C.

3.2.2. Fuzzy Analytical Hierarchical Process

In a very heavy hazard like a damage the officers' expertise and judgment should be taken into account. Their subjective guessing should be obtained through interviews and transformed into weights by means of a standard Analytical Hierarchy Process (AHP). As officers usually feel more confident to give interval judgments rather than expressing their opinions in the form of single numerical values, a fuzzy group AHP method is deemed particularly suitable in the risk analysis for ship safety if one wishes to tolerate vagueness and ambiguity.

All pairwise comparisons will be converted into triangular fuzzy numbers, because of their simplicity and computational efficiency (see Appendix B), to adjust the fuzzy subcriteria and criteria weights.

The main steps of the fuzzy AHP procedure are as follows:

- *Structuring the decision hierarchy*. Similar to conventional AHP, the first step is to break down the complex decision making problem into a hierarchical structure, from the top through the intermediate levels to the lowest level (see Figure 2).
- *Developing pairwise fuzzy comparison*. The weighting problem is considered at a level with n subcriteria or criteria, where comparison judgments are represented by fuzzy triangular numbers $\tilde{a}_{ij}$. As in the conventional AHP, the judgments are further used to construct a fuzzy reciprocal comparison matrix $\tilde{A} = \{\tilde{a}_{ij}\}$
- *Consistency check and derivation of weights*. This step checks for consistency and extracts the weights from the pairwise comparison matrices. According to Buckley [19], a fuzzy comparison matrix $\tilde{A} = \{\tilde{a}_{ij}\}$ is consistent if $\tilde{a}_{ik} \otimes \tilde{a}_{kj} \approx \tilde{a}_{ij}$ where $i, j, k = 1, 2, \ldots, n$, $\otimes$ is the symbol for fuzzy multiplication operation and $\approx$ denotes fuzzy equal to. Once the pairwise comparison matrix, $\tilde{A}$, passes the consistency check, fuzzy weights $\tilde{w}_i$ can be calculated with standard AHP. Then, the weight vector $(w_1, w_2, \ldots, w_n)^T$ can be obtained from the comparison matrix by applying an eigenvalue method.

The details of the fuzzy AHP can be read in Appendix D. Once the normalized weight of each criterion is worked out, the risk index of the same criterion is calculated by multiplying each criterion outcome with the corresponding weight.

3.3. Aggregation methods

As stated before, the bottom up approach of the Delphi risk-based framework, e.g., from the attributes' risk-indexes at the third level to the global risk index at zero level, is a synthesis process which allows the aggregation of the lower level indexes into one index related to the upper level. To emphasize potentially critical aspects in the whole risk assessment process the so-called "corrected average approach" is introduced, whilst the "min-min approach" and "the direct score approach" are applied only at the third level to handle some special cases.

3.3.1. Corrected Average Approach

The corrected average approach allows to take into account the crucial aspects of a subcriterion or a criterion better than a standard weighted average, which reads:

$$RI = \sum_{i=1}^{n} w_i \cdot RI_i$$

where RI is the risk index of the upper criterion, whilst RI_i and w_i denote the actual value of the risk index and the weight (importance) of the lower level of the i-th criterion, respectively.

The lower level criteria RI_i are distinguished in two categories (see Figure 3):

- Primary: each primary lower level criterion contributes to the upper level risk index through a weighted average; in addition, if at least one lower level risk index classified as primary tends to the minimum value (0), the risk index of the upper level tends to the minimum value too.

– Secondary: each secondary lower level criterion contributes to the upper level risk index only through a weighted average.

For primary elements, a correction to the value of the upper level risk index is applied; this correction takes into account how near to the maximum value is the worst primary lower level criterion. If this value reaches the minimum (0), also the risk index will reach the minimum value. The correction reads:

$$RI_a = RI + (P_{min} - RI) \cdot (1 - P_{min})$$

where RI_a is the corrected value of the upper level risk index and P_{min} is the minimum value of the lower level non-corrected risk indexes RI_i.

3.3.2. Min-Min Approach

The min-min approach is applied at the third level of the framework if risk depends on a great number of elements of the same type (such as margin line points or control points of a stress curve). In these cases, the value of the upper level risk index is evaluated as the minimum value spotted on the fuzzified scores of ship properties

$$RI_a = \min RI_i$$

3.3.3. Direct Score Approach

The direct score approach is applied at the third level of the framework to determine the sub-risk indexes of the essential equipment. The risk connected to any essential equipment is generally related to the loss of one among the indispensable capabilities of the ship. Therefore, for each essential device grouped in a subcriterion, a Boolean status (operative/inoperative) is assigned. A device is defined as inoperative whether flooding water reaches its location, or ship's heel/trim angle reaches a limit value, or another element, on which the specific equipment is dependent, is inoperative. Therefore, the sub-risk index value is calculated as follows:

$$RI = \frac{N_{d,op}}{N_{d,tot}}$$

where $N_{d,op}$ is the number of still operative essential devices and $N_{d,tot}$ is the total number of the same-type devices installed on board.

4. Real Time Operating Control

To evaluate the safety state of the ship, the Delphi EDSS performs several risk assessments distinguishing between intact and damage condition while starting simulations from the current ship floating position. All these data are provided in a Graphical User Interface (GUI), designed to be very user-friendly while providing all the necessary information in a smart way and easy to read.

In intact condition, the Delphi EDSS is capable to estimate and compare among each other different potential risk situations:

– in current loading condition, in order to evaluate safety state of the ship;
– in the worst case spotted by LFA, in order to anticipate dangerous situations.

In damage condition, in order to ascertain an acceptable level of safety, the Delphi EDSS is capable to perform and compare the risk level:

- in current stage of flooding, including flooding water from the most probable damage scenario;
- at final stage of flooding, from the most probable damage scenario.

Moreover, an additional risk assessment evaluated in a potential loading condition or damage scenario could be compared to the previous ones. The related input data are defined through simulation tools and could be based on

- the current loading condition;
- a saved loading condition;
- the current stage of flooding;
- the final stage of flooding;
- the worst damage scenario spotted by LFA.

For sake of easiness in understanding, only results of one simulation at a time is shown together with the previous risk assessments, therefore, the Delphi EDSS shows not more than three risk assessments at a time. Thus, comparison is a key feature of the Delphi EDSS, allowing an immediate understanding of the evolution of flooding as well as the result of a simulated counter act.

Moreover, the GUI gives a simple and clear representation of the data provided by the risk-based framework. Checking the actual state of the ship is facilitated by introducing the concept of risk level, which varies from 0 (no risk) to 100 (utmost risk). The risk level RL, always provided in graphical form is derived from the risk index RI as follows:

$$RL = (1 - RI) \cdot 100$$

At each level of the framework (see Figure 2) a proper panel is provided to the user in order to allow a rapid and guided access to all data evaluated by the Delphi system. The first level, which collects the representation of all the main criteria of the framework (Ship Survey, Structural Integrity, Stability, etc.), allows a quick look to identify a potentially critical situation and its origin. The second level is represented by each risk criterion of the ship, which is exploded into its subcriteria. At the third level, the attributes values associated with the corresponding subcriterion are provided. This approach permits an immediate understanding of whichever anomaly with a detail necessitated by the officers to take quick and rational decisions in order to preserve human life and ship integrity.

The first and the second levels are associated to risk panels, whereas the third level is described by detail panels with ship properties' values which are the only output of a standard loading computer system. Considering the great amount of information provided by the Delphi EDSS, the upper levels are essential in order to avoid human errors and/or the omission of essential information during the evaluation of a critical situation.

4.1. Smart Navigation GUI

During the development of the Delphi EDSS, particular attention was paid to navigation through GUI. Therefore, a dashboard was created in order to navigate between criteria risk panels, risk summary (the first-level risk panel provides the risk levels for all criteria) and loadmaster (the panel devoted to manage the loading condition of the ship). Another dashboard allows the officers to select among the tools and open the corresponding input panels.

Three switches allow - and select, if more than one simulation is evaluated - the required risk assessment(s) to be shown. The switches provide also a fixed legend in order to identify unequivocally which risk assessment the data shown are related to. Thus, the officers could turn on or hide the risk assessments according to their needs, thus making it possible a flexible and simple comparison.

4.2. Risk Panel

The Risk Panel (see Figure 4) is the most important feature to provide the officers with a simple and smart graphical representation of one or more risk assessments as well as to make easy comparison among them.

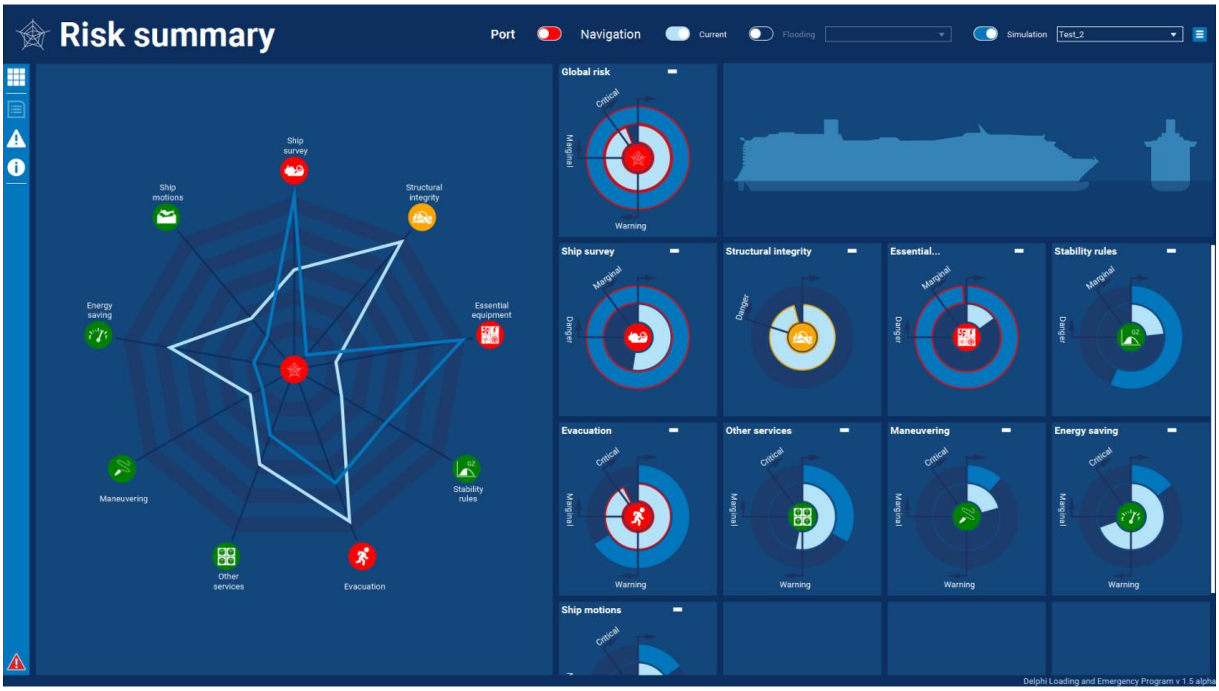


Fig. 4 Risk Summary

As previously stated, the number of visible risk assessments is limited to three, each one identified by a different grade of blue. The aim is to compare and highlight the different risk levels which concur to the global risk or to the risk level associated to each criterion or subcriterion. Therefore, the risk levels are provided through two main elements:

– the Diamond Risk Meter (DRM) on the left side;
– the Risk Gauges (RG), one for each criterion or subcriterion, on the right side.

Another RG, located on the top of the panel, provides the representation of the global risk. On its right a small panel enables an overview of some specific data which differ for each criterion; for example, it provides the graph of the stress level for the structural integrity criterion or the righting arm curve as to the stability rules criterion. Otherwise, sketch of the floating position of the ship is shown.

The immediate understanding of the situation is guaranteed by using colour language and icons. Each criterion or subcriterion is identified by a unique icon coloured according to the risk level: green colour denotes a safe condition, yellow a warning condition, red a dangerous condition, blinking red a critical condition (i.e., the risk reaches the maximum value).

4.2.1. Diamond Risk Meter

The DRM provides a simultaneous graphical representation of the risk associated to all the criteria or subcriteria that contribute to the global risk or to a criterion and subcriterion risk, respectively. Each diamond axis represents the risk level of a criterion or subcriterion.

The farther the tip is from the centre, the higher the risk level. Thus, the extent of the diamond area represents the global risk level, also highlighted by the central icon. In order to allow an immediate comparison among the different risk levels, the DRM shows all the enabled risk assessments simultaneously and highlights the worst condition through the tip icons colour. The Delphi DRM is the best solution to combine simplicity and quality of information, in order to keep the situation under control without having to directly deal with technical data and variables.

4.2.2. Risk Gauges

The RGs allow a simple representation of the risk level, individually related to any criterion or subcriterion, for all the enabled risk assessments. Each criterion is identified by name and icon located in the centre of the corresponding gauge. The icon colour varies alike in the risk panel. Likewise the DRM, a RG can provide the level of risk for one up to three risk assessments at the same time by using circular sectors round the icon. An empty sector stands for no risk, whereas a completely filled sector holds for a critical condition.

To provide a faster understanding of the risk condition, some thresholds which discretize the gauge in sectors, are highlighted through radial axes. A keyword is associated to each axis. This approach could help the officers in understanding the consequences of a risk level's raising without switching to a deeper level of information. Finally, to facilitate an immediate understanding of the risk level while waiting for worldwide experts' decisions, a temporary semantics is used in the following upward order: warning, danger, marginal, critical.

5. EDSS System Architecture

The Delphi EDSS is the most complete module in the Delphi Suite. Completeness obviously implies complexity in the structure of the code and algorithms, but not at all in the hardware (architecture) of the system. The aim of Delphi EDSS is to provide a powerful tool to handle emergency without resorting to expensive investments in hardware. In particular, the system is conceived to be further integrated with a marine automation system, so reducing the additional set of instruments to a minimum.

In addition, to satisfy specific requirements from shipping companies, the Delphi EDSS should be developed and released in two different versions:

- A stand-alone software to be placed on the navigation bridge (standard solution).
- An "enterprise" application to enable all officers to gain access to information through any device connected to the ship net, by running a browser such as tablet, smartphone and wearable devices.

The latter solution is a true innovation in the on board emergency systems and has already caught cruise companies' attention. By the way, this solution still requires to be deepened, by stimulating IMO MSC and classification societies in cooperative development.

5.1. Hardware Arrangement

The minimum hardware required by the Delphi EDSS consists of an inertial platform to record ship's heel and trim as well as linear and angular acceleration components, and a set of level radars to take the current draft. Flooding sensors can be utilized by the system if the ship is already equipped with them; otherwise, sensors' installation is not required.

The inertial platform has to be installed integral with the ship and isolated in order to avoid noise from external forces such as people walking or machines running. To guarantee redundancy and a more accurate data analysis, it is recommended to place two inertial platforms: one placed at bow and the other at stern. Six radars should be installed integral with the ship in pairs (port and starboard) at bow (on/under the navigation bridge), midship and stern. For new buildings, as an alternative to radars, two surge pipes are recommended, one placed at bow and the other at stern. The weather station can be placed anywhere on-board; it is recommended to place another one for sake of redundancy. The slightest configuration of the recognition devices is shown in Fig. 5.

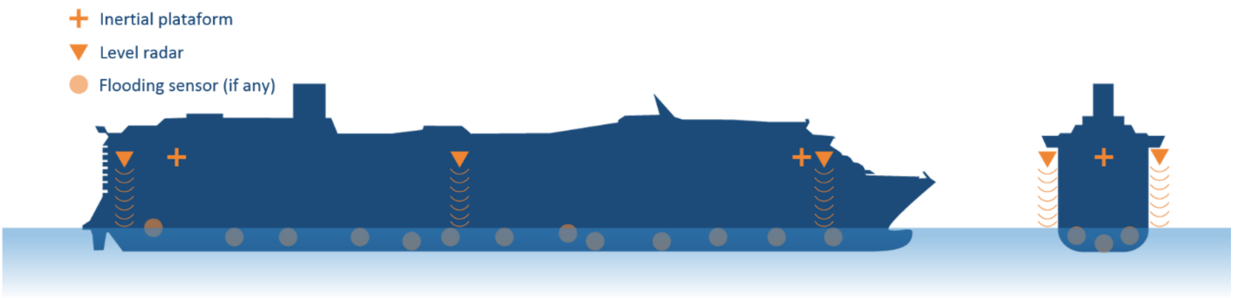


Fig. 5 Recognition devices

5.1.1. Marine Automation System integration

To handle each operation, the Delphi EDSS is designed to receive data from any authorized client using a HTTP connection and the CRUD protocol based on XML files. This architecture makes the program completely open to all devices and makes the integration with other software easier and cost effective.

To perform a complete risk assessment, the Delphi EDSS requires the information given in Table 1.

Table 1 Required information from marine automation system

Information description	State	Data
Weather data	online/offline	Wind speed and direction
Ship route data	online/offline	GPS position
Watertight door data	online/offline	Opened/closed
Tanks sensor level	online/offline	Measured level
Bilge and ballast pumps	online/offline	Standby/running
Essential equipment data	online/offline	Standby/running
Flooding sensors (if any)	online/offline	Measured level

These data can be transmitted to the Delphi modules through a data collector, the so called Metreo. It converts automation rough input data in a well formatted XML and sends them to the Delphi system. This approach permits to customize the link software for each ship and to release a standard and certified version of the EDSS.

5.1.2. Stand-Alone Software Layout

In order to ensure compliance with the rule requirements as well as IMO guidelines, the Delphi EDSS will be installed on two separate workstations, each one with a monitor and a printer and connected to an UPS [20]. A simple sketch of the Delphi EDSS on board hardware is given in Figure 6.

To comply with IMO 1/Circ.1400 [9], two systems should be installed, each one connected to the ship net to ensure redundancy and preserve operability in case of failure. Each Delphi system consists of two workstations: the former runs the Metreo Data Collector dedicated to communicate with external instruments, whereas the latter runs the Delphi EDSS. Both workstations write on two servers to generate a historical log.

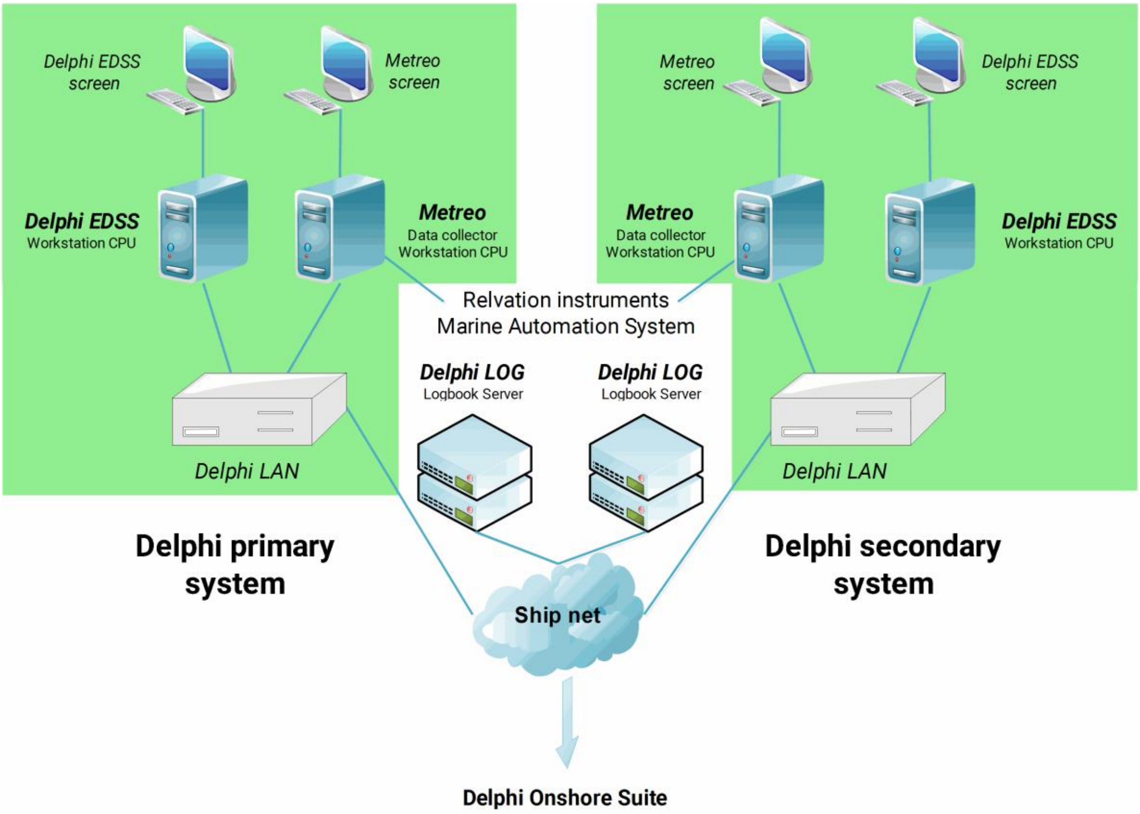


Fig. 6 Delphi technical arrangement

The Delphi system is redundant and designed to operate even in case of a single point hardware failure. A failure on the secondary system is not deemed critical for ship safety. Several single failure modes on the primary system have been foreseen and due reactions have been planned.

5.1.3. Enterprise Application Arrangement

Nowadays there is no emergency program developed in an enterprise way. This kind of deployment should be run inside a web container installed in the on board data centre that is connected to the ship network.

This release makes data available to all authorised applications; the officers can consult them from any device running a web-browser or using a dedicated app. Due to the centralised architecture, the application could send notifications and warnings to all connected devices.

5.2. Ship Modelling

To ensure hull breach recognition and risk-assessment, the Delphi EDSS requires a complete three-dimensional model of the ship. This model comprises geometrical definition of the hull form and internal spaces divided by watertight boundaries (bulkheads and decks) and relevant non-watertight boundaries.

In addition, it is necessary to model the shape and size of all the connections between those spaces that may either slow the spread or change the evolution of flooding. The links which are essential to estimate the fluxes of water between main compartments at each time step are the following:

- free outflow connections,
- shell doors,
- watertight doors,
- cross/down flooding ducts.

Special care should be taken of spaces with a high grade of subdivision with non-watertight boundaries, such as cabin areas. These spaces should be aggregated in a low number of watertight spaces connected by large openings [21].

In addition, in order to consider essential equipment operation, the model should include all the essential devices, including their position, limit angles of operation, as well as interconnections and dependencies among them.

6. Damage Motion Tracking

For the time being, there are no marine workstations which can perform in due time a number of simulations sufficient to identify the actual damage position and extent without flooding sensors, while ensuring the required level of probability to detect the damage evolution during the intermediate stages of the process. Such an estimation can be reached using an inverse method based on flooding sensors. However, this method does not guarantee to get a recognition of flooding location and size [22].

To solve this problem definitively, the damage motion tracking (DMT) system is developed inside the Delphi EDSS. It assumes and claims a database where a huge set of damage scenarios and their evolution in time, obtained by numerical simulations at various loading and environmental conditions, are stored. At damage occurrence signalled by early warnings, the stored simulations are compared with the evolution of the actual flooding situation in order to identify the most probable damage scenario. Then the DMT system is capable to mimic the actual damage scenario during the transient flooding stages, so assuring a more and more accurate prediction of flooding evolution and final outcome.

6.1. Early Warning

At damage occurrence, the Delphi EDSS submits the officers an early warning and simultaneously activates the DTM system. There are five different conditions which can trigger the DTM system, namely,

- sudden accelerations,
- unknown deadweight increase,
- heel variation,
- alarm from flooding sensors (if any),
- manual starting,

which are given a short explanation below.

At grounding or collision occurrence, the ship is subject to an instantaneous acceleration due to mechanical impact, which could be detected by the inertial platform. If this acceleration overtakes a given threshold, the DTM system is activated. The threshold value is to be taken as the lowest which avoids the DTM starting, accurately enough, when the ship suffers from acceleration below that value.

The Delphi EDSS continuously monitors the actual displacement of the ship. The unknown deadweight, i.e., the difference between actual displacement and total ship weight calculated by the loading instrument, can be used to detect flooding, especially if the phenomenon lasts long enough. If this difference overtakes a given threshold, the DTM system starts to operate.

In the early stages of transient flooding, especially for significant hull breach, ship's heel varies significantly. Therefore, an unexpected change of heel and trim is another starting condition for the DTM system. Obviously, it is important to choose reasonable thresholds in order to avoid DTM's activation due to wave-induced ship motions. To lower these thresholds, heel and trim values detected by the external instruments should be filtered to reduce ship motion induced disturbance.

The DTM may be activated by the flooding sensors, if any, and manually by the ship officers. These systems allow an efficient and early damage detection allowing the DTM system to start at damage occurrence for whichever type of aforementioned flooding consequences.

6.2. Recognition of Damage Location

After damage occurrence, the floating position parameters (i.e., mean draft, heel and trim) of the ship change because of the inflow of flooding water. They are monitored by the external instruments and compared with the time-domain outcomes of the hydraulic simulations stored in database. The simulation that best reproduces the recorded transient flooding is considered the most probable evolution, and the corresponding hull breach is assumed as the most probable damage. The detection process of the most probable damage is sketched in Figure 7.

The most important element of the DMT system is the curve fitting algorithm. It evaluates the closeness between the variation in time of the ship's floating position parameters due to the actual damage and variation of the same parameters for the recorded simulation. The curve fitting algorithm is applied from damage occurrence up to the successful mimic of the current transient stage of damage for each flooding simulation under analysis. This is the key feature of the Damage Motion Tracking, whose basic concept is to spot the damage since its symptoms.

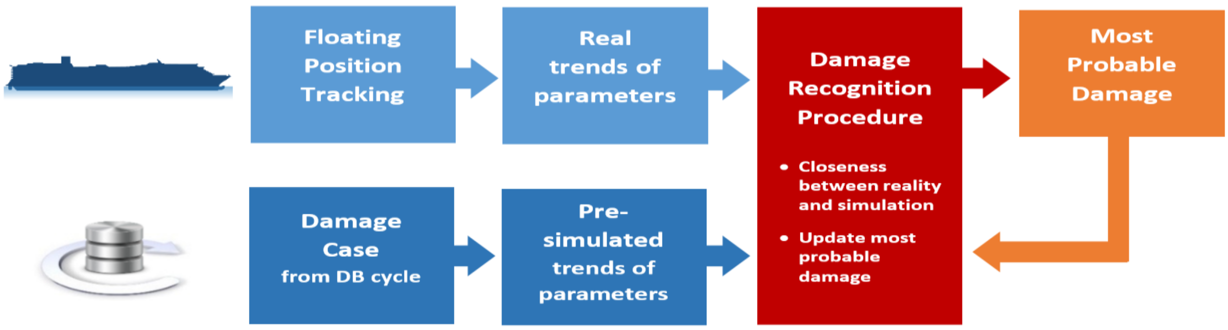


Fig. 7 DMT logical framework

The DMT solution does not require flooding sensors with a consequent saving of money and time for installation. Nevertheless, for recent, present and future buildings, flooding sensors are mandatory and data provided by them can be taken into account by the DTM system in two ways, depending on the alternative type of flooding sensors:

– On/off flooding sensors. If any, they provide only a Boolean response about the presence of flooding water in the compartments. This information can be used by the DMT to guide the database search procedure, so making it faster since it eliminates all the damage scenarios that do not involve the flooded compartments.
– Head flooding sensors. They provide a measure of the level of flooding water inside a compartment. This parameter can be included in comparing actual and simulated flooding evolution during database search, so increasing accuracy of the system.

Therefore, the Damage Motion Tracking can work and provide useful decision support also in case of failure of one or more devices for flooding detection as well as in total absence of them. This feature makes the system particularly suitable for existing ships allowing to have on board a tool capable to increase safety during emergencies at lower cost and reliability higher than systems completely dependent upon flooding sensors.

6.3. Database

After damage occurrence, there is a limited time to make counter actions which can mitigate the risk of capsize. Direct estimation of the time-to-capsize or time-to-evacuation would involve several uncertainties and require too fast computational methods. On the other hand, it would be useless to turn to conventional damage codes conceived for design purpose. As stated before, the solution is found in building a database where all envisaged damage scenarios are numerically simulated at several initial floating positions of the intact ship, while also accounting for transient stages of the flooding process.

The database is the key element of the DMT system to reach the required precision and search speed (time to perform a complete cycle of comparison on all the damage cases stored in the database). Higher the number of the stored damage cases, higher the accuracy; but, at the same time, the search speed decreases.

To reduce the number of stored damage simulations and make faster the search of the most probable damage scenario, all the damage cases which comprehend more than a maximum number of watertight compartments should be excluded. Also the damage scenarios with a very fast evolution to an end (less than 15 minutes for a cruise ship) should be excluded since, in case of occurrence, the severity of damage is immediately clear and the time to manage the emergency is insufficient. Using an appropriate structure of the database and properly speed-up algorithms based on the flooding physics can heavily reduce the time needed to identify the most probable damage scenario.

To ensure a sufficient accuracy, the parametric generation of damage cases could be tightened in critical areas such as those near watertight bulkheads, in order to reduce the difference between the time evolutions of two subsequent cases.

7. Concluding Remarks

A comprehensive computer code, the Delphi EDSS, is proposed to determine the time-to-capsize with sufficient accuracy by means of a time simulation method of damage stability assessment, to be installed on board and duplicated onshore. A new approach for assessing the overall risk level of a passenger ship associated with damage scenarios is suggested by assessing a global risk index in real time in order to evaluate and monitor the overall safety of the ship in both intact and damage condition.

The main breakthrough of the proposed framework is identification of the hull breach's location and size also without the presence of sensors inside compartments. All possible damage scenarios are calculated off-line and stored in a database to simplify and speed up the time-domain simulation of the actual damage situation once the damage is identified.

The various steps to calculate contribution to risk of primary properties of the struck ship (stability, structural integrity, seakeeping responses, critical equipment, and evacuation) have been outlined. Thresholds of the risk levels attained by integrating the criteria related to struck ship' properties have been specified. Obviously, the validity of such an approach entirely depends on the best possible assessment of all elements related to the damage phenomenon.

In this respect, the calculation of the progressive ingress water through a hull breach is still an unresolved matter as regards its accuracy, hence reliability. An intensive and thorough experimental programme should be performed to improve and refine the calculation procedures. Since model tests are expensive and damage data do not exist for large passenger ships, it is hoped that a co-operative project between international research institutions will be planned in order to reduce the amount of theoretical and experimental work to a reasonable level. In particular, further studies and improvements related to the following topics would be welcome:

- flooding simulations in calm water and waves;
- time-to-capsize simulations.

Acknowledgements

The authors like express their sincere appreciation to MarineLab for their assistance in coordinating and advertising the Delphi project. The authors thank Captain Roberto Surez for his detailed and helpful suggestions on development of the research project.

REFERENCES

[1] VASSALOS, D., KONOVESSIS, D.: "The Thematic Network SAFER EURORO: An Integrated Approach to Safe European Ro-Ro Ferry Design", Marine Technology, Vol. 45, no. 1, pp. 1-8, 2008.

[2] GUARIN, L. KONOVESSIS, D., VASSALOS, D.: "Safety Level of Damaged RoPax Ships: Risk Modelling and Cost Effectiveness Analysis", Ocean Engineering, Vol. 36, no. 12, 13, pp. 941-951, 2009.

[3] VAN'T VEER, R., SERRA, A.: "Large Passenger Ship Safety: Time to Sink Simulations", Proceedings of the Passenger Ship Safety Conference, RINA, London, 2003.

[4] KATAYAMA, T., TAKEUCHI, Y., IKEDA, Y.: "An Experimental Study on Roll Motion of a Damaged Large Passenger Ship in Intermediate Stages of Flooding", Journal of the Kansai Society of Naval Architects of Japan, no. 253, 2005.

[5] RUPONEN, P.: "Progressive Flooding of a Damaged Passenger Ship", Doctoral Dissertation, Helsinki University of Technology, Department of Mechanical Engineering, Helsinki, 2007.

[6] DANKOWSKI, H.: "A Fast and Explicit Method for the Simulation of Flooding and Sinkage Scenarios on Ships", Ph.D. Thesis, Hamburg University of Technology, Institute of Ship Design and Ship Safety, Hamburg, 2013.

[7] JALONEN, R.: "FLOODSTAND, Project Final Report", Aalto-Korkeakoulusäätiö, Helsinki, 2009.

[8] IMO: "Interim Guidelines for Evacuation Analyses for New and Existing Passenger Ships", MSC/Circ.1033, London, 2002.

[9] IMO: "Guidelines on Operational Information for Masters of Passenger Ships for Safe Return to Port by Own Power or Under Tow", MSC.1/Circ.1400, London, 2011.

[10] http://www.navium.it/index.php/it/delphi-project/delphi-edss.html (03.06.2016)

[11] IMO: "Guidance for Watertight Doors on Passenger Ships Which May Be Opened During Navigation", MSC.1/Circ.1380, London, 2010.

[12] IACS: "Requirements for Loading Conditions, Loading Manuals and Loading Instruments", UR S1 Rev.7, London, 2010.

[13] IMO: "International Code on Intact Stability", London, 2008.

[14] IMO: "Safety of Life at Sea", SOLAS Chapter II-Part B, Construction - Subdivision and Stability, Machinery and Electrical Installations, London, 2009.

[15] IACS: "On Board Computers for Stability Calculations", UR L5 Rev.2, London, 2006.

[16] IMO: "Performance Standards for the Systems and Services to Remain Operational on Passenger Ships for Safe Return to Port and Orderly Evacuation and Abandonment After a Casualty", MSC.1/Circ.1214, London, 2006.

[17] IMO: "Standards for Ship Manoeuvrability", MSC 76/23/Add.1, London, 2002.

[18] SHANNON, C., E.: "The Mathematical Theory of Communication", Bell Systems Technical Journal, Vol. 27, no. 3, pp. 379-423, 1948. http://dx.doi.org/10.1002/j.1538-7305.1948.tb01338.x.

[19] BUCKLEY, J.J.: "Fuzzy Hierarchical Analysis", Fuzzy Sets and Systems, Vol. 17, pp. 233-247, 1985. http://dx.doi.org/10.1016/0165-0114(85)90090-9.

[20] DNV: "Loading Computer Systems (LCS) for Stability and Longitudinal Strength", DNV Pt. 6 Ch. 9, Norway, 2011.

[21] IMO: "Large Passenger Ship Safety - Survivability Investigation of Large Passenger Ships", SLF 47/INF.6, London, 2004.

[22] PENTTILÄ, P., RUPONEN, P.: "Use of Level Sensors in Breach Estimation for a Damaged Ship", 5th International Conference on Collision and Grounding of Ships, Espoo, 2010.

[23] ZADEH, L.: "Fuzzy Sets", Information and Control, Vol. 8, no. 3, pp. 338-353, 1965. http://dx.doi.org/10.1016/S0019-9958(65)90241-X.

[24] BELLMAN, R., ZADEH, L.A.: "Decision Making in a Fuzzy Environment", Management Science, Vol. 17, no. 4, pp. 141-164, 1970. http://dx.doi.org/10.1287/mnsc.17.4.B141.

[25] CHEN, S.M., LEE, M.W.: "Fuzzy Multiple Attributes Group Decision-Making Based on the Interval Type-2 TOPSIS Method", Expert Systems with Applications, Vol. 37, no. 4, pp. 2790-2798, 2010. http://dx.doi.org/10.1016/j.eswa.2009.09.012.

[26] MIKHAILOV, L.: "Deriving Priorities from Fuzzy Pairwise Comparison Judgments", Fuzzy Sets and Systems, Vol. 134, pp. 365-385, 2003. http://dx.doi.org/10.1016/S0165-0114(02)00383-4.

[27] KARSAK, E.E.: "Distance-Based Fuzzy MCDM Approach for Evaluating Flexible Manufacturing System Alternatives", International Journal of Production Research, Vol. 40, no. 13, pp. 3167-3181, 2002. http://dx.doi.org/10.1080/00207540210146062.

[28] ZADEH, L.: "A Fuzzy Algorithmic Approach to the Definition of Complex or Imprecise Concepts", Electronics Research Lab. Memorandum ERL-M474, College of Engineering, University of California, Berkeley, 1974.

[29] CHEN, S.H., HSIEH, C.H.: "Representation, Ranking, Distance and Similarity of L-R Type Fuzzy Number and Application", Australian Journal of Intelligent Information Processing Systems, Vol. 6, no. 4, pp. 217-229, 2000.

[30] HWANG, C.L., YOON, K., *Multiple Attribute Decision Making: Methods and Applications*, Springer-Verlag, Berlin, 1981.

[31] SAATY, T.L.: "A Scaling Method for Priorities in Hierarchical Structures", Journal of Mathematic Psychology, Vol. 15, no. 3, pp. 234-281, 1977. http://dx.doi.org/10.1016/0022-2496(77)90033-5.

[32] SAATY, T.L.: "The Analytical Hierarchy Process", McGraw-Hill, New York, 1980.

[33] CHOU, S-W., CHANG, Y-C.: "The Implementation Factors that Influence the Enterprise Resource Planning Benefits", Decision Support Systems, Vol. 46, no. 1, pp. 149-157, 2008. http://dx.doi.org/10.1016/j.dss.2008.06.003.

Appendix A – Membership Grade Functions

Fuzziness in imprecise and ambiguous problems stems from the complexity and imprecise nature of deterministic prediction methods. The theory of fuzzy sets [23], alternatively referred to as fuzzy logic, offers background for mathematical operations on data expressed in vague and imprecise terms. U sing fuzzy sets avoids sharp transition between acceptable and unacceptable when a crisp constraint has to be complied with.

Since Bellman and Zadeh [24] developed the theory of decision behaviour in a fuzzy environment, various methods have been developed for representing and treating uncertainty in multicriteria decision making processes [25, 26].

To present the notion that an element x is a member of a set A either fully or not at all, the concept of membership function μ is introduced. For every x in a crisp set A, $\mu_A(x)$ assigns a value that determines the grade of membership x has in the set A as

$$\mu_A(x) = \begin{cases} 1 & \text{for } x \in A \\ 0 & \text{for } x \notin A \end{cases}$$

In fuzzy set theory the membership function μ_A of the fuzzy set A models the concept that the statement x belongs to A is not necessarily true or false only; on the contrary, it denotes the grade of an element x in the set A. This property is generalized by accepting even partial membership, that is

$$0 \leq \mu_A(x) \leq 1$$

To rate and normalise the score related to each ship property and criterion, triangular fuzzy numbers are used in this study for representing the linguistic variable (see Appendix B). The primary reason for using triangular fuzzy numbers can be stated in their intuitive and computationally efficient representation [27].

The membership grade function of a fuzzy set can be defined by a fuzzy recognition algorithm [28]. At this stage let introduce a few plausible functions yielding the degree of closeness (membership grade) of x_i^k to the threshold value (anchor point) x_i^* for each individual simulation:

If x_i^* is a maximum, then $\mu_i^k = \frac{x_i^k}{x_i^*}$

If x_i^* is a minimum, then $\mu_i^k = \frac{x_i^*}{x_i^k}$

If x_i^* is a feasible goal value and is preferred to all x_i^k smaller and larger than x_i^*, then

$$\mu_i^k = \left[\frac{1}{2}\left(\frac{x_i^k}{x_i^*} + \frac{x_i^*}{x_i^k}\right)\right]^{-1}$$

If the most distant feasible score is to be labelled by zero regardless of its actual closeness to x_i^*. After stating the position

$$x_{i*} = \min_k x_i^k$$

the membership function is written as

$$\mu_i^k = \frac{x_i^k - x_{i*}}{x_i^* - x_{i*}}$$

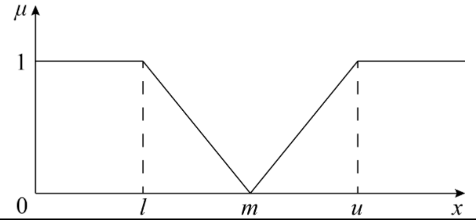
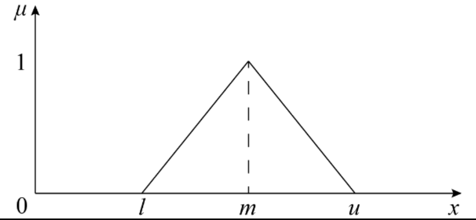
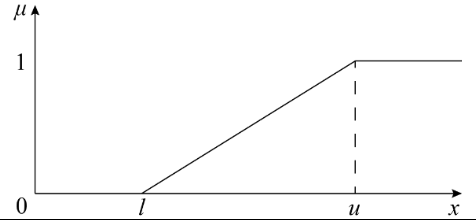
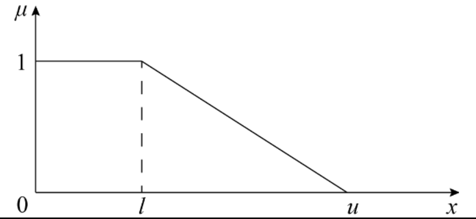
Degrees of closeness are not of great value in the case of single attribute. However, simulations are usually characterized by multiple scores, i.e., by vectors $\boldsymbol{x}^k = (x_1^k, x_2^k, \ldots, x_n^k)$. In each column of the scores matrix an anchor point is located and the scores are transformed into the corresponding degrees of closeness, i.e., all x_i^k's would be changed into μ_i^k's according to a particular membership function as, for example, the four function types written earlier.

Appendix B – Triangular Fuzzy Numbers

Triangular fuzzy numbers are simply represented as a triplet (l, m, u) where the parameters l, m and u , being $l \leq m \leq u$, indicate the smallest possible bound, the modal (crisp) value, and the largest possible value that describe a fuzzy event, respectively.

The membership grade function of triangular fuzzy numbers $\mu(x)$ is as follows. Each triangular fuzzy number has linear representation on both its left and right side. In this study different types of triangular fuzzy numbers are used in different circumstances. The Λ_l-type and Λ_r-type can be also denoted as loss-type indicators and benefit-type indicators, respectively. Table B1 provides a summary of the types and the definition of their membership grade functions.

Table B1 Membership Functions

V-type	$\mu(x) = \begin{cases} 1 & \text{if} \quad x \le l \\ (l-x)/(l-m) & \text{if} \quad l < x < m \\ 0 & \text{if} \quad x = n \\ (x-u)/(m-u) & \text{if} \quad m < x < u \\ 1 & \text{if} \quad x \ge u \end{cases}$	
Λ -type	$\mu(x) = \begin{cases} 0 & \text{if} \quad x \le l \\ (x-l)/(m-l) & \text{if} \quad l < x < m \\ 1 & \text{if} \quad x = m \\ (u-x)/(u-m) & \text{if} \quad m < x < u \\ 0 & \text{if} \quad x \ge u \end{cases}$	
Λ_l-type	$\mu(x) = \begin{cases} 0 & \text{if} \quad x \le l \\ (x-l)/(u-l) & \text{if} \quad l < x < u \\ 1 & \text{if} \quad x \ge u \end{cases}$	
Λ_r-type	$\mu(x) = \begin{cases} 1 & \text{if} \quad x \le l \\ (u-x)/(u-l) & \text{if} \quad l < x < u \\ 0 & \text{if} \quad x \ge u \end{cases}$	

Algebraic operations

While there are various operations on triangular fuzzy numbers, only the basic arithmetic operations used in this paper are illustrated. According to Zadeh's extension principle [28], the algebraic operation of any two positive fuzzy numbers $\widetilde{M}_1 = (l_1, m_1, u_1)$ and $\widetilde{M}_2 = (l_2, m_2, u_2)$ can be expressed as

Fuzzy addition $\qquad \widetilde{M}_1 \oplus \widetilde{M}_2 = (l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$

Fuzzy subtraction $\qquad \widetilde{M}_1 \ominus \widetilde{M}_2 = (l_1, m_1, u_1) - (l_2, m_2, u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2)$

Fuzzy multiplication $\qquad \widetilde{M}_1 \otimes \widetilde{M}_2 = (l_1, m_1, u_1) * (l_2, m_2, u_2) = (l_1 * l_2, m_1 * m_2, u_1 * u_2)$

Although multiplication operation on triangular fuzzy numbers does not necessarily yield a triangular fuzzy number, triangular fuzzy number approximation is used as it is suggested for many practical applications.

Defuzzification

For solving the problem of defuzzification of triangular fuzzy numbers, the graded mean integration representation method (GMIR) proposed by Chen & Hsien [29] is used, where the representation $R(A_i)$ of a triangular fuzzy number A_i is

$$R\lfloor \mu(x) \rfloor = \frac{l_i + 4m_i + u_1}{6}$$

Appendix C – Fuzzified Entropy Weight

Entropy is the most fundamental concept in information theory as well as in the statistical mechanics, since it has many properties that agree with the intuitive notion of what a measure of information should be. It can also measure the effective information provided by the data; therefore, the entropy can be used to determine the weights.

It measures the uncertainty associated with random phenomena of the expected information content [18]. This uncertainty, that is, the occurrence of each examined event, can usually be estimated by its probability distribution, p_j $(0 \leq p_j \leq 1)$, which agrees that a broad distribution represents more uncertainty than does a sharply peaked one. Since the terms 'entropy' and 'uncertainty' are considered synonymous in statistical mechanics, E is called the 'entropy of the probability distribution p_j, $(j = 1, 2, \ldots, m)$, since it depends only on the single probabilities of a discrete random variable to take values x_j.

The more distinct and differentiated are the scores, i.e., the larger is the contrast intensity of the i-th attribute, the greater the amount of decision information contained in and transmitted by the attribute.

Supposing there are m damage simulations for n kinds of attributes, the original data matrix is formed by a probability distribution of entries x_{ij}, where x_{ij} is the eigenvalue of the j-th damage simulation to the i-th attribute

$$\boldsymbol{D} = \left(x_{ij}\right)_{mxn} \quad i = 1, 2, \ldots, n \;\; \text{and} \;\; j = 1, 2, \ldots, m$$

This matrix is normalized to eliminate anomalies with different measurement units and scales among various criteria. So, the new matrix allows for comparisons of different criteria

$$\boldsymbol{R} = \left(r_{ij}\right)_{mxn}$$

where $r_{ij} \in [0, 1]$ is the value of the j-th evaluating damage simulation on the i-th attribute. Among these attributes, for the larger the better, they are

$$r_{ij} = \frac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \qquad \forall \; j$$

while, for the smaller the better, they are

$$r_{ij} = \frac{\max\{x_{ij}\} - x_{ij}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \qquad \forall \; j$$

Then the probability value p_{ij} for each entry in the decision matrix can be simply determined by normalizing the values at each damage simulation; that is

$$p_{ij} = \frac{r_{ij}}{\sum_{j=1}^{m} r_{ij}} \qquad \forall \; i \in \{1, \ldots, n\} \quad j \in \{1, \ldots, m\} \tag{C1}$$

According to the definition of entropy, the entropy E_i for the i-th attribute for m damage simulations is named as

$$E_i = -E_0 \sum_{j=1}^{m} p_{ij} \cdot \ln p_{ij} \qquad \forall \; i \in \{1, \ldots, n\} \tag{C2}$$

where $\ln$ denotes natural logarithm, $E_0 > 0$ denotes the entropy constant with a value of $\ln m$ at E_{max}, which guarantees that $0 \le E_i \le 1$, and $p_j \cdot \ln p_j = 0$ if $p_j = 0$.

$E(p_1, p_2, \ldots, p_m)$ will take its maximum value, $E_{max} = \ln m$, when the scores of all damage simulations have the same probability $p_j = 1/m$; the entropy value will reach its minimum of 0 if and only if there exist an index j such that $p_j = 1$. These two properties state that the entropy measure reflects how equal the probabilities $p_1, p_2, \ldots, p_m$ are among themselves. The finding that $E_{max} = \ln m$ greatly simplifies the computations.

The total information entropy can be computed as

$$E = \sum_{i=1}^{n} E_i$$

Since the weight w_i assigned to an attribute is directly related to the average intrinsic information generated by a given set of damage simulations over that attribute [30] and because weight is reversely related to E_i, it will be based on the objective 'degree of diversification' d_i, defined as

$$d_i = 1 - E_i \qquad \forall\, i$$

After normalization to ensure that $0 \le w_i \le 1$ and $\sum w_i = 1$, the set of objective weights w_i's above the i-th attribute has elements

$$w_i = \frac{d_i}{\sum_{j=1}^{n}(1 - E_j)} = \frac{d_i}{n - E}\ , \qquad 0 \le w_i \le 1 \tag{C3}$$

When the entropy weight vector **w** is formed, the next step is to determine the fuzzy evaluation matrix. Membership grade of each attribute is obtained by putting the calculated value of the attribute into one of the membership function - see the taxonomy in Table B1 – by distinguishing between benefit-type attributes and loss-type ones.

Appendix D – Fuzzified Analytical Hierarchical Process

Saaty's AHP

Extensively adopted across multiple domains, the analytical hierarchical process (AHP) has successfully been used in prioritization processes. AHP, which was developed by Saaty [31], integrates experts' opinions about criteria into a simple elementary hierarchy system by decomposing complicated problems into a hierarchy of sub-problems from higher to lower ones.

AHP has several advantages including simplicity to follow and analyse, ease of understanding and use, and over-specification of judgment. More than that, it has proved to be a methodology capable of producing results that agree with perceptions. The outcomes of subjective expectations are easily traced through computations by converting subjective evaluations into numerical values.

The following list provides a brief summary of the steps for evaluating relative weights using the AHP approach:

- decompose the problem into a hierarchical network of goal, criteria, sub-criteria and attributes;

- for the lower layer of the hierarchical network perform a pairwise comparisons all the associated elements;
- estimate the relative weights of decision criteria by using a prioritization method;
- check the consistency.

The comparative judgments allow to set up a comparison matrix at each hierarchy level by comparing pairs of subcriteria and criteria. At the end, synthesis of priorities is conducted to calculate a composite weight for each criterion and subcriterion based on preferences derived from the comparison matrix.

To perform the pairwise comparison, officers of a cruise shipping company will be given an instruction on how to conduct the comparison among criteria and subcriteria. The subjective preferences of the officers are elicited in form of ratios to obtain a numerical pairwise comparison matrix. The importance of one criterion or(subcriterion over another is converted to a numerical value a_{ij} by rating that importance based on the qualitative, numerical scale, provided by Saaty [32], in nine gradations. Then a prioritization method, e.g., the eigenvector method, is selected to derive a priority vector from the numerical pairwise comparison matrix.

The numerical values representing the judgments of the comparisons are arranged in a matrix for further calculation. Notationally, the positive reciprocal comparison matrix $\boldsymbol{A}$ for comparing n attributes is

$$\boldsymbol{A} = [a_{ij}]_{nxn} \quad \text{where} \quad a_{ii} = 1 \quad \text{and} \quad a_{ij} = 1/a_{ji}, \quad i,j = 1,2,\dots,n.$$

with reciprocal ratio scale across the diagonal and the main diagonal always all ones.

The preference matrix A is formed as a result of pairwise comparison of attributes

$$a_{ij} = \frac{\text{importance of attribute } i}{\text{importance of attribute } j}$$

The Saaty's method obtains the principal eigenvector of A as the desired weight vector $\boldsymbol{w}$, which can be obtained by solving the linear system

$$\boldsymbol{A}\,\boldsymbol{w} = \lambda_{max}\,\boldsymbol{w}$$

where λ_{max} is the maximum eigenvalue of the preference matrix.

Finally, the weight w_i is assessed by normalizing the eigenvector v_λ corresponding to the largest eigenvalue λ_{max} of the preference matrix

$$w_i = \frac{v_\lambda}{\sum_{i=1}^{n} v_\lambda(i)} \tag{D1}$$

where the vector of weights maintains the order of the rows of the pairwise comparison matrix.

Nonetheless, it is important to ensure whether the preference matrix, e.g. the subjective judgments of the officers, is consistent. Consistency of the preference matrix A, which is randomly generated, may be estimated by the consistency ratio criterion, which generally has to be less than 0.1; that is,

$$I_{CR} = \frac{I_C}{I_R} < 0.1 \tag{D2}$$

where the consistent index is calculated as

$$I_C = \frac{\lambda_{max} - n}{n - 1}$$

whilst I_R, the random consistency index, is given in Table D1.

Table D1 The random consistency index

n	1	2	3		4	5	6	7	8	9	10
I_R	0	0	0.58		0.90	1.12	1.24	1.32	1.41	1.45	1.49

If the consistency ratio criterion fails to comply with constraint given in (D2), then officers' answers to comparisons should be re-examined.

Alternatively, the normalized geometric mean of the row of the preference matrix may be used as the weights

$$w_i = \left(\prod_{i=1}^{n} a_{ij} \right)^{1/n} \qquad \text{(D3)}$$

Fuzzy AHP

Basically, fuzzy AHP method represents the elaboration of a standard AHP method into a fuzzy environment by using fuzzy numbers for calculating instead of real numbers.

The steps of the methodology are as follows:

Step 1: The officers compare the criteria via the linguistic scale of Saaty, shown in Table D2. According to the corresponding triangular fuzzy numbers of these semantics, for example if the third officer states "Criterion 1 is strongly important than Criterion 2", then it takes the fuzzy triangular scale as (6, 7, 8). On the contrary, in the pairwise matrix of criteria, comparison of criterion 2 to criterion 1 will take the fuzzy triangular scale as (1/8, 1/7, 1/6).

The pairwise contribution matrix is shown in the matrix (C1), where $\tilde{d}_{ij}^k$ denotes the k^{th} officer's preference ($k = 1, 2, \ldots, K$) for each i^{th} criterion over the j^{th} criterion, assessed in the form of triangular fuzzy numbers. Symbol '~' represents the triangular number assignment; for the example case, $\tilde{d}_{12}^3$ is the third officer's preference of the first criterion over the second criterion, and equals to $\tilde{d}_{12}^3$ = (6, 7, 8).

$$\tilde{D}^k = \{\tilde{d}_{ij}\} = \begin{bmatrix} \tilde{d}_{11}^k & \tilde{d}_{12}^k \ldots & \tilde{d}_{1n}^k \\ \tilde{d}_{21} & \tilde{d}_{22}^k \ldots & \tilde{d}_{2n}^k \\ \cdots & \cdots & \cdots \\ \tilde{d}_{n1} & \tilde{d}_{n2}^k \ldots & \tilde{d}_{nn}^k \end{bmatrix} \qquad \text{(D4)}$$

Table D2 The linguistic scale and corresponding triangular fuzzy numbers

Saaty Scale	Linguistic scale	Triangular Fuzzy Numbers
1	equally important	(1, 1, 1)
3	moderately more important	(2, 3, 4)
5	fairly more important	(4, 5, 6)
7	strongly more important	(6, 7, 8)
9	extremely more important	(9, 9, 9)
2		(1, 2, 3)
4	intermediate values between	(3, 4, 5)
6	two adjacent scales	(5, 6, 7)
8		(7, 8, 9)

Step 2: If more than one officer is interviewed, preferences of each officer, $\tilde{d}_{ij}^{k}$, are averaged by integrating group judgment; each entry of the normalized fuzzy criterion is calculated as in equation (D2)

$$\tilde{d}_{ij} = \frac{\sum_{k=1}^{K} \tilde{d}_{ij}^{k}}{K} \tag{D5}$$

Step 3: According to averaged preferences, the fuzzy pairwise contribution matrix is updated as follows

$$\tilde{D} = \begin{bmatrix} \tilde{d}_{11} & \tilde{d}_{12} \ldots & \tilde{d}_{1n} \\ \tilde{d}_{21} & \tilde{d}_{22} \ldots & \tilde{d}_{2n} \\ \\ \tilde{d}_{n1} & \tilde{d}_{n2} \ldots & \tilde{d}_{nn} \end{bmatrix} \tag{D6}$$

Step 4: According to Buckley [19], the geometric mean of fuzzy comparison values of each criterion is calculated as shown in equation (D7), where $\tilde{r}_i$ still represents a triangular value

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{d}_{ij}\right)^{1/n} \quad , \quad i = 1, 2, \ldots, n \tag{D7}$$

Step 5: The fuzzy weight of each criterion $\tilde{w}_i$ is found by multiplying the reverse of vector summation of each $\tilde{r}_i$ with each $\tilde{r}_i$

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 + \tilde{r}_2 + \cdots + \tilde{r}_n)^{-1} \tag{D8}$$

Step 6: Since $\tilde{w}_i$ are still fuzzy triangular numbers, they need to be defuzzified; the relative non-fuzzy weight of each criterion, C_i, is calculated by applying the "centre of area method" [33]

$$C_i = \frac{l \cdot w_i + m \cdot w_i + u \cdot w_i}{3}$$

Submitted: 30.05.2016.

Accepted: 25.10.2016.

Giorgio Trincas, trincas@units.it
University of Trieste, Department of Engineering and Architecture
Via A.Valerio, 10, 34129 Trieste, Italy
Luca Braidotti, luca.braidotti@navium.it
Navium S.r.l.s, via T. Drusin, 21/1B, 33044 Manzano (UD), Italy
Lorenzo De Francesco, lorenzo.defrancesko@navium.it
Navium S.r.l.s, via T. Drusin, 21/1B, 33044 Manzano (UD), Italy