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A subjective modelling tool applied to formal ship safety assessment

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Abstract

Formal safety assessment of ships has attracted great attention over the last few years. In this paper, following a brief review of the current status of marine safety assessment, formal ship safety assessment is discussed in detail. A subjective safety-analysis-based decision-making framework is then proposed for formal ship safety assessment in situations where a high level of uncertainty is involved. In the framework, failure events at the lowest level are modelled using fuzzy sets and safety synthesis at the different levels of a hierarchy is carried out using evidential reasoning. Multiple safety analysts' judgements can also be synthesised using the framework. Subjective safety and cost assessments obtained can finally be combined to produce the preference degrees associated with the design/operation options for ranking purposes. An example is used to demonstrate the framework. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In the UK offshore industry, a safety case approach was introduced following the public inquiry into the Piper Alpha accident of 6 July 1988 which caused 167 deaths (Department of Energy, 1990). The safety case regulations came into force in two phases — at the end of May 1993 for new installations and November 1993 for existing installations. The regulations require operational safety cases to be prepared for all offshore installations. Both fixed and mobile installations are included.

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Additionally all new fixed installations require a design safety case. A safety case should include sufficient particulars to demonstrate that hazards with the potential to cause major accidents have been identified, risks have been evaluated and measures have been taken to reduce them to As Low As Reasonably Practicable (ALARP) (Department of Energy, 1990). Offshore operators must submit operational safety cases to the Health and Safety Executive (HSE) Offshore Safety Division for acceptance. An installation cannot legally operate without an accepted operational safety case. A submitted safety case may be studied by looking at the accident scenarios and the assessment of the consequences of each scenario together with steps taken to control risks. To be acceptable, a safety case must show that all hazards with the potential to produce a major accident have been identified and that associated risks are below a tolerability limit and have been reduced as low as is reasonably practicable.

In the shipping industry, over the last few years, quite a few serious accidents, including the capsize of the Herald of Free Enterprise and the Exxon Valdez tragedy, have shocked the public and attracted great attention to ship safety. Studies on how similar accidents may be prevented have been actively carried out at both national and international levels. The adoption of the safety case approach in the UK offshore industry has also encouraged marine safety analysts to look at the possibility of employing a similar “goal setting” pro-active approach to the marine industry. In 1992 Lord Carver’s report into ship safety raised the issue of a more scientific approach to the subject and recommended that emphasis be given to a performance-based regulatory approach (House of Lords, 1992). That gave the initial idea for formal ship safety assessment. Ship safety may be significantly improved by introducing a formal “goal setting” safety assessment approach so that the challenge of new technologies and their application to ship design and operation may be dealt with properly.

2. Formal ship safety assessment

As serious concern is raised over the safety of ships all over the world, the International Maritime Organisation (IMO) has continuously dealt with safety problems. The improvement of safety at sea has been highly stressed. After Lord Carver’s report on the investigation of the capsize of the Herald of Free Enterprise was published in 1992, the UK Marine Coastguard Agency (MCA) quickly responded and in 1993 proposed to the IMO that formal safety assessment should be applied to ships to ensure a strategic oversight of safety and pollution prevention. The UK MCA also proposed that the IMO should explore the concept of formal safety assessment, and introduce formal safety assessment in relation to ship design and operation. The IMO reacted favourably to the UK’s formal safety assessment submission. Since then, substantial work has been done in this area. The application of formal safety assessment has reached an advanced stage (Ruxton, 1996).

Safety assessment in ship design and operation may offer great potential incentives. The application of it may improve the safety performance of the current fleet, be able to measure the performance change and ensure that new ships are good designs; ensure that experience from the field is used in the current fleet and that any lesson learned is incorporated into new ships; and provide a mechanism for predicting and controlling the most likely scenarios that could result in incidents.

The IMO is likely to adopt the key elements of risk-based and formal safety assessment schemes within its major review of Chapter II-2 of the 1974 SOLAS (Safety Of Life At Sea) Convention. Formal safety assessment involves much more scientific aspects than previous conventions. It is a new approach to marine safety which involves using the techniques of risk and cost–benefit assessment to assist in the decision-making process. The benefits of adopting formal safety assessment as a regulatory tool include (Marine Safety Agency, 1993):

1. a consistent regulatory regime which addresses all aspects of safety in an integrated way;
2. cost effectiveness, whereby safety investment is targeted where it will achieve the greatest benefit;
3. a pro-active approach, enabling hazards that have not yet given rise to accidents to be properly considered;
4. confidence that regulatory requirements are in proportion to the severity of the risks; and
5. a rational basis for addressing new risks posed by ever changing marine technology.

A formal ship safety assessment framework consists of the identification of hazards; the assessment of risks associated with those hazards; the identification of ways of managing the risks identified; cost–benefit assessment of the options; and making decisions on which options to select.

The identification of hazards aims at identifying and generating a selected list of hazards specific to the problem under review. Hazard identification is concerned with using "brainstorming" techniques involving trained and experienced personnel to determine the hazards. An accident is defined as "a status of the vessel, at the stage where it becomes a reportable incident which has the potential to progress to loss of life, major environmental damage and/or loss of the vessel" (Marine Safety Agency, 1993). Accident categories include: (1) contact or collision; (2) explosion; (3) external hazards; (4) fire; (5) flooding; (6) grounding or stranding; (7) hazardous substances; (8) loss of hull integrity; (9) machinery failure; and (10) loading and unloading related failure. Human error issues also need to be systematically dealt with in the formal safety assessment framework. Significant risks can be chosen in this step by screening all the identified risks. Various scientific safety assessment approaches, such as Preliminary Hazard Analysis (PHA), Failure Mode, Effects and Criticality Analysis (FMECA), and HAZard and Operability (HAZOP) study, can be applied in this step.

The assessment of risks aims at assessing risks and factors influencing the level of safety. Risk assessment involves studying how hazardous events or states develop and interact to cause an accident. Shipping consists of a sequence of distinct phases between which the status of ship functions changes. The major phases include: (1) design, construction and commissioning; (2) entering port, berthing, unberthing and leaving port; (3) loading and unloading; (4) dry docking; and (5) decommissioning and disposal. A ship consists of a set of systems such as machinery, the control system, the electrical system, the communication system, the navigation system, the piping and pumping system and the pressure plant. A serious failure of a system may cause disastrous consequences. Risk assessment may be carried out with respect to each phase of shipping and each marine system. The occurrence likelihood of each failure event and its possible consequences can be assessed using various safety assessment techniques such as an influence diagram which is a combination of fault tree analysis and event tree analysis (Marine Safety Agency, 1993). An influence diagram may be used to deal with the escalation of an accident and mitigation aspects, such as the evaluation of people, containment of oil pollutants, etc. Generic data or expert judgements may be used in risk assessment.

The identification of ways of managing the risks aims at proposing effective and practical risk control options. High risk areas can be identified from the information produced in risk assessment and then the identification of risk control measures can be initiated. The ways of managing risks identified include preventative or mitigating measures, redundant arrangement and better design arrangements, etc. Risk control measures can reduce the frequency of failures and/or mitigate their possible efforts and consequences. Structural review techniques may be used to identify all possible risk control measures for cost–benefit decision making.

Cost–benefit assessment aims at identifying benefits from reduced risks and costs associated with the implementation of each risk control option for comparisons. To conduct cost–benefit assessment, it is required to set a base case that can be used as a reference for comparisons where a base case reflects the existing situation, that is, what actually happens rather than what is supposed to happen. The evaluation of costs and benefits may be conducted using various methods and techniques. It should be initially carried out for the overall situation and then for those interested entities influenced by the problem consideration.

Decision making is aimed at making decisions and giving recommendations for safety improvement. The information generated can be used to assist in the choice of cost-effective and equitable changes and to select the best risk control option.

In the decision-making process, criteria may be used to determine if risks are acceptable, unacceptable or need to be reduced to ALARP. When Quantitative Risk Assessment (QRA) is performed, it is required to use numerical risk criteria. Recently QRA has been used extensively for ships carrying hazardous cargoes in port areas and for ships operating in the offshore industry (Spouse, 1997). Risk assessment involves uncertainties. Therefore it may not be suitable to use risk criteria as inflexible rules. The application of numerical risk criteria may not always be appropriate because of uncertainties in inputs. Accordingly, acceptance is unlikely to be based solely on a numerical risk assessment. Risk criteria may be different for different individuals. They would also vary between societies and alter with time, accident experience and changing expectation of life. Risk criteria can therefore only assist judgements and be used as guidelines for decision making.

The guidelines for the application of formal safety assessment have been approved by the IMO. At the moment, the major concerns on the practical application of formal ship safety assessment are the simplification of the approach and the study of test cases for producing more detailed guidelines. The possible application can be categorised into two groups. One is closely relevant to the IMO rule-making process and the other may be relevant to specific ships (Sekimizu, 1997). The individual ship approach may have a great impact on marine safety and change the nature of the safety regulations at sea since it may lead to deviation from traditional prescriptive requirements in the conventions towards performance-based criteria. However, this would raise concerns due to the difficulty in the safety evaluation process by other administrations particularly when acting as port states although the merits of it may also be very significant.

It is also very important to take into account human error problems in formal safety assessment. The application of formal safety assessment may also encourage the Flag States to collect operational data. Another important aspect that needs to be addressed is the data problem. The confidence of formal safety assessment greatly depends on the reliability of failure data. If formal safety assessment is applied, it may facilitate the collection of useful data on operational experience which can be used for effective precausional safety assessment.

3. A decision support framework based on subjective safety and cost analyses

Large ships constantly involve the use of new approaches, new technology, etc. and each element brings with it a new hazard in one form or another. Furthermore, large ships often work in a very changeable environment where human error plays a very important role in safety analysis. These create difficulties in applying traditional PRA methods in formal ship safety assessment. In addition, the lack of safety data has always been a problem in ship safety assessment. Therefore, in many circumstances, safety analysts often have to use subjective descriptors to describe the safety associated with an event.

Subjective modelling may be more appropriate to deal with safety problems with a high level of uncertainty (Wang and Ruxton, 1997). To assess the safety associated with an event, it is required to synthesise the associated occurrence likelihood, consequence severity and failure probability where the failure likelihood defines the probability that the event occurs, the consequence severity describes the magnitude of the possible consequence and the failure consequence probability defines the probability that consequences happen given the occurrence of the event (Karwowski and Mital, 1986; Keller and Kara-Zaitri, 1989; Wang et al., 1995). Those three parameters can be judged by safety analysts in terms of subjective descriptors and the judgements produced can then be synthesised. To obtain the subjective safety description associated with a marine system, it is required to synthesise the failure events. The safety assessment of a marine system is often a hierarchical process. Fig. 1 shows a typical hierarchical safety modelling process where safety assessments at higher levels are determined by the safety assessment at lower levels. Therefore, a hier-

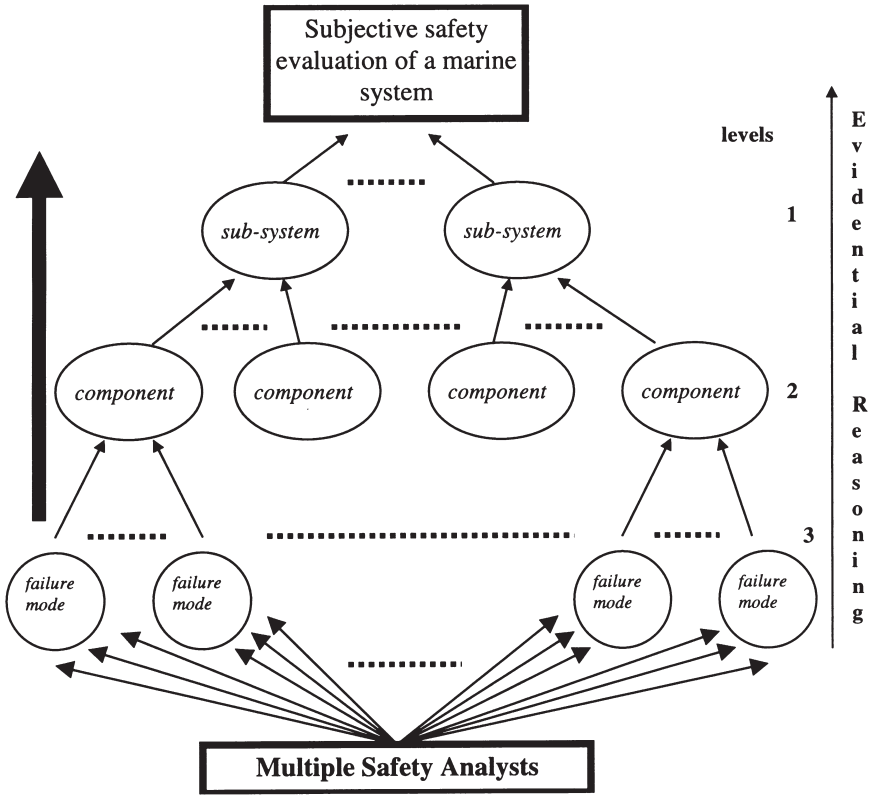

Fig. 1. A hierarchy of subjective safety modelling.

archical procedure is required to synthesise the information produced at lower levels to obtain the safety assessment of the system. To make use of the information produced for decision-making purposes, it is also required to assess the costs incurred on a subjective basis. Subjective safety and cost assessments can be studied together to determine the best risk reduction action and to choose the best design/operation option.

A design/operation selection framework is shown in Fig. 2. Multiple safety analysts can make their subjective judgements for each design/operation option on both cost and safety aspects. Their judgements can then be processed to obtain the cost and safety estimates of each option using the evidential reasoning approach that will be described. The cost and safety estimates of each option can finally be synthesised to produce the associated preference degree. As soon as all preference degrees of all options are produced, the best option can be chosen.

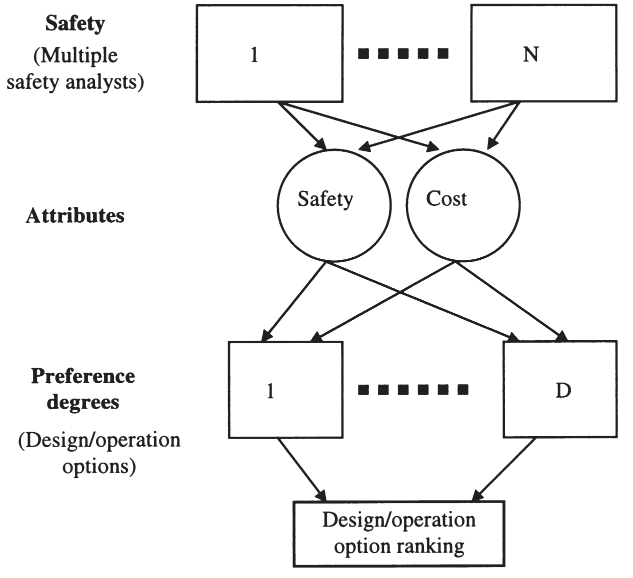

Fig. 2. A hierarchical safety-based design/operation option ranking framework.

3.1. Subjective safety modelling

Three basic parameters (i.e. failure likelihood, consequence severity and failure consequence probability) are usually used to assess the safety associated with an event on a subjective basis. These three parameters can be described by subjective linguistic variables. To estimate the failure likelihood, for example, one may often use such variables as "*highly frequent*", "*frequent*", "*reasonably frequent*", "*average*", "*reasonably low*", "*low*" and "*very low*"; to estimate the consequence severity, one may often use such variables as "*catastrophic*", "*critical*", "*marginal*" and "*negligible*"; and to estimate the failure consequence probability, one may often use such variables as "*definite*", "*highly likely*", "*reasonably likely*", "*likely*", "*reasonably unlikely*", "*unlikely*" and "*highly unlikely*". Such subjective linguistic variables can be further described by membership functions. A membership function is a description which consists of membership values to categories. The typical linguistic variable for describing failure likelihood, consequence severity and failure consequence probability may be defined in terms of membership degrees belonging to the seven categories defined as shown in Tables 1–3 (Wang et al., 1995, 1996).

Suppose C, E and L represent the fuzzy sets of the consequence severity, failure consequence probability and failure likelihood of an event, respectively. The corresponding subjective safety description S can be defined as $S=C^\circ E\times L$ (Karwowski and Mital, 1986; Wang et al., 1995) where the symbol "°" presents the composition operation and "×" the Cartesian product operation in fuzzy set theory. The relationship between the membership functions associated with S, C, E and L is described as $\mu_S=\mu_C{}^\circ\mu_E\times\mu_L$.

Table 1
Failure likelihood descriptors

μ_L Linguistic variables	Categories 1	2	3	4	5	6	7
Highly frequent	0	0	0	0	0	0.75	1
Frequent	0	0	0	0	0.75	1	0.25
Reasonably frequent	0	0	0	0.75	1	0.25	0
Average	0	0	0.5	1	0.5	0	0
Reasonably low	0	0.25	1	0.75	0	0	0
Low	0.25	1	0.75	0	0	0	0
Very low	1	0.75	0	0	0	0	0

Table 2
Consequence severity descriptors

μ_C Linguistic variables	Categories 1	2	3	4	5	6	7
Catastrophic	0	0	0	0	0	0.75	1
Critical	0	0	0	0.75	1	0.25	0
Marginal	0	0.25	1	0.75	0	0	0
Negligible	1	0.75	0	0	0	0	0

Table 3
Failure consequence probability descriptors

μ_E Linguistic variables	Categories 1	2	3	4	5	6	7
Definite	0	0	0	0	0	0.75	1
Highly likely	0	0	0	0	0.75	1	0.25
Reasonably likely	0	0	0	0.75	1	0.25	0
Likely	0	0	0.5	1	0.5	0	0
Reasonably unlikely	0	0.25	1	0.75	0	0	0
Unlikely	0.25	1	0.75	0	0	0	0
Highly unlikely	1	0.75	0	0	0	0	0

It is commonly understood that safety can be expressed by degrees to which it belongs to such linguistic variables as “*poor*”, “*fair*”, “*average*” and “*good*”, terms that are referred to as safety expressions. To evaluate S in terms of those safety expressions, it is necessary to characterise them using membership degrees with respect to the same categories used, in order to project the obtained subjective safety description onto the safety expressions. The four safety expressions are defined as shown in Table 4 (Wang et al., 1995, 1996; Wang and Ruxton, 1997).

Suppose the safety expressions "*poor*", "*fair*", "*average*" and "*good*" are described by the safety expressions H_1, H_2, H_3 and H_4, respectively. The extent β^m (m=1,2,3 or 4) to which S belongs to the mth (m=1,2,3 or 4) safety expression can be obtained using the best-fit method (Wang et al., 1995):

$$\beta^m = \frac{\alpha^m}{\sum_{T=1}^{4} \alpha^T}$$

where α^m (m=1,2,3 or 4) represents the reciprocal of the relative distance between S and the mth safety expression. α^m can be obtained by (Wang et al., 1995):

$$\alpha^m = \frac{1}{d^m/d^M}$$

where d^m is the Euclidean distance between S and the mth safety expression, and d^M is the minimum value of d^m (m=1,2,3 and 4).

Suppose there are N safety analysts who assign membership degrees of three basic safety parameters associated with an event. Suppose C_n, E_n and L_n represent the three basic safety parameters associated with the failure event judged by safety analyst n (n=1,..., or N), respectively. The subjective safety description S_n associated with the event judged by safety analyst n can be obtained as S_n=$C_n{}^\circ E_n \times L_n$. S_n (n=1,..., or N) can be mapped back onto the defined safety expressions to obtain the safety evaluation $S(S_n)$ associated with the failure event judged by safety analyst n. $S(S_n)$ can be expressed in the following form:

$$S(S_n) = \{(\beta_n^1, \text{“}poor\text{”}), (\beta_n^2, \text{“}fair\text{”}), (\beta_n^3, \text{“}average\text{”}), (\beta_n^4, \text{“}good\text{”})\}$$

where β_n^m (m=1,2,3 or 4) represents the extent to which S_n belongs to the mth safety expression, i.e. H_m.

An evidential reasoning approach can be employed to synthesise $S(S_n)$ (n=1,…, and N) to obtain the safety evaluation associated with the event. The evidential reasoning approach is well suited for handling uncertain and inconsistent safety evaluations (Yang and Singh, 1994; Yang and Sen, 1994). This approach is based

Table 4
Four safety expressions

μ_S	Categories						
Linguistic variables	1	2	3	4	5	6	7
1. Poor	0	0	0	0	0	0.75	1
2. Fair	0	0	0	0.75	1	0.25	0
3. Average	0	0.25	1	0.75	0	0	0
4. Good	1	0.75	0	0	0	0	0

on the principle that it will become more likely that a given hypothesis is true if more pieces of evidence support that hypothesis. Whether the safety evaluation associated with an event belongs to “*poor*”, “*fair*”, “*average*” or “*good*” can be regarded as a hypothesis. If the judgement on a failure event produced by a safety analysis is to some extent evaluated as “*good*”, for example, then the safety associated with the failure event would be to some extent evaluated as “*good*”, depending on the judgement itself and the weight of the safety analyst in the evaluation process.

Let λ_n (n=1,…, or N) be the normalised relative weight of safety analyst n in the safety evaluation process where $0\leq\lambda_n\leq 1$. λ_n can be calculated on the basis of the relative weights of safety analysts. In this paper, it is assumed that if all safety analysts judge the safety associated with an event as “*good*”, the safety associated with the event is evaluated as “*good*” with a confidence degree Ω of over 99.5%. The following formula can be used to obtain the value of λ_n (n=1,…, or N) (Yang and Singh, 1994; Yang and Sen, 1994):

$$\lambda_n=\varepsilon\frac{\xi_n}{\xi_{\max}}$$

$$\prod_{n=1}^{N}\left(1-\varepsilon\frac{\xi_n}{\xi_{\max}}\right)\leq 1-\Omega$$

where ξ_n (n=1,…, or N) is the relative weight of the nth safety analyst; $\xi_{\max}$ is the largest value among ξ_n (n=1,…, and N); and ε is a priority coefficient representing the importance of the role that the most important safety analyst plays in the evaluation of the safety associated with the event. Given all ξ_n (n=1,…, and N), ε can be calculated and λ_n can then be obtained.

Suppose M_n^m (n=1,…, or N) is a degree to which $S(S_n)$ supports the hypothesis that the safety evaluation associated with the failure event is confirmed to H_m (m=1,2,3 or 4). Then, M_n^m can be obtained as $M_n^m=\lambda_n\times\beta_n^m$ (Wang et al., 1995; Yang and Singh, 1994). Suppose M_n^H (n=1,…, or N) is the remaining belief unassigned after commitment of belief to all H_m (m=1,2,3 and 4) for $S(S_n)$. M_n^H can be obtained as follows (Wang et al., 1995, 1996):

$$M_n^H=1-\sum_{m=1}^{4}M_n^m$$

Suppose MM_n^m (m=1,2,3 or 4; n=1,…, or N) represents the degree to which the safety associated with the event belongs to H_m as a result of the synthesis of the judgements produced by safety analysts 1,…, and n. Suppose MM_n^H represents the remaining belief unassigned after commitment of belief to all H_m (m=1,2,3 and 4) as a result of the synthesis of the judgements produced by safety analysts 1,…, and n. The algorithm for synthesising the analysts’ judgements to obtain the safety evaluation associated with the event can be stated as follows (Yang and Sen, 1994):

Initial conditions:

$$MM_1^m = M_1^m \quad MM_1^H = M_1^H$$

$$\{H_m\} \; MM_{n+1}^m = K_{n+1}(MM_n^m M_{n+1}^m + MM_n^m M_{n+1}^H + MM_n^H M_{n+1}^m) \; m = 1,2,3,4$$

$$\{H\} \; MM_{n+1}^H = K_{n+1} MM_n^H M_{n+1}^H$$

$$K_{n+1} = \left[1 - \sum_{T=1}^{4} \sum_{R=1\, R \neq T}^{4} MM_n^T M_{n+1}^R\right]^{-1} \; n = 1,\ldots,N-1$$

MM_N^m can be obtained by $N-1$ iterations of the above algorithm. MM_N^m is the degree to which the safety evaluation associated with the event belongs to H_m (m=1,2,3 or 4).

The safety evaluation associated with a failure event can then be presented in the following form:

$$S(S) = \{(\beta^1, \text{"}poor\text{"}), (\beta^2, \text{"}fair\text{"}), (\beta^3, \text{"}average\text{"}), (\beta^4, \text{"}good\text{"})\}$$

where β^m (m=1,2,3 or 4) is equal to MM_N^m.

In a hierarchical subjective safety evaluation process shown in Fig. 1, safety synthesis can be progressed up to a higher (next) level. Suppose the next level is the component level. The safety of a component can be obtained by synthesising the associated possible failure events. The safety associated with an event is confirmed to H_m (m=1,2,3 or 4) to the extent that it can be viewed as a piece of evidence when the safety associated with the component is evaluated to H_m. Given the normalised relative weight of each failure event in the process of assessing the safety associated with the component, the evidential reasoning approach can be applied to synthesise the safety evaluations of the failure events associated with the component to obtain the safety of the component. Such a hierarchical evaluation can be progressed up to the system level to obtain the required safety evaluation of the system.

3.2. Cost modelling

When making safety-based design/operation decisions for a marine system, it is necessary to take cost aspects into account. The cost incurred in the safety improvement associated with a design/operation option is usually affected by many factors that often have large uncertainties of estimation. Therefore, it may be more appropriate to model the cost incurred in safety improvement associated with a design/operation option on a subjective basis. The cost incurred in a design/operation option can be described using linguistic variables such as "*very low*", "*low*", "*moderately low*", "*average*", "*moderately high*", "*high*" and "*very high*". Such linguistic descriptors are referred to as cost expressions that are defined in terms of membership degrees belonging to the seven defined categories as shown in Table 5. The membership values describing the cost incurred in a design/operation option may be given by safety analysts with reference to Table 5.

Table 5
Cost descriptors

μ_{Cost} Linguistic variables	Categories 1	2	3	4	5	6	7
Very high	0	0	0	0	0	0.75	1
High	0	0	0	0	0.75	1	0.25
Moderately high	0	0	0	0.75	1	0.25	0
Average	0	0	0.5	1	0.5	0	0
Moderately low	0	0.25	1	0.75	0	0	0
Low	0.25	1	0.75	0	0	0	0
Very low	1	0.75	0	0	0	0	0

3.3. Design/operation option ranking

To synthesise both safety and cost objectives for decision-making purposes, it is necessary to define a utility space that can be used to evaluate safety and cost on the same scale (Wang et al., 1996). Four exclusive utility expressions (i.e. "*slightly preferred*", "*moderately preferred*", "*preferred*" and "*greatly preferred*") are defined as shown in Table 6. The safety associated with each design/operation option and the cost incurred in each design/operation option are then mapped onto the utility space and expressed in terms of the utility expressions.

Since the safety expressions and the utility expressions are defined by the same membership functions with respect to the seven categories, a safety description can be directly mapped onto the utility space. For example, if the safety description associated with a design/operation option is $S(i)$={(μ_i^1"*poor*"), (μ_i^2,"*fair*"), (μ_i^3,"*average*"), (μ_i^4,"*good*")}, then the corresponding utility description is $U(S(i))$={(μ_{Si}^1, "*slightly preferred*"), (μ_{Si}^2, "*moderately preferred*"), (μ_{Si}^3, "*preferred*"), (μ_{Si}^4, "*greatly preferred*") } where $\mu_i^j=\mu_{Si}^j$ for j=1,2,3,4. Given the membership values of a cost description for a design/operation option with reference to Table 5, the best-fit method can also be used to map the subjective cost description onto the defined utility expressions. The cost $C(i)$ incurred in the ith design/operation option can be evaluated in terms of the utility expressions as follows:

Table 6
Four utility expressions

μ Linguistic variables	Categories 1	2	3	4	5	6	7
1. Slightly preferred	0	0	0	0	0	0.75	1
2. Moderately preferred	0	0	0	0.75	1	0.25	0
3. Preferred	0	0.25	1	0.75	0	0	0
4. Greatly preferred	1	0.75	0	0	0	0	0

$$U(C(i)) = \{(\mu_{Ci}^1, \text{"slightly preferred"}), (\mu_{Ci}^2, \text{"moderately preferred"}), (\mu_{Ci}^3, \text{"preferred"}), (\mu_{Ci}^4, \text{"greatly preferred"})\}$$

Suppose there are D design/operation options in hand. Given the relative importance of cost against safety, denoted by ω, $U(S(i))$ and $U(C(i))$ can be synthesised using the evidential reasoning approach to obtain a preference estimate associated with design option i in terms of the utility expressions. The synthesised preference estimate $U(U(i))$ for a design/operation option can be expressed as follows:

$$U(i) = \{(\mu_{Ui}^1, \text{"slightly preferred"}), (\mu_{Ui}^2, \text{"moderately preferred"}), (\mu_{Ui}^3, \text{"preferred"}), (\mu_{Ui}^4, \text{"greatly preferred"})\}$$

Preference degree P_i associated with design/operation option i can be obtained by (Yang and Singh, 1994):

$$P_i = \sum_{j=1}^{4} \mu_{Ui}^j \times K_j + \left(1 - \sum_{j=1}^{4} \mu_{Ui}^j\right) \times \frac{1}{4} \times \sum_{j=1}^{4} K_j$$

where $[K_1\ K_2\ K_3\ K_4] = [0.217\ 0.478\ 0.739\ 1]$; $\left(1 - \Sigma^4_{j=1}\mu_{Ui}^j\right)$ describes the remaining belief unassigned after commitment of belief in the synthesis of cost and safety descriptions; and $\frac{1}{4} \times \Sigma^4_{j=1} K_j$ is the average value of the K_js.

A larger P_i means that design/operation option i is more desirable. Each P_i (i=1,2,...D) represents the comparison with others. The best design/operation option with the largest preference degree can be selected on the basis of the magnitudes of P_i (i=1,2,...D).

4. An illustrative example

A hydraulic hoisting transmission system of a marine crane consists of five subsystems: a hydraulic oil tank, an auxiliary system, a control system, a protection system and a hydraulic servo transmission system (Wang et al., 1995, 1996). Each subsystem is associated with several failure modes. Suppose there are four safety analysts and the opinions given by safety analysts 2 and 3 are twice as important as those given by designers 1 and 4. There are four design options in hand. Those options are option 1: eliminating no failure modes in the design review process; option 2: eliminating failure modes “hoist up limit failure” and “hoist down limit failure” associated with the protection system; option 3: eliminating the failure modes involving “major leak” and “no output from the package motor” associated with the hydraulic servo transmission system; and option 4: eliminating the two failure modes associated with the protection system in design option 2 and the two failure modes associated with the hydraulic servo transmission system in design option 3 (Wang et al., 1995, 1996).

Suppose four safety analysts make the judgements on each failure mode of each subsystem for design option 1. Suppose four safety analysts make the judgements on the cost incurred in each design option. If safety and cost objectives are considered to be of equal importance, then the utility descriptions of four design options are obtained as given below (Wang et al., 1996).

4.1. Option 1

$$S(1)=\{(0.111942,\text{“}\textit{poor}\text{”}),\ (0.175782,\text{“}\textit{fair}\text{”}),$$
$$(0.451996,\text{“}\textit{average}\text{”}),(0.228256,\text{“}\textit{good}\text{”})\}$$

$$U(S(1))=\{(0.111942,\text{“}\textit{slightly preferred}\text{”}),\ (0.175782,\text{“}\textit{moderately preferred}\text{”}),$$
$$(0.451996,\text{“}\textit{preferred}\text{”}),\ (0.228256,\text{“}\textit{greatly preferred}\text{”})\}$$

The safety associated with design option 1 is assessed as “*poor*” with a belief of 11.1942%, as “*fair*” with 17.5782%, as “*average*” with 45.1996% and as “*good*” with 22.8256%. The utility description on the safety associated with the option is assessed as “*slightly preferred*” with a belief of 11.1942%, as “*moderately preferred*” with 17.5782%, as “*preferred*” with 45.1996% and as “*greatly preferred*” with 22.8256%.

The judgements produced can then be synthesised to obtain the utility description on the cost incurred in design option 1.

$$U(C(1))=\{(0,\text{“}\textit{slightly preferred}\text{”}),\ (0,\text{“}\textit{moderately preferred}\text{”}),$$
$$(0,\text{“}\textit{preferred}\text{”}),\ (1,\text{“}\textit{greatly preferred}\text{”})\}$$

The utility description on the cost incurred in the design option is assessed as “*slightly preferred*” with a belief of 0%, as “*moderately preferred*” with 0%, as “*preferred*” with 0% and as “*greatly preferred*” with 100%.

The utility description of the option and the preference degree associated with the description are obtained as follows:

$$U(1)=\{(0.020365,\text{“}\textit{slightly preferred}\text{”}),\ (0.031979,\text{“}\textit{moderately preferred}\text{”}),$$
$$(0.082230,\text{“}\textit{preferred}\text{”}),\ (0.845756,\text{“}\textit{greatly preferred}\text{”})\}$$

$$P_1=0.93820$$

4.2. Option 2

$$S(2)=\{(0.099336,\text{“}\textit{poor}\text{”}),\ (0.151830,\text{“}\textit{fair}\text{”}),$$
$$(0.372342,\text{“}\textit{average}\text{”}),\ (0.343967,\text{“}\textit{good}\text{”})\}$$

$$U(S(2))=\{(0.099336,\text{“}\textit{slightly preferred}\text{”}),\ (0.151830,\text{“}\textit{moderately preferred}\text{”}),$$
$$(0.372342,\text{“}\textit{preferred}\text{”}),\ (0.343967,\text{“}\textit{greatly preferred}\text{”})\}$$

$$U(C(2))=\{(0.007316,\text{“}\textit{slightly preferred}\text{”}),\ (0.009727,\text{“}\textit{moderately preferred}\text{”}),$$
$$(0.967102,\text{“}\textit{preferred}\text{”}),\ (0.007588,\text{“}\textit{greatly preferred}\text{”})\}$$

$U(2)=\{(0.017574,$ "*slightly preferred*"), (0.027231, "*moderately preferred*"), (0.881336, "*preferred*"), (0.057597, "*greatly preferred*")}

$P_2=0.73563$

4.3. Option 3

$S(3)=\{(0.022057,$ "*poor*"), (0.032674, "*fair*"), (0.071220, "*average*"), (0.844790, "*good*")}

$U(S(3))=\{(0.022057,$ "*slightly preferred*"), (0.032674, "*moderately preferred*"), (0.032674, "*preferred*"), (0.032674, "*greatly preferred*")}

$U(C(3))=\{(0.017512,$ "*slightly preferred*"), (0.024162, "*moderately preferred*"), (0.929696, "*preferred*"), (0.018746, "*greatly preferred*")}

$U(3)=\{(0.014738,$ "*slightly preferred*"), (0.021939, "*moderately preferred*"), (0.608031, "*preferred*"), (0.322949, "*greatly preferred*")}

$P_3=0.80565$

4.4. Option 4

$S(4)=\{(0.012699,$ "*poor*"), (0.018534, "*fair*"), (0.034916, "*average*"), (0.907020, "*good*")}

$U(S(4))=\{(0.012699,$ "*slightly preferred*"), (0.018534, "*moderately preferred*"), (0.034916, "*preferred*"), (0.907020, "*greatly preferred*")}

$U(C(4))=\{(0.0015137,$ "*slightly preferred*"), (0.977743, "*moderately preferred*"), (0.005671, "*preferred*"), (0.004724, "*greatly preferred*")}

$U(4)=\{(0.005851,$ "*slightly preferred*"), (0.553364, "*moderately preferred*"), (0.017471, "*preferred*"), (0.382421, "*greatly preferred*")}

$P_4=0.68599$

The ranking of the four design options is as follows:

Ranking	Options	Preference degrees
1	Option 1	P_1=0.93820
2	Option 3	P_3=0.80565
3	Option 2	P_2=0.73563
4	Option 4	P_4=0.68599

The ranking of design options varies with the relative importance of cost factor against safety factor. Fig. 3 shows the preference degrees associated with the four design options at different values of relative importance of cost against safety (Wang et al., 1996). For example, when the safety factor is considered to be twice as important as the cost factor, then the ranking of the four design options is option 1, option 2, option 3 and option 4. Given the particular requirements on safety and cost, the ranking of design options can be found in Fig. 3.

5. Concluding remarks

Shipping is a very complicated process with high uncertainty involved. A ship is a complex and expensive engineering structure composed of many systems and is usually different from other ships. Ships need to constantly adopt new approaches, new technology, new hazardous cargoes, etc. Therefore, a very generic formal safety assessment framework should cover all possible areas including those where it is difficult to apply traditional safety assessment techniques. Lack of reliable safety data and lack of confidence in safety assessment have been two major problems in safety analysis of various engineering activities. This is particularly true in formal ship safety assessment due to the fact that the level of uncertainty is high. The subjective safety analysis approach presented in this paper provides marine safety

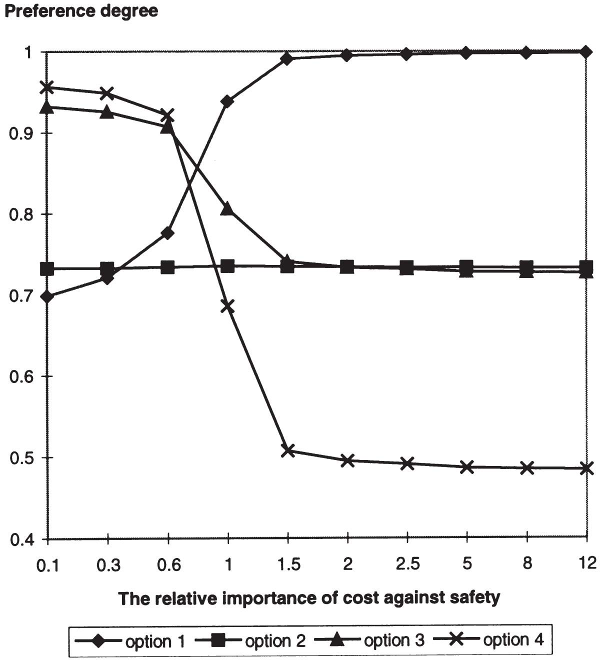

Fig. 3. Ranking of the design options.

analysts with flexibility in articulating judgements produced by multiple safety analysts. The approach can be used as an alternative for analysts to conduct formal ship safety assessment, especially in situations where non-numerical safety data is supplied.

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