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Multi-stakeholder decision-making in the risk-based design of a RO-PAX double bottom for grounding

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Abstract: Grounding accidents can be fatal for ships. This paper discusses decision-making in risk-based design to avoid such outcomes for a 30 000 GT RO-PAX in a powered hard grounding. Five alternatives of a double-bottom structure are suggested to reduce the risks of loss of life, environmental damage, and material damage. Risk assessment concentrates on the consequences, applying numerical grounding simulations to model the energy absorption of the proposed alternatives. To determine the risks, 1295 Monte Carlo simulations are performed running a quasi-static model of ship motions. Accounting for these risks and the added production costs and operational loss, a new multi-stakeholder approach for selecting alternatives is proposed assuring simultaneous maximal satisfaction to both the shipyard and the ship owner. As an outcome, two alternatives are selected, the first increasing the bottom shell thickness by 50 per cent, and the second increasing the stiffness of longitudinal stiffeners by 90 per cent. If observing their performance, it is possible to recommend the latter as the most effective solution. Such an outcome is in accordance with the established practical opinions in increasing safety for grounding, proving sagacity of the presented approach.

Keywords: grounding, decision-making, stakeholder, risk-based design, RO-PAX

1 INTRODUCTION

Ship grounding is one of the most common types of marine accidents. Fortunately, the consequences are often limited to structural damage with no or only slight loss of water tightness. However, in worst cases, the consequences may reach disastrous proportions, especially in the case of ships transporting passengers due to a potential loss of life. According to IMO [**1**], grounding's share in all serious to very serious accidents for the year 2003 was 22.5 per cent.

Studies related to grounding risk often focus on the operational items, see e.g. [**2**, **3**]. But if grounding occurs, a ship with sound design should endure certain damage. What are then the possibilities that the ship designer possesses and what decisions should be made in order to reduce the risks of grounding by rationally improving the ship's structural design?

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This paper studies a generic 30 000 GT RO-PAX in powered hard grounding, with 120 passengers and crew on board, and roughly 1000 t of heavy fuel oil, specified in Table 1. In order to enhance the safety above the minimal requirements, five representative design alternatives (DAs) of a double-bottom structure are studied, as follows.

1. DA-A: The original double bottom, seen in Fig. 1, with a height of 1.6 m and a 12-mm outer shell thickness.
2. DA-B: Double bottom height increased by 50 per cent from DA-A to 2.4 m.
3. DA-C: Bottom plate thickness increased by 50 per cent from DA-A.
4. DA-D: The stiffness of double bottom longitudinals increased by about 90 per cent from DA-A by changing the profiles from HP260 × 10 to HP300 × 13.
5. DA-E: Intercostal girders instead of longitudinal stiffeners.

These DAs are judged in two contractual situations (CSs): CS-I, assuming the need to preserve the cargo

Table 1 Main particulars of the studied RO-PAX

Length overall	146.27 m
Breadth	25.35 m
Drought	7.35 m
Gross tonnage	30 000
Output	14 000 kW
Speed	20.8 kn

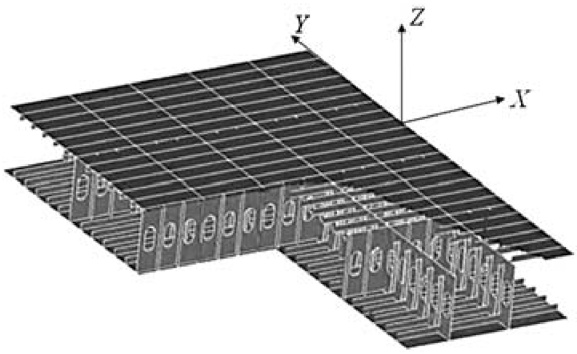

Fig. 1 The original double bottom structure of DA-A

capacity by enlarging the ship, and CS-II, in which the ship's main particulars are kept constant, while allowing for reduction of cargo capacity. Such considerations are not untypical, especially the former. The latter can be reasoned, e.g. with the limitations of ports to which the ship calls.

Three risk measures are considered when judging DAs: the loss of life, the environmental damage, and the material damage. Skjong and Ronold [**4**] present a practical criterion for decision-making involving the risk of loss of life based on the value of the implied cost of averted fatality (ICAF). Assuming operations in the Northern Baltic, the optimum acceptable value of ICAF is then roughly £2 000 000. Friis-Hansen and Ditlevsen [**5**] define a criterion for environmental protection called Nature Preservation Willingness Index. However, this index does not provide a simple numerical criterion. When considering multiple design measures, the decision-support systems in ship design mostly apply the methods of multi-attribute decision-making (for example, references [**6**] to [**8**]). The goal is to obtain a Pareto front, which is introduced to decision-making applying different metrics, e.g. Euclidean or Chebyshev [**9**]. The choice of metric and its weighting is left for a designer, and it is often aided by visualizing the attribute space. Based on the subjective set of preferences, a designer then selects one DA that appears to be the most efficient.

Ship design is, however, strongly influenced by the multiple requirements set by various stakeholders, such as the shipyard, ship owner, ship operator, cargo owner or passenger, maritime organizations, e.g. IMO, flag state, society, etc. Often, these requirements set the minimal thresholds, to guarantee, e.g. safety, but can also represent incentives, desires and wishes, e.g. about performance of the ship. Generally, the shipyard as producer and the ship owner as customer directly control the design parameters, while the other stakeholders more often exert indirect influence. Here, this complex situation is simplified by solely considering the requirements set by the shipyard and the ship owner through which all the requirements of other stakeholders are also represented.

The shipyard and the ship owner often posses conflicting interests, and, as a result, they value DAs differently, e.g. the shipyard prefers DAs that are inexpensive to produce, and the owner those that increase profitability. Hence, the designer's selection is dependent on the adopted views of a certain stakeholder. Since this paper aims to suggest a rational way to increase safety, it is essential to mutually address the shipyard's and the ship owner's preferences. But, as indicated later, simply unifying these within a single set of preferences might result in possibly irrational decisions, not at all satisfactory for the stakeholders. Hence, another approach is suggested based on the axiomatic group decision-making, conveniently named here the multi-stakeholder decision-making.

In the following section of the paper, this approach will be presented, stakeholders' preferences will be defined, and the three conditions, which need to be satisfied if a DA should be selected, will be introduced. The third section presents the assessment of risks in grounding and the evaluation of the attributes, on which basis the selection is made in the fourth section, choosing the most efficient DA.

2 THE MULTI-STAKEHOLDER APPROACH TO RISK- BASED DESIGN

The multi-stakeholder approach essentially requires determination of the stakeholders' preferences. Presuming that these preferences contradict, it is required to further define the decision-making model through which it is possible to select the most efficient alternative.

2.1 Definition of stakeholders' utility functions

Assuming that the ship is in the conceptual phase of design, the prime interest of the ship owner becomes her performance in terms of safety and the income generated by operations. Having better safety record improves market image and also decreases insurance costs. The shipyard is mostly interested in reduction of production costs, not forgetting the overall performance of the ship, wishing to leave a positive impact in the market, and strengthen the possibility for the long-term relationship with the owner.

There are five attributes that effectively underline the measures implied by the stakeholders to value every design alternative. The three attributes as the measures of risk are:

1. the risk of loss of life, L;
2. the risk of environmental damage, E;
3. the risk of material damage, M;

and the two to measure the costs of applying the particular design alternative are:

4. the costs for the shipyard, P;
5. costs for the owner, O.

To grasp the preferences over these attributes, a notion of utility is applied. A utility, u, can be simply described with the following: $u_A < u_B$, if an alternative B is preferred over an alternative A. The numerical value of utility to a stakeholder will be called payoff. To define payoffs for every DA, two utility functions are applied. An additive function

$$u_j^+ = \sum_i a_{ij} r_{ij} \tag{1}$$

where r_{ij} is an attribute utility function and a_{ij} its importance weight coefficient, and a product function

$$\dot{u}_j = \prod_i r_{ij}^{a_{ij}} \tag{2}$$

Figure 2 illustrates these two functions in an attribute space. The additive function u^+ results in higher payoffs than product function $\dot{u}$, but it is also indifferent to the character of an attribute value. On the contrary, the product function strongly penalizes those alternatives for which attribute values are small. Therefore, if a stakeholder focuses on the overall behaviour of DAs, it is preferable to apply the former function, since the latter filters those DAs behaving the poorest over attribute(s). The latter is then applicable for stakeholders additionally interested in particular DAs' performance over attributes. For further interpretation about the nature of these and possible other utility functions, see Marler and Arora [**10**].

Preference ordering depends on the CS. In CS-I, the ship's enlargement will cause significant increase in production costs, P_{SHIP}. It is assumed that this increase will be taken on by both stakeholders evenly. Such reasoning emerges from the notion that the owner can always search for another, cheaper yard prior to contract signing, but also has to cover the changes in ship particulars. In CS-II, as the main dimensions are fixed, the owner does not cover the added production costs, but faces a potential loss, O_{LOSS}, in the operational profit due to the reduced cargo capacity. The amount of additional costs, P_{DB}, in the implementation of DAs will not add to the overall production costs in a same scale as in CS-I, as the changes now limit to the double bottom. This reduced amount of additional costs compared to CS-I will be beneficial for the yard, which consequently reduces the importance of minimizing the costs. On the other hand, the owner will reconsider

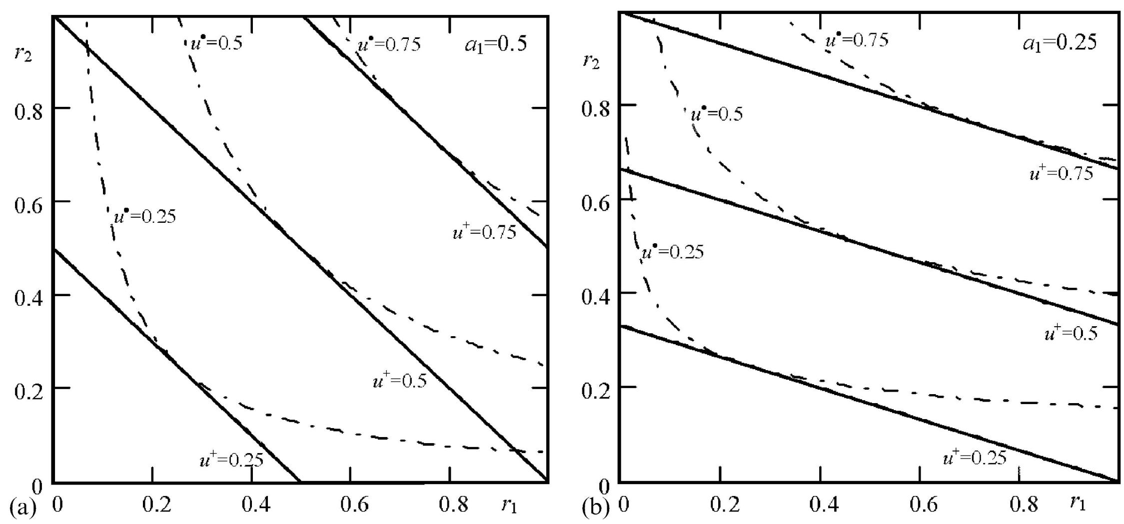

Fig. 2 Normalized additive u^+ and product u^* utility functions for (a) equal weighting of attributes, and (b) 75% importance of attribute r_2

the preferences towards the risk minimization, expressing stronger interest to accommodate an effective risk control option without a major loss of cargo space.

The intention is to jointly assess the two contractual situations. This allows for comprehensive judgement of DAs and answers which contractual situation satisfies stakeholders better. It also imposes combining costs into a single attribute for both stakeholders according to the mentioned assumptions

$$P = \frac{P_{SHIP}}{2} + P_{DB} \tag{3}$$

$$O = \frac{P_{SHIP}}{2} + O_{LOSS} \tag{4}$$

Selection-wise, the number of proposed DAs now doubles.

Applying the analytic hierarchy process (AHP) [**11**], it is possible to numerically model the knowledge on stakeholders' preferences into weights. The preference weights, a, are specified through the following stakeholders' pair-wise comparison matrices, **A**

$$\mathbf{A}_{\mathrm{SY,I}} = \begin{array}{c} \\ L \\ M \\ E \\ P \end{array} \begin{array}{c} \begin{array}{cccc} L & M & E & P \end{array} \\ \begin{bmatrix} 1 & 9 & 5 & 1/5 \\ 1/9 & 1 & 1/3 & 1/9 \\ 1/5 & 3 & 1 & 1/7 \\ 5 & 9 & 7 & 1 \end{bmatrix} \end{array} \tag{5}$$

$$\mathbf{A}_{\mathrm{SY,II}} = \begin{array}{c} \\ L \\ M \\ E \\ P \end{array} \begin{array}{c} \begin{array}{cccc} L & M & E & P \end{array} \\ \begin{bmatrix} 1 & 9 & 5 & 1/5 \\ 1/9 & 1 & 1/3 & 1/7 \\ 1/5 & 3 & 1 & 1/5 \\ 2 & 7 & 5 & 1 \end{bmatrix} \end{array} \tag{6}$$

$$\mathbf{A}_{\mathrm{SO,II}} = \begin{array}{c} \\ L \\ M \\ E \\ O \end{array} \begin{array}{c} \begin{array}{cccc} L & M & E & O \end{array} \\ \begin{bmatrix} 1 & 9 & 5 & 5 \\ 1/9 & 1 & 1/5 & 1/5 \\ 1/5 & 5 & 1 & 1/2 \\ 1/5 & 5 & 2 & 1 \end{bmatrix} \end{array} \tag{7}$$

$$\mathbf{A}_{\mathrm{SO,II}} = \begin{array}{c} \\ L \\ M \\ E \\ O \end{array} \begin{array}{c} \begin{array}{cccc} L & M & E & O \end{array} \\ \begin{bmatrix} 1 & 9 & 5 & 1 \\ 1/9 & 1 & 1/5 & 1/7 \\ 1/5 & 5 & 1 & 1/2 \\ 1 & 7 & 2 & 1 \end{bmatrix} \end{array} \tag{8}$$

Table 2 Scale for preference rating [**11**]

1	attribute i is equally important as attribute j
3	attribute i is weakly more important than attribute j
5	attribute i is essentially more important than attribute j
7	attribute i is dominantly more important than attribute j
9	attribute i is absolutely more important than attribute j

Numbers 2, 4, 6, and 8 are used for intermediate preference. Inverse values are used when comparing attribute j with attribute i.

marked for the shipyard (SY) and the ship owner (SO) in contractual situations I and II. The comparison values are determined in accordance with the scale in Table 2.

As seen in the matrices, it is assumed that the shipyard values predominantly more the DAs bearing smaller production costs and the risk of loss of life, followed by the risk of environmental damage, since the ship carries a limited amount of pollutants. This preference ordering is stronger for the minimization of production costs in the CS-I, since there the costs for the yard are assumed to be higher. The owner is assumed to treat the reduction of the risk of loss of life as the most important attribute, as this is the primary objective of the project – to enhance safety of life onboard. But, the costs of implementation are given second to third strongest importance. They are in line with the risk of environmental damage as the potential cleaning costs of 1000 t of pollutant could account to approximately \$10 000 000 [**5**, p. 15]. Opposite to the preference ordering of the yard, the owner strongly prefers a decrease in losses in CS-II, as the profits diminish due to the reduced payload.

Saaty [**11**] defines preference weights based on the eigenvector of the comparison matrix with maximal eigenvalue. The maximal eigenvalues of the matrices **A** in equations (5) to (8) are then, respectively: 4.337, 4.14, 4.194, and 4.132. These values indicate that the comparisons are consistent, assuring reasonable transitiveness in ordering.[1] Namely, their consistency ratios are calculated at 0.1, 0.042, 0.058, and 0.039, respectively, satisfying the criterion of Saaty [**11**] of not being bigger than 0.1. Eigenvectors with maximal eigenvalues are then scaled to a unit interval to obtain the attribute weights of equations (1) and (2)

$$\mathbf{a}_{\mathrm{SY,I}} = (0.252 \quad 0.037 \quad 0.076 \quad 0.636)^{\mathrm{T}} \tag{9}$$

$$\mathbf{a}_{\mathrm{SY,II}} = (0.365 \quad 0.046 \quad 0.098 \quad 0.491)^{\mathrm{T}} \tag{10}$$

$$\mathbf{a}_{\mathrm{SO,I}} = (0.631 \quad 0.042 \quad 0.191 \quad 0.191)^{\mathrm{T}} \tag{11}$$

$$\mathbf{a}_{\mathrm{SO,II}} = (0.469 \quad 0.042 \quad 0.151 \quad 0.339)^{\mathrm{T}} \tag{12}$$

[1]Transitive ordering of preferences assumes that if $A \succ B \succ C$ and $B \succ C$ then $A \succ C$.

where the vectors' members are attribute weights, respectively for the risk of loss of life, material damage and environmental damage, and the costs.

2.2 Multi-stakeholder decision-making

Arrow [**12**] proves that group decision-making tends to become irrational, even if all the decision-makers follow perfectly rational transitive behaviour. It is then probable that the group of stakeholders will exhibit intransitive preferences that thus cannot be modelled with a single function [**13**, p. 165]. Hence, instead of defining a joint stakeholder utility function, this multi-stakeholder decision problem is tackled here axiomatically.

Assuming that stakeholders are not willing to renounce any of their payoffs, u, for the sake of others, their relationship becomes competitive [**14**]. If their utility functions are also conflicting, then there exists a Pareto surface, $\mathbf{U}_0$, in a utility space, see Fig. 3. Competitive relationship is often present between shipyards and ship owners, as they are willing to gain at the expense of one another. In terms of design, this is often witnessed, e.g., through the strict set of requirements laid down by the owner, demanding adjustments in production and causing possible losses to a yard. To assure satisfaction of all stakeholders in such relationship, the following three conditions are suggested, where if the alternative, $\boldsymbol{u}^*$, member of the attainable set of all alternatives $\mathbf{U}$, satisfies:

Condition 1 – Compromise

$$\ldots \text{ if } \nexists\, u \in \mathbf{U} | \underset{\smile}{\boldsymbol{u}} < \boldsymbol{u}^* < \boldsymbol{u} \tag{13}$$

Condition 2 – Efficiency

$$\ldots \text{ if } \nexists\, \mathrm{u} \in \mathbf{U} | u_j^* = u_j,\ \forall j \in m \backslash i \text{ and } u_i^* < u_i,\ i \in m \tag{14}$$

Condition 3 – Maximal stakeholders' satisfaction in the competitive relationships (MaSSCoR)

$$\ldots \text{ if } \boldsymbol{u}^* \geqslant \{\tilde{\boldsymbol{u}} | \tilde{u}_1 = \cdots = \tilde{u}_m \text{ when } \forall \boldsymbol{u} \in \mathbf{U},\ \mathbb{P}(\boldsymbol{u}) \in \mathbf{U}\} \tag{15}$$

it is the solution of a problem.

Compromise and efficiency are respectively described as weak and strong Pareto optimality. Compromise is required due to the two specific properties. It is collectively stable, since no decision exists which can jointly increase the payoffs [**15**], and it strictly refers to DAs with utility gains, or stakeholders' strong individual rationality (SIR) [**16**]. Scott & Antonsson [**17**] consider SIR in the multi-attribute design as the axiom of annihilation, concluding that if the preference towards attribute sinks to zero the overall preference for the design is zero. Analogically, this prescribes here in a form that if a stakeholder j does not gain more than in a nadir vector $\boldsymbol{u}$ then considering j as a stakeholder is paradoxical.

MaSSCoR stipulates a solution $\tilde{\boldsymbol{u}}$, which for problems having symmetric and convex hull, $\mathbf{U}^{con}$, seen in Fig. 4, and defined through equation (15), always yields a DA with equal payoffs to stakeholders. Many authors (for example, references [**18**] to [**20**]), discuss this equality, arguing that if the overall wealth can be separated equally to individuals, then it should be as such given in equal amounts. The stakeholders in this problem are therefore equally profiting with the DA satisfying MaSSCoR. Certainly, they are then treated justly and objectively, while all the subjectivity is compiled strictly within the preference vector, $\boldsymbol{a}$. The possible skewed payoffs of chosen DAs from non-convex or asymmetric attainable sets are then only the result of a system performance and a design situation.

Nash [**21**] defines an equilibrium point (Nash equilibrium, NE) for non-cooperative games as the point for which n-tuple of decision strategies, $\boldsymbol{s}$,

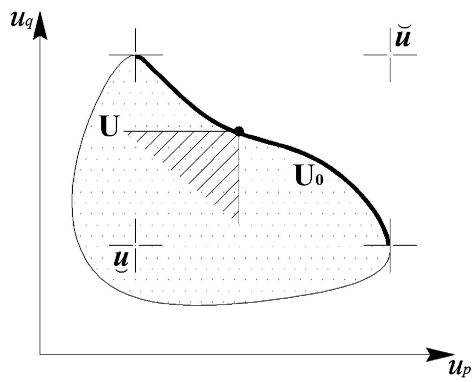

Fig. 3 Arbitrary utility space

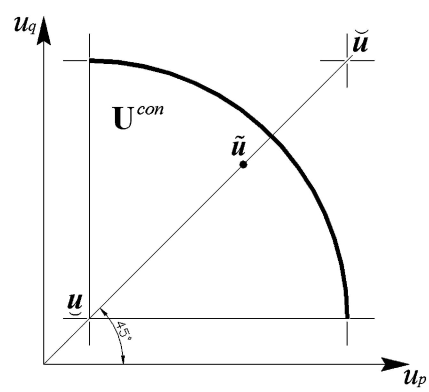

Fig. 4 Convex and symmetric attainable hull $\mathbf{U}^{con}$

maximizes a payoff of a player while keeping the strategies of others fixed; and states that if the game is finite and symmetric, this point will always have symmetric strategies. This coincides well with the studied problem and the assumptions of MaSSCoR. As shown in Appendix 2, if the game is played between the two stakeholders, where their pairs of strategies strictly yield Pareto optimal DAs, the NE guarantees equal payoffs. Thus, payoffs obtained for the NE are accepted as the criterion for satisfying MaSSCoR.

Clearly, from the definitions of strong and weak Pareto optimality, DA satisfying efficiency satisfies compromise. The behaviour of the NE is, however, dependent on the problem, and if feasible it is not guaranteed to be strongly Pareto optimal. But, it is considered individually stable as any unilateral alterations in stakeholder's decision would result in a loss of payoff [**15**]. Hence, the alternative which satisfies the three conditions of the multi-stakeholder design simultaneously possesses the properties of collective and individual stability. Successful engineering outlines decisions that determine strong Pareto optimal designs as collectively stable solutions. By satisfying the individual stability, it is then possible to reduce the number of such decisions and determine the most-efficient DA.

Henceforth, only the strong Pareto optimal alternatives satisfying MaSSCoR are acceptable as solutions. Proceeding with the conclusions of Appendix A, these can be identified with the following decision function

$$\boldsymbol{u}^* = \boldsymbol{u} \in \Lambda(\bar{\omega}) | \nexists \boldsymbol{u}' \in \mathbf{U}, \boldsymbol{u}' \geqslant \boldsymbol{u} \tag{16}$$

$\boldsymbol{u}^*$ is then a member of the minimal isometric cone Λ of the uniformly weighted Chebyshev metrics, see Appendix 2, thus maintaining the payoffs obtained in the NE. As it simultaneously satisfies both stakeholders in the competitive relationship, and it is strongly Pareto optimal, it is also regarded as the competitive optimum (CO).

3 THE RISK ASSESSMENT AND COST EVALUATION

In order to accurately determine the stakeholders' payoffs, a new approach, presented by Jalonen [**22**], is applied for the estimation of attributes. When modelling the structural damage to the ship bottom in powered hard grounding, it is important to find out several probable outcomes, e.g. whether a ship stops on a rock, or does she and people onboard survive. The consequences of grounding are strongly linked to the structural damage. If the water penetrates several compartments, the ship may capsize and eventually sink. Rupture of a fuel tank may, on the other hand, lead to an oil leak with possibly high environmental damage. The proposed risk assessment model therefore composes of three sub-models, seen in Fig. 5. An additional model is defined for the evaluation of implementation costs and operational losses.

3.1 Probabilistic input data model

The probability of grounding is determined for the northern Baltic Sea. An estimate of $p = 0.02$ groundings/ship-year is found reasonable according to NWEPRS [**3**]. Since grounding is a complicated process, the analysis is limited to a ship in deep calm waters heading in a straight course towards a rock. Three main parameters are selected in the analysis: the ship velocity, the lateral location of the contact, and the water depth. The first two are considered uniformly distributed, where the former varies from 0 to 21 kn. Following the ship's lateral symmetry, the latter is varied between the centre line and the beam. The water depth at the tip of the rock extends with the triangular distribution [**23**] from the keel at 7.35 m to a depth of 8 m, to allow for a proper account of sinkage and trim.

3.2 Grounding process model

Actual grounding is assumed as a point of contact between the ship and the rock. The rock is modelled

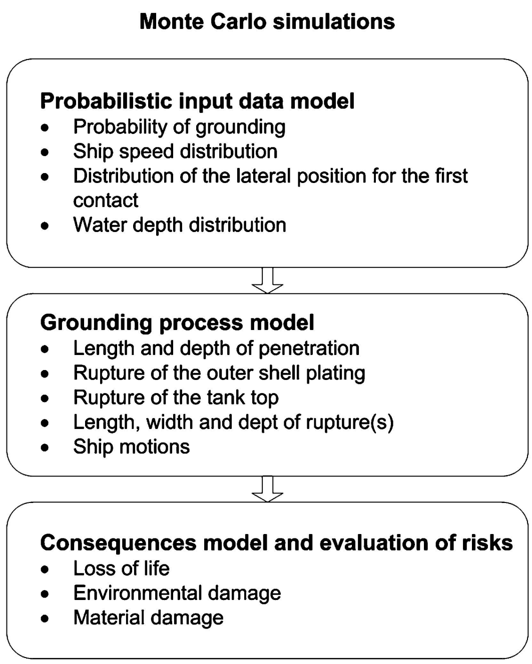

Fig. 5 Risk assessment model

as a single isolated pinnacle represented with a cone having a semi-apex angle of 45° and a rounded top with a radius of 1.1 m. The structural damage is approximated on the basis of non-linear finite element simulations of grounding, as presented by Tabri [**24**]. By linearizing the computed force–penetration curves, it is possible to determine the vertical and the horizontal forces for the ship to a rock contact, and eventually a dependency between the rupture of the outer shell and the tank top with the kinetic energy of a ship.

A quasi-static model, based on Simonsen [**25**], with four degrees of freedom is selected for the calculation of ship's motions. This model is, however, further simplified according to the results of grounding model tests [**26**]. It is possible to omit the two components of motion, the sway and the yaw, leaving only the effects of speed on the pitch and heave. The effects of squat are omitted due to the assumed point-contact grounding. The computational grounding model, given in detail in Fig. 6, is validated with the mentioned model tests. As seen in Fig. 7, the results compare sufficiently well.

3.3 Consequence model

To model the consequences, 1295 simulated groundings for each DA are generated applying the Monte

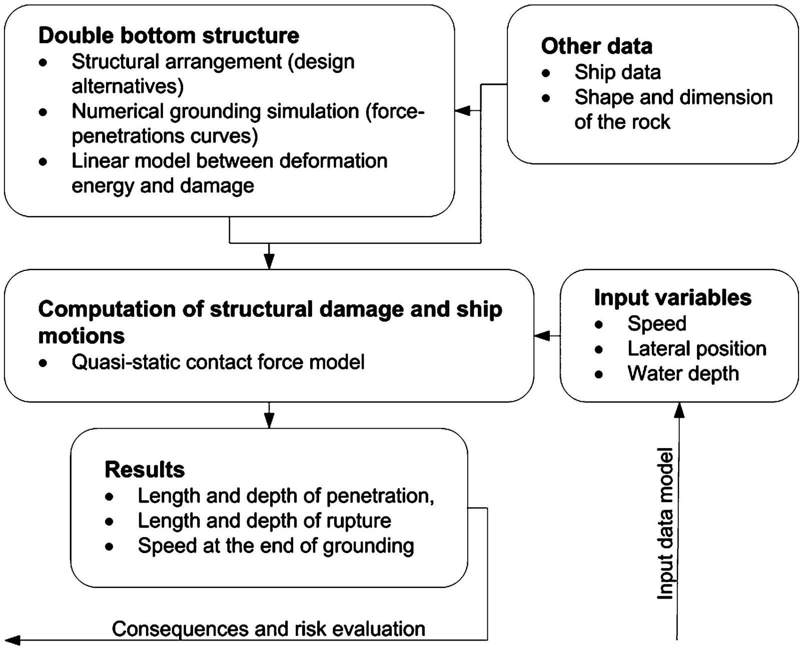

Fig. 6 Grounding process model

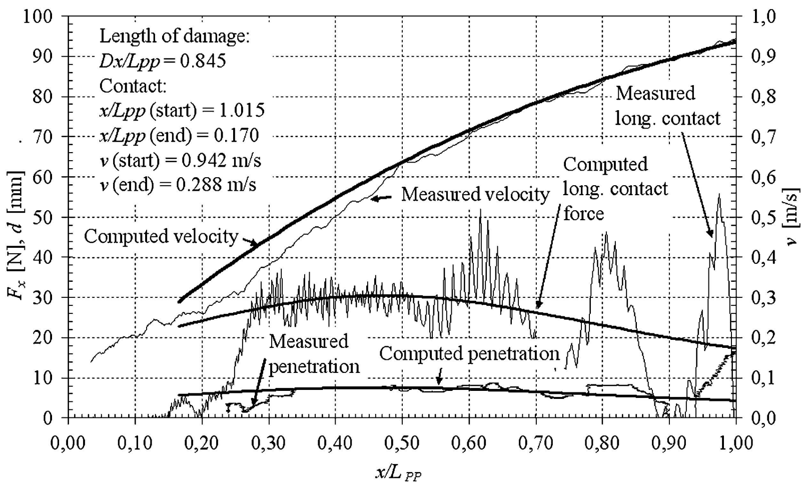

Fig. 7 Comparison of results between the computed motions and model tests for the velocity, v, the longitudinal contact force, F_x and the depth of penetration, d [**22**]

Carlo simulations. Using the presented grounding model, for every simulated grounding it is possible to determine the extent of structural damage and the final state of the ship. Quantitative estimates for the consequences of grounding are obtained using the separate parts for: the loss of life in number or fatalities, the environmental damage in number of oil leaks, and the material or structural damage in value of repair costs. The results of simulations are seen in Table 3.

The extent of damage in simulated grounding is used as an input for the model of loss of life through the estimate of ship survivability. According to 16 initial stability calculations in damaged condition for each DA (see reference [**27**]), it is possible to assume a linear relationship between the survivability index and the length and the location of damage. Consecutively, the hypothetical loss of life in each of the simulated groundings is estimated by the use of an event tree. The event tree considers the type and the extent of a calculated damage, the state of the ship, the necessity of an evacuation, and its assumed outcome. Based on this, it is then possible to estimate the annual fatality rate (AFR) of a DA, hence evaluate the risk of loss of life.

The use of the presented model leads to a rather high estimate of AFR, as seen in Table 4. The estimated share of fatalities is as high as 90 per cent at the highest velocity interval of 18–21 kn, occurring regularly for groundings experiencing tank top rupture. However, all five DAs' F-N curves fall into the 'as long as reasonably practicable' (ALARP) zone seen in Fig. 8, based on the criteria in [**3**].

The environmental damage is assessed with the assumption of fixed location of fuel tanks. The tanks are located in the double bottom, below the lower hold, just above the outer shell plating. The environmental risk is computed based on the counted number of hypothetical leaks in simulated groundings. The amount of leaking oil is, however, not estimated,

Table 3 Different types of structural damage in percentage of total number of simulations

Design alternatives (DA)	**A**	**B**	**C**	**D**	**E**
Number of ruptures (scratches, scuff marks, dents)	32	29	42	35	30
Proportion of bottom plate ruptures	58	66	51	57	62
Proportion of tank top ruptures	10	5	7	8	8

Table 4 Annual fatality rate as the measure of risk of loss of life

Design alternatives (DA)	**A**	**B**	**C**	**D**	**E**
AFR	0.024	0.009	0.013	0.018	0.013
Difference to DA-A, ΔAFR	–	0.015	0.011	0.006	0.011
ΔAFR (%)	–	−62.5	−45.8	−25	−45.8

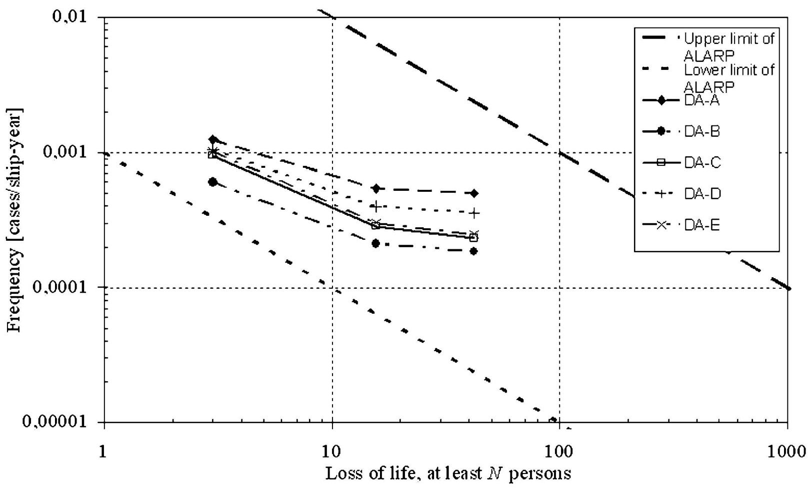

Fig. 8 F-N curves of DAs within the ALARP-zone

as the selected approach is deemed sufficient due to the assumption of a constant cost for each fuel oil leak. Table 5 presents the results.

The risk of material damage is accounted through the costs of probable material damage. The amount of material damage is estimated from the length, the width, and the depth as well as the location and the path of damage. The weight estimate of deformed steel is converted to the repair costs, applying the constant ratio of 8.5 €/kg [**22**]. Some separate items are also included in this value, such as the costs due to the flooded machinery spaces and flooded 1st cargo deck, or costs due to damaged propeller and rudder. These costs are assumed to be 50 per cent of the total costs of material damage. The risk of material damage is given in Table 6.

3.4 Production cost and operational loss sub-model

The production costs and operational losses are evaluated in comparison with the original version of a double bottom DA-A, based on the added steel weight. In CS-I, the added weight is multiplied by the Normand's number of 2.1 [**28**], and the specific ship price of 5.6 €/kg [**29**]. In CS-II, the added weight is multiplied solely with the specific production costs of steel structure as the changes limit to the double bottom. Annual operational losses in CS-II are solely a product of lost cargo capacity due to the additional steel weight multiplied by a specific cargo price of transport, taken at, e.g. 2.94 €/t for Helsinki–Stockholm route [**22**], and 360 fully laden trips per year. Table 7 brings the numerical values for these costs.

4 DECISION ANALYSIS AND DESIGN SELECTION

Decision-makers tend to possess subjective preferences towards attribute values. This emerges from various uncertainties, like factors not considered within a model [**30**], or the inaccuracy of a model, or it can be simply a product of stakeholder's irrationality. Therefore, determining the exact marginal utility function to describe such behaviour becomes difficult [**13**], and is thus regularly approximated, as in, for example, Gurnani and Lewis [**31**]. To facilitate the design selection certain simplifications are then adopted here. First, that both stakeholders express transitive ordering of DAs and, second, that they measure DAs objectively, solely on the basis of attribute values. Transitiveness allows forming marginal utility functions, *r*, as monotonous, while the objectiveness allows for their continuity and

Table 5 The risk of environmental damage

Design alternatives (DA)	A	B	C	D	E
Number of oil leaks	132	142	114	132	130
Probability of a leak per ship-year $\times 10^{-3}$	2.039	2.139	1.761	2.039	2.008
Difference to DA-A (%)	–	7.6	−13.6	0	−1.5

Table 6 Risk of material damage

Design alternatives (DA)	A	B	C	D	E
Probability of a total loss per grounding	0.0085	0.0038	0.0057	0.0069	0.0061
Average grounding cost (€ $\times 10^6$/grounding)	2.55	1.81	2.09	2.25	2.32
Average grounding costs (€ $\times 10^3$/ship-year)	51	36	42	45	46
Benefits compared to DA-A (€ $\times 10^3$), B	–	15	9	6	5
Difference to DA-A (%)	–	−29%	−18%	−12%	−9%

Table 7 Added production costs and operational loss

Design alternatives (DA)	A	B	C	D	E
Added weight in the double bottom only (t)	–	71	98	31	91
Added weight for the enlarged ship (t)	–	149	205	65	190
Added costs in production of double bottom, P_{bott} (€ $\times 10^3$)	–	114	157	50	146
Added costs in production of double bottom*, P_{bott} (€ $\times 10^3$/ship-year)	–	4.56	6.28	2	5.84
Added costs in production of enlarged ship, P_{Ship} (€ $\times 10^3$)	–	834.4	1148	364	1064
Added costs in production of enlarged ship*, P_{Ship} (€ $\times 10^3$/ship-year)	–	33.4	45.9	14.6	42.6
Loss of income, O (€ $\times 10^3$/ship-year)	–	75.1	103.7	32.8	96.3

*Ship is assumed to be in use for 25 years.

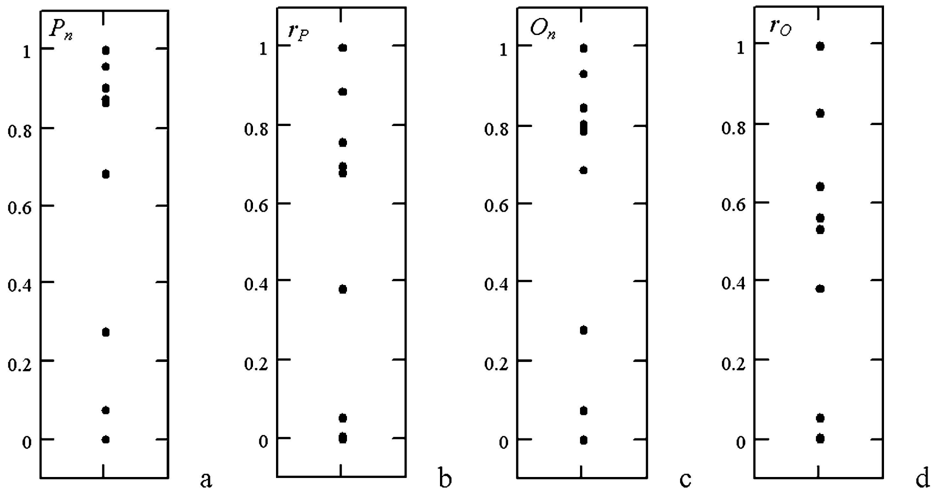

Fig. 9 Normalized attributes (a) P_n and (c) O_n, and their marginal utility values (b) r_P and (d) r_O

Table 8 Attributes, their utility values and stakeholder payoffs for every DA in for both CSs

	Utilities	DA	A-I	B-I	C-I	D-I	E-I	A-II	B-II	C-II	D-II	E-II
	Attribute utilities	r_L	0	1	0.783	0.433	0.733	0	1	0.783	0.433	0.733
		r_M	0	1	0.621	0.414	0.31	0	1	0.621	0.414	0.31
		r_E	0.364	0	1	0.364	0.455	0.364	0	1	0.364	0.455
		r_P	1	0.053	0	0.382	0.037	1	0.755	0.676	0.855	0.696
		r_O	1	0.054	0	0.383	0.035	1	0.638	0.533	0.826	0.56
Payoffs u	Additive function	Yard	0.663	0.322	0.296	0.394	0.233	0.527	0.781	0.745	0.647	0.668
		owner	0.205	0.76	0.784	0.472	0.639	0.394	0.529	0.544	0.405	0.426
	Product function	Yard	0	0	0	0.394	0.24	0	0	0.739	0.604	0.656
		owner	0	0	0.745	0.452	0.603	0	0	0	0.404	0.108
Normalized payoffs u_n	Additive function	Yard	0.785	0.163	0.115	0.295	0	0.535	1	0.933	0.756	0.793
		owner	0	0.959	1	0.462	0.749	0.326	0.559	0.585	0.345	0.382
	Product function	Yard	0	0	0	0.533	0.032	0	0	1	0.817	0.888
		owner	0	0	1	0.606	0.809	0	0	0	0.542	0.145

general validity for both stakeholders. To define their shape, an additional criterion is introduced.

It is assumed that the marginal utility functions should allow reasonably uniform distribution of utility values, enabling easier distinction of orderings between DAs. This becomes helpful if several attractive DAs become crowded due to the simultaneous consideration of strongly weak values within the same utility function. Figures 9(a) and 9(c) show the normalized[2] values for attributes P_n and O_n, respectively. The preferred DAs are crowded, and as it is rational to expect that stakeholders wish to avoid the costly alternatives, the minor differences in terms of utility could then insufficiently influence the design selection. Hence, the attribute utilities for production, r_P, and operational costs, r_O, are approximated using the following exponential functions

$$r_P = 2^{P_n^2} - 1 \tag{17}$$

$$r_O = 2^{O_n^2} - 1 \tag{18}$$

where the chosen exponent value of 2 is decided upon difference between the obtained attribute utility and the attribute values seen in Fig. 9. For the three risk attributes, the normalized values are already distributed evenly over the unit interval, see Fig. 10, hence they are directly adopted as utilities (Table 8).

$$r_L = L_n \tag{19}$$

$$r_E = E_n \tag{20}$$

$$r_M = M_n \tag{21}$$

Based on the computations in section 3, Fig. 10 presents the actual values of attribute utilities and

[2] Normalization stands for conversion $f_n = (\max f - f)/(\max f - \min f)$.

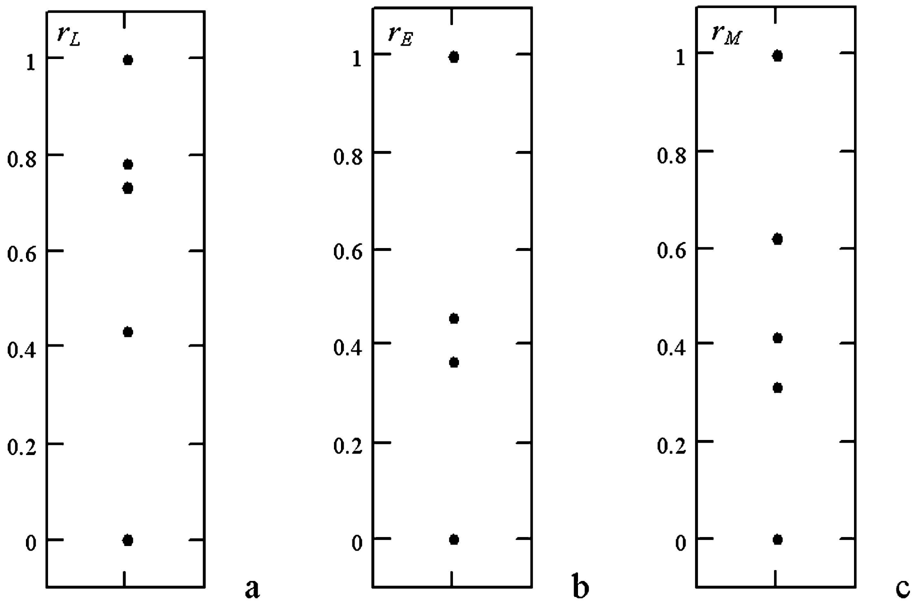

Fig. 10 Utility values for the risk attributes

stakeholders' payoffs. The last four rows are plotted in the normalized utility space; see Fig. 11. There are six dominated DAs: A-I, A-II, D-I, D-II, E-I, and E-II, if applying the additive stakeholder utility function. Designs B-II and C-I form the ideal vector possessing extreme stakeholders' utility values. For the product function, the DAs D-I, D-II, E-I, and E-II become now dominant alongside C-I and C-II.

According to equation (16), the minimal isometric cone Λ of uniformly weighted Chebyshev metrics will mark the COs. As seen in Fig. 11, the CO for the additive utility function, u^+, is then DA-C-II, while for the product utility function, $\dot{u}$, there is a family of DAs: DA-D-I and DA-D-II. To choose between these two outcomes, a comparison is performed based on the ICAF, as it accounts for the significant attributes of the risk of loss of life, the added production costs, and the operational losses. Table 9 shows the ICAF values for each CS. CS-II requires high investments for the obtained benefits, considerably higher than demanded by society. For that reason, the ship should be increased in size if at all possible to avoid high operational losses occurring in CS-II.

The selected DA-C-II might then prove to be a questionable alternative, especially for the ship owner. With the ICAF at £6.1 million, it is the most expensive alternative to implement, ensuring the largest operational losses. As it does not reduce the risk of loss of life comparably to its ICAF value, and if the main dimensions are to be fixed, a more reasonable choice would be then the DA-B-II with

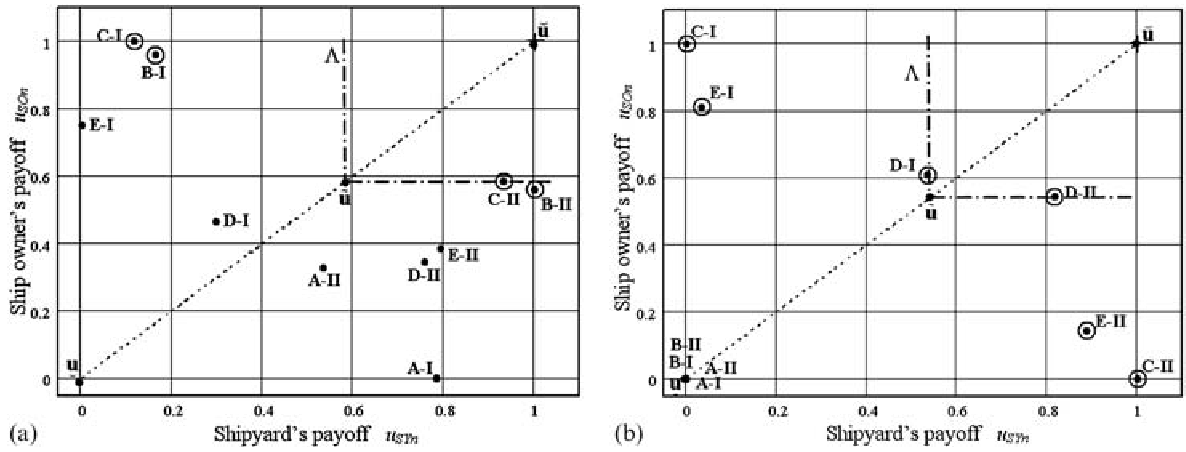

Fig. 11 Normalized utility space defined with the (a) additive and (b) product stakeholder utility function

Table 9 ICAF values for the CS-I and the CS-II

Design alternatives (**DA**)	**A**	**B**	**C**	**D**	**E**
NC-I = $P_{SHIP} - B$ (€ × 10^3)	–	18.4	36.9	8.6	37.6
ICAF-I* = NC-I/ΔAFR (£ × 10^6)	–	0.8	2.0	0.9	2.2
NC-II = $P_{DB} + O_{LOSS} - B$ (€ × 10^3)	–	64.5	101	28.8	97.1
ICAF-II* = NC-II/ΔAFR (£ × 10^6)	–	2.9	6.1	3.2	5.9

*A conversion rate of €1.5 for £1 is applied.

the ICAF at £2.9 million. This outcome is clearly affected by the applied additive utility function, which does not recognize alternatives that under-perform others regarding certain attributes. But, when applying the product utility function, such alternatives can be penalized and are filtered out of consideration for selection, as seen in Fig. 11(b). Thus, the pair of alternatives DA-D-I and -II, selected for the product utility function, are a more preferable option with their ICAF values reduced to £0.9 and £3.2 million, respectively. Since they also represent a single alternative, the DA-D, in two contractual situations, it seems then opportune to recommend increasing the stiffness of bottom longitudinals by 90 per cent to rationally decrease the risks of grounding for the 30 000 GT RO-PAX vessel.

5 CONCLUSION

Driven by the need to rationally improve safety for grounding, this paper summarized various design aspects, ranging from the evaluation of risks and implementation costs to the modelling of realistic design conditions. The complexity of considering multiple attributes of risk and costs within a realistic environment demanded the application of a new approach for multi-stakeholder design based on axioms of group decision-making. This excluded designer's subjectivity, but accounted for that of stakeholders. Using AHP, it was practical to model the fuzzy and subjective preferences of stakeholders, and thus mathematically express their design objectives.

The considered attributes concentrated on the grounding consequences. Previous studies have been mostly contemplating operational safety, thus a practical method was devised here particularly encompassing structural behaviour during the accident. By coupling non-linear numerical evaluation of grounding with Monte Carlo simulations, three different types of risks were determined for every design alternative of the double bottom.

By observing the results of the design selection, one has to account for the influence of the assumed model of stakeholders' preferences. Hence, the results should not as such be considered absolute, but exemplar. Nonetheless, the proposed DAs C and D present a typical type of risk control measure applied in practice when aiming to increase the safety of a ship in grounding. Obviously, this serves then as a confirmation that the overall approach to a risk-based design of a double bottom was sensible.

Following that, the definition of stakeholders' objectives and preferences towards issues of safety should be considered more thoroughly in the future. In parallel, the choice of stakeholder utility functions needs to be addressed as well, to raise the accuracy of the decision model. In that sense, a clear distinction in importance between the preservation of human life, environment, and material property would aid in establishing the rational control of risk at sea.

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APPENDIX 1

Notation

a	weight for attribute importance
$\mathbf{A}$	comparison matrix
B	benefits obtained by reducing material costs in grounding
d	depth of penetration
E	risk of environmental damage
E_n	normalized risk of environmental damage
f	function
F_x	longitudinal contact force
$\mathbf{G}$	game
GT	gross tonnage
l	infinite line passing through the ideal vector $\mathbf{1}$ and the arbitrary weighting vector $\boldsymbol{\omega}$
L	risk of loss of life
L_n	normalized risk of loss of life
m	number of stakeholders
M	risk of material damage
M_n	normalized risk of material damage
O	costs for the ship owner
O_{Loss}	operational loss
O_n	normalized costs for the ship owner
p	probability of grounding

P	costs for the shipyard
P_{DB}	additional costs for the production of a double bottom
P_n	normalized costs for the shipyard
P_{SHIP}	additional production costs for the ship enlargement
$\mathbb{P}(\boldsymbol{u})$	set of all permutations on vector $\boldsymbol{u}$
r	marginal utility function
s	stakeholder's game strategy
$\boldsymbol{s}$	set of all strategies available to a stakeholder
$\mathbf{S}^*$	rational reaction set
u	payoff to a stakeholder
u_n	normalized payoff to a stakeholder
$\dot{u}$	product stakeholder utility function
u^+	additive stakeholder utility function
$\boldsymbol{u}$	vector of design alternative in utility space
$\boldsymbol{u}^*$	competitive optimum
$\breve{\boldsymbol{u}}$	ideal vector
$\underset{\smile}{\boldsymbol{u}}$	nadir vector
$\hat{\boldsymbol{u}}$	tip of the minimal isometric cone
$\tilde{\boldsymbol{u}}$	Nash equilibrium
$\mathbf{U}$	set of all feasible design alternatives
$\mathbf{U}_0$	set of Pareto optimal design alternatives
v	speed in contact during grounding
x	design variables
$\boldsymbol{x}$	design alternative
X	longitudinal direction of the ship
$\boldsymbol{y}$	partial set of design variables x
Y	transversal coordinate of the ship
z	hypothetical design alternatives
Z	vertical coordinate of the ship
λ	*Chebyshev* metrics in the normalized utility space
Λ	the minimal isometric cone of *Chebyshev* metrics
ω	weight for stakeholder importance
$\bar{\varpi}$	weighting for stakeholders for a pair of strategies
$\tilde{\varpi}$	uniform weighting vector in *Chebyshev* metrics

APPENDIX 2

The applicability of NE to MaSSCoR is shown here for a bi-stakeholder problem. Let $\mathbf{G}$ be a non-cooperative game played between two stakeholders, p and q, where each controls some partial set of design variables $\boldsymbol{y} \subset \boldsymbol{x}$, for which is valid

$$\hat{\boldsymbol{x}} = \boldsymbol{y}^p \cup \boldsymbol{y}^q | \boldsymbol{u}(\hat{\boldsymbol{x}}) \in \mathbf{U}_0 \tag{22}$$

where $\mathbf{U}_0$ is a set of Pareto optimal designs. Equation (22) strongly restricts the number of applicable variable values and finding these becomes impractical. Hence, another approach is suggested.

Let λ be a weighted Chebyshev metric of utilities in a normalized utility space in Fig. 12

$$\lambda(u, \omega) = \left\{ \sum_{j=1}^{m} [\omega_j(1 - u_j)]^{\infty} \right\}^{1/\infty} \tag{23}$$

and Λ its minimal isometric cone consisting of hypothetical z and feasible DAs $\boldsymbol{u}$

$$\Lambda(\omega) = \{\arg\min \lambda(u, \omega)\} \cup \{\arg\min \lambda(z, \omega) | \min \lambda(z, \omega) = \min \lambda(u, \omega)\} \tag{24}$$

Let $l(\omega)$ be ... an infinitely long line passing through the ideal point, $\mathbf{1}$, and the weighting point, ω, in a normalized utility space, see Fig. 13. The following equation can then map the entire Pareto front [**32**]

$$\hat{\boldsymbol{u}}(\omega) = \Lambda(\omega) \cap l(\omega) \tag{25}$$

such that for any weighting vector ω, $\hat{\boldsymbol{u}}$ is unique. Since Λ consists of hypothetical alternatives, $\hat{\boldsymbol{u}}$ is not guaranteed to be feasible, hence $\{\hat{\boldsymbol{u}}\} \supset \mathbf{U}_0$. Now, let stakeholders' strategies in game $\mathbf{G}$ be a set of weight vectors $\boldsymbol{s}_q = \{(\omega_p, 1 - \omega_p)^{\mathrm{T}}\}$ and $\boldsymbol{s}_q = \{(1 - \omega_q, \omega_q)^{\mathrm{T}}\}$, where $0 < \omega_p, \omega_q < 1$, and let payoffs to stakeholders be determined with equation (25), where weighting

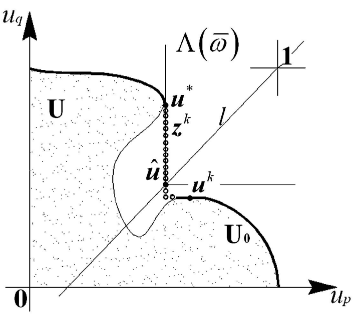

Fig. 12 Normalized utility space

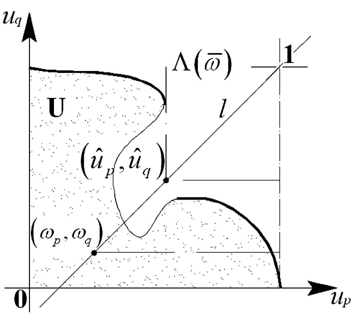

Fig. 13 Similar triangles

in $\hat{\boldsymbol{u}}(\omega)$ is an average of chosen strategies

$$\bar{\boldsymbol{\omega}} = \left[\frac{\omega_p + 1 - \omega_q}{2}, \frac{1 - \omega_p + \omega_q}{2}\right]^{\mathrm{T}}. \tag{26}$$

Theorem 1. *The* NE *of* **G** *is the couple of strategies for which the average weighting vector* $\bar{\omega}$ *is uniform.*

Proof is given with two lemmas.

Lemma 1. $\hat{u}'_j > \hat{u}_j$ *if* $\omega'_j > \omega_j$.

Proof. Suppose line l marking payoffs for arbitrary weighting. From the similarities of triangles in Fig. 13

$$\hat{u}_q = 1 - \frac{(1-\omega_q)(1-\hat{u}_p)}{\omega_q} \tag{27}$$

Payoff $\hat{u}$ is thus a strictly increasing function of a weight factor ω, which concludes the proof. ■

Lemma 2. *Strategy* $s^*_j \equiv \max \omega_j$ *is the only strategy member of a rational reaction set*[3] $\mathbf{S}^*$ *of* **G**.

Proof. Suppose any strategy $s'_j \in \mathbf{S}^* < \max \omega_j$ member of a rational reaction set. The payoff to a stakeholder j for s'_j should be $\hat{u}'_j > \hat{u}^*_j$, which is then contrary to ***Lemma 1***, thus concluding the proof. ■

Following ***Lemma 2***, it is rational to assume that every player in **G** is best off with the strategy $s_j \equiv \omega_j \simeq 1$. Due to equation (25), the weighting in NE is then uniform $\tilde{\omega}$, thus completing the proof of ***Theorem 1***. ■

The NE of **G**, or denoted $\tilde{\boldsymbol{u}} = \hat{\boldsymbol{u}}(\tilde{\omega})$, is always the centre of the uniformly weighted Chebyshev orthant, and accordingly symmetric in normalized payoffs and independent of other alternatives, thus showing the applicability for MaSSCoR.

[3]Rational reaction set is the set of strategies securing highest payoff to a stakeholder for the strategies of another, making it irrational to choose any other strategy.