Publication P4

Alan Klanac and Petri Varsta. 2011. Design of marine structures with improved safety for environment. Reliability Engineering and System Safety, volume 96, number 1, pages 75-90.

Reliability Engineering and System Safety 96 (2011) 75–90

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Design of marine structures with improved safety for environment

Alan Klanac*, Petri Varsta

Marine Technology Group, Department of Applied Mechanics, Helsinki University of Technology, P.O. Box 5300/Tietotie 1C Espoo, 02015TKK, Finland

ARTICLE INFO

Article history:
Received 15 October 2009
Received in revised form
11 June 2010
Accepted 23 June 2010
Available online 1 July 2010

Keywords:
Safety
Risk
Environment
Structure
Multi-stakeholder
Game theory
Design

ABSTRACT

The paper describes a method for design of marine structures with increased safety for environment, considering also the required investment costs as well as the aspects of risk distribution onto the maritime stakeholders. Practically, the paper seeks to answer what is the optimal amount that should be invested into certain safety measure for any given vessel. Due to the uneven distribution of risk, as well as the differing impact of costs emerging from safety improvements, stakeholders experience conflicting ranking of alternatives. To solve this multi-stakeholder decision-making problem, in which each stakeholder is a decision-maker, the method applies concepts of group decision-making theory, namely the Game Theory. The method fosters axiomatic definition of the optimum solution, arguing that the solution, or the final selected design, should satisfy the non-dominance, efficiency, and fairness. These three are thoroughly discussed in terms of structural design, especially the latter. Considering the coupling of environmental risk and structural design, the method also builds on the preference structure of four maritime stakeholders: yards, owners, oil receivers and the public, who either share the risks or directly influence structural design. Method is presented on a practical study of structural design of a tanker with a crashworthy side structure that is capable of reducing the risk of collision. The outcome of this study outlines a number of possibilities for successful improvement of tanker safety that can benefit, concurrently, all maritime stakeholders.

1. Introduction

Maritime safety is arranged nowadays through the set of international conventions, e.g. SOLAS [1], MARPOL [2], etc. agreed between maritime stakeholders, including ship owners and operators, yards, cargo owners or charterers, seamen, the officials, the public. Based on their preferences, and accounting for the acceptance of risk, these conventions set the minimally acceptable levels of safety [3]. In that sense, an approach of ALARP (As Low As Reasonably Practical), fostering a band of cost-effective risk tolerance, has been established as a tool for effective risk management, Refs. [4–6].

Since increasing safety regularly demands investments or added expenses, most of the vessels are in the end designed only to satisfy the minimal safety requirements, and are thus on the boundary of unacceptable risk. The upper levels of ALARP are on the other hand typically not targeted. With desire to challenge such a practice, this paper presents a methodology to determine the best possible compromise between safety improvements and corresponding investments for any given design problem. Hence, outline the optimum level of safety. The methodology is aimed for application in design of marine structures, identifying designs that are economical and that approach the levels of negligible risk.

Existing methodology is not fully capable to treat this problem as desired, especially as the focus of the study is on particular design problem such as that of a ship structural design. Existing methodology predominantly addresses more general 'rule-making' level, or regulations. The gap for the application of existing methodology relates to its incapacity to concurrently consider preferences of multiple stakeholders and be sensitive to the particulars of structural design. There however exist contributions in the literature that form the basis of the proposed methodology. These specifically relate to the criteria of risk acceptance and risk modelling.

Thus, Skjong and Ronold [7], Ditlevsen [8] and Friis-Hansen and Ditlevsen [9] venture to outline firm criteria for the public acceptance of risk based on financial value. The main assumption is that the public or society in general, excluding ship owners that manage risk, is mostly interested in maintaining a positive difference between trade benefits and risks of loss with no specific desire to maximize this difference, i.e. move beyond the minimum acceptable levels of safety.

Wang et al. [10,11] make deeper analyses of trade-offs between safety and related costs with objective to find a solution that maximizes former and minimizes latter for a particular design problem. Alternatively to the above methodology, this approach utilizes concepts of multi-criteria decision-making.

* Corresponding author. Present address: as2con-alveus ltd., J.P. Kamova 19, Rijeka, Croatia. Tel.: +385 51 218 430x222; fax: +385 51 218 270.
E-mail addresses: alan.klanac@as2con.com, alan.klanac@tkk.fi (A. Klanac), petri.varsta@tkk.fi (P. Varsta).

0951-8320/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ress.2010.06.016

However, the approach focuses on the multi-expert evaluation of safety and cost of design alternatives, and not on stakeholders. While the multi-expert evaluation is similar to the elicitation of multi-stakeholder preferences from the decision point of view, it does not consider the actual facts of maritime market and industry in general.

Rosqvist and Tuominnen [12] and French et al. [13] focus on the other hand onto preferences of maritime stakeholders. In their study they argue the necessity to formally treat stakeholder preferences. They also indicate the concept of compensation between stakeholders to allow for the fair distribution of cost and benefits when improving safety. In that sense, Rosqvist [14] outlines a 'compensation' criterion, which, when minimized, identifies an alternative that is the fairest compromise for all stakeholders. The criterion, however, assumes full coupling between stakeholder benefits and costs, meaning that a loss to one stakeholder is another stakeholder's gain. On the industry-level such an assumption is valid, but on the particular design-level the same is difficult to show. For example, the economics of particular ship design, and of her production and exploitation is far too complex to be modelled accurately to realize the effective compensation. Thus, Klanac et al. [15,16], proceed to outline a more relaxed approach, where the fairest design alternative is selected without the need for assumption that differing stakeholder costs and benefits need to be coupled. This is especially useful if we consider that design of marine structures does not involve all maritime stakeholders, but only a few.

The latter approach is further established here. It is applied for the problems involving more than two stakeholders. The approach is considered also in the context of actual market conditions and determination of structural scantlings. It is coupled with the model of risk distribution amongst stakeholders and the model for sharing of costs induced by improvements in safety. In the end, it enables ranking and selection of structural design alternatives according to the stakeholders' preferences.

All these contributions are illustrated by revisiting a practical design study of Klanac et al. [17]. In that study, utilizing optimization, crashworthiness of hull structure of a 40 000 DWT tanker was improved with minimum addition of extra material, resulting with multiple alternatives of structural design that range between low hull crashworthiness with low mass and high crashworthiness with increased mass. Adopting these results, we extend the study and perform selection, outlining the alternative that is the best for a multiple of stakeholders' preferences. The paper is thus split into two parts. The first part describes the theory, its background and our contributions in Sections 2 and 3. The second part describes the implementation of the theory to the practical study in Section 4, and makes the conclusion of the paper in Section 5.

2. Stakeholders and their preferences

2.1. The stakeholders

Cho et al. [18] specify extensive list of maritime stakeholders. These include: the shipowner, the shipyard, the classification society, the flag state and port authorities, the seamen, the cargo senders and receivers, the insurers (P&I clubs) and financiers (e.g. banks, private investors), the public, incl. e.g. fishing and on-shore industry, citizens and particularly coastal communities. This list can be somewhat reduced since some of these stakeholders are not affected by variations in structural design, see Refs. [19,20]. The preferences of financiers, seamen, classification societies, flag states, port authorities and the insurers can be thus omitted from the consideration.

Besides the issue of sensitivity to structural design, international conventions identify a general framework for compensation in cases of marine pollution, effectively defining the distribution of risk. According to these, the liability for pollution damage specifically lies on the shipowner, oil receiver while the public is forced to take on the damage costs beyond the liability of the former two stakeholders. Since the yard is in direct control of structural design, it can be considered as a relevant stakeholder. In the remainder of the paper we thus focus on the preferences of these stakeholders.

2.2. The preferences

Stakeholder preferences are established through the definition of a consequence $C(\boldsymbol{x})$ that an attribute value $y(\boldsymbol{x})$ of some design alternative $\boldsymbol{x}$ inflicts on stakeholders multiplied by the consequence's probability of occurrence. In general, such a value under uncertainty is addressed as utility, and with respect to safety, it is perceived as risk [21]. Beyond safety, as we mentioned, stakeholders face also the costs to produce such an alternative. The preference towards these costs can be also represented with utility.

According to Ref. [22], the utility u of some attribute consequence i for an alternative is defined as

$$u_i(\boldsymbol{x}) = \int_t p_i(t,\boldsymbol{x}) \cdot C_i(t,\boldsymbol{x}) dt, \tag{1}$$

where t is the uncertain, or uncontrollable parameter, C_i the consequence of an attribute i and p_i the probability of its occurrence. Considering for example the problem of ship-to-ship collisions, studied later in this paper, t can represent a 'traffic' parameter, such as the available collision energy, while C can be some part of environmental damage, such as the cost of a clean-up.

To determine the net stakeholder gain of some risk reduction, according to Ref. [23], we are free to subtract the costs induced by this reduction from its benefits. Since both the costs and the benefits can result from multiple consequences, a general additive function applies. The net-gain is effectively a multi-attribute utility function, defined as

$$u_j(\boldsymbol{x}) = \sum_i u_i(\boldsymbol{x}). \tag{2}$$

Once such multi-attribute utility functions are established for every stakeholder j, to select the alternative that concurrently satisfies preferences of a multiple of stakeholders, we need to take all the functions into account. To perform this with the requirements for consistent group decision-making [24,25], a space of stakeholders' utilities $\mathbf{Z}$ is established.

The definition of this multi-stakeholder decision-making problem summarizes Fig. 1. To define stakeholder preferences we need to parameterize the decision problem on three decision spaces. The first two, the design $\mathbf{X}$ and attribute $\mathbf{Y}$ spaces are essential for the definition of preferences (Fig. 1a and b), while the third, the space of stakeholder utilities $\mathbf{Z}$ (Fig. 1c), helps select the 'fairest' alternative.

As seen in Fig. 1c, this space is characterized by *reservation* $\breve{\boldsymbol{u}}$ and *aspiration* point $\check{\boldsymbol{u}}$ and by the set of acceptable alternatives, $\mathbf{U} \subset \mathbf{Z}$. The points respectively mark the minimally acceptable performance levels and levels towards which the design characteristics should be improved. They can be freely determined, e.g. as ideal, utopia and nadir vectors,[1] or simply as arbitrary points in the space of stakeholder utilities according to the

[1] c.f. Ref. [26] for their definition.

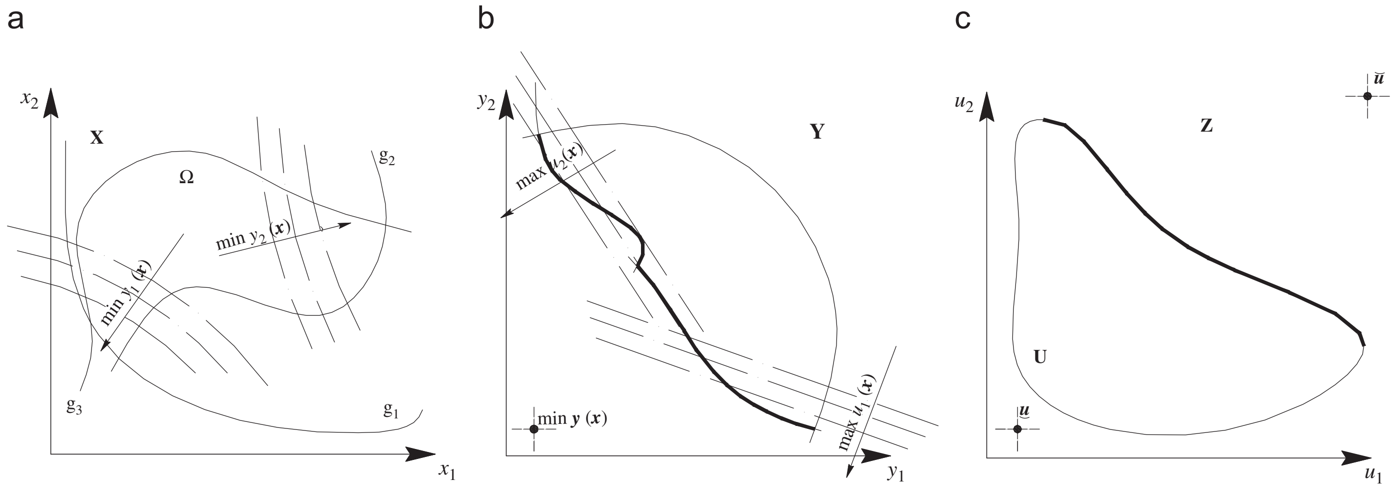

Fig. 1. Parameterization of: (a) design space **X**, (b) attribute space **Y** , (c) utility space **Z**. The dot-dash lines are contours of attributes in the design space (a), and contours of utilities in the attribute space (b).

following:

Definition 1. The reservation point $\underset{\sim}{\boldsymbol{u}} = [u_1(\underset{\sim}{\boldsymbol{x}}),\ldots,u_m(\underset{\sim}{\boldsymbol{x}})]^{\mathrm{T}} \in \Re^m$ in the utility space compounds individual stakeholders' utility thresholds which are to be surpassed.

Definition 2. The aspiration point $\check{\boldsymbol{u}} = [u_1(\check{\boldsymbol{x}}),\ldots,u_m(\check{\boldsymbol{x}})]^{\mathrm{T}} \in \Re^m_+$, $\check{\boldsymbol{u}} > \underset{\sim}{\boldsymbol{u}}$ in the utility space compounds individual stakeholders' utility thresholds which are to be reached.

Definition 3. The set of attainable alternatives $\mathbf{U} = \{\boldsymbol{u}(\boldsymbol{x}) \in \mathbf{Z} | \boldsymbol{x} \in \boldsymbol{\Omega}\}$ contains stakeholder utilities of all feasible alternatives $\boldsymbol{\Omega} = \{\boldsymbol{x} | \mathbf{g}(\boldsymbol{x}) \geq 0\}$.[2]

The reservation and aspiration points are defined in the spirit of reference-based decision-making method [27], and can be called jointly the 'reference points'. Physically, the reservation point could represent a prototype design, while the aspiration point can be taken as the point arising from the perception of the satisfactory attribute maxima amongst stakeholders.

3. Multi-stakeholder decision-making

3.1. The conditions of selection

Klanac et al. in Refs. [15,16] propose three fundamental conditions to be satisfied by a design alternative $\boldsymbol{u}^*$ in order to maximally satisfy stakeholders' preferences.

Condition 1 – *Compromise*: Every normalized design alternative $\boldsymbol{u}$, which is not strictly dominated by others and considers only positive normalized utilities, is deemed to be a compromise between stakeholders. $\boldsymbol{u}^*$ is therefore a compromise…

$$\ldots\text{if } \nexists \boldsymbol{u} \in \mathbf{U} | \underset{\sim}{\boldsymbol{u}} < \boldsymbol{u}^* < \boldsymbol{u}, \tag{3}$$

Condition 2 – *Efficiency*: A design alternatives is efficient if there does not exist any other compromise design which gives higher normalized utility to a stakeholder j for the utilities of other stakeholders $\boldsymbol{u}^*$ is therefore efficient…

$$\ldots\text{if} \nexists \boldsymbol{u} \in \mathbf{U} | u_j^* = u_j, \quad \forall j \in m \backslash i \quad \text{and} \quad u_i^* < u_i, i \in m, \tag{4}$$

Condition 3 – *Maximal stakeholders' satisfaction in the competitive relationships (MaSSCoR)*: If this condition holds for a design alternative k then all stakeholders receive at least such utility that if the problem would be symmetric their utilities would be equal. $\boldsymbol{u}^*$ therefore satisfies MaSSCoR…[3]

$$\ldots\text{if } \boldsymbol{u}^* \geq \{\tilde{\boldsymbol{u}} | \tilde{u}_1 = \cdots = \tilde{u}_m \text{ when } \forall \boldsymbol{u} \in \mathbf{U}, \mathbb{P}(\boldsymbol{u}) \in \mathbf{U}\}. \tag{5}$$

The first two conditions relate to the notion of non-dominance, which can be formally described through a well-known economical concept of Pareto optimality. The third condition, MaSSCoR, determines the fairest solution with respect to the specified preferences of stakeholders, following the general recommendation of FSA [28] that stakeholders are to be treated fairly. It is also based on the assumption that stakeholders are in the competitive relationship since their preferences differ. In such relations, stakeholders are not willing to renounce any of their benefits as they try to maximize them independently [29].

As defined in Eq. (5), MaSSCoR[4] is effectively an extension of the basic decision-making axiom of 'anonymity' [30], which can be colloquially described with the following: *"If some wealth of benefits can be shared equally amongst stakeholders then it should be shared equally if these stakeholders are equal"*. To explain MaSSCoR formally, we present the following derivation.

3.2. MaSSCoR

Let us define a non-cooperative 'mathematical' game in normal form **G**, and let us solve it for its standard solution, the Nash equilibrium [31]. Let **G** contain stakeholder utilities of all Pareto optimal design alternatives in the attainable set of alternatives, **U**.

To construct this game, let λ be a weighted *Chebyshev* metrics

$$\lambda(\boldsymbol{u},\boldsymbol{\omega}) = \left\{ \sum_{j=1}^{m} [\omega_j (1-u_j)]^\infty \right\}^{1/\infty}, \quad \omega_j > 0, \quad \sum_j \omega_j = 1 \tag{6}$$

and $\boldsymbol{\Lambda}$ its minimal isometric cone consisting now of some hypothetical $\boldsymbol{z}$ and feasible DAs, $\boldsymbol{u}$, see Fig. 2

$$\boldsymbol{\Lambda}(\boldsymbol{\omega}) = \left\{ \underset{\mathbf{x} \in \boldsymbol{\Omega}}{\operatorname{argmin}} \lambda(\boldsymbol{u},\boldsymbol{\omega}) \right\} \cup \left\{ \underset{x \in \mathbf{Z}}{\operatorname{argmin}} \lambda(\boldsymbol{u},\boldsymbol{\omega}) \middle| \min \lambda(\mathbf{z},\boldsymbol{\omega}) = \min \lambda(\boldsymbol{u},\boldsymbol{\omega}) \right\}. \tag{7}$$

[2] $\mathbf{g}(\boldsymbol{x}) \geq 0$ marks the feasible vector of constraint value on a design alternative $\boldsymbol{x}$.

[3] $\mathbb{P}(\boldsymbol{u})$ marks the set of all permutations on a stakeholders' utility vector.

[4] MaSSCoR has been validated for the 'two-stakeholder' problem in Klanac et al. (2007). Here, it is extended to a general case of three and more stakeholders.

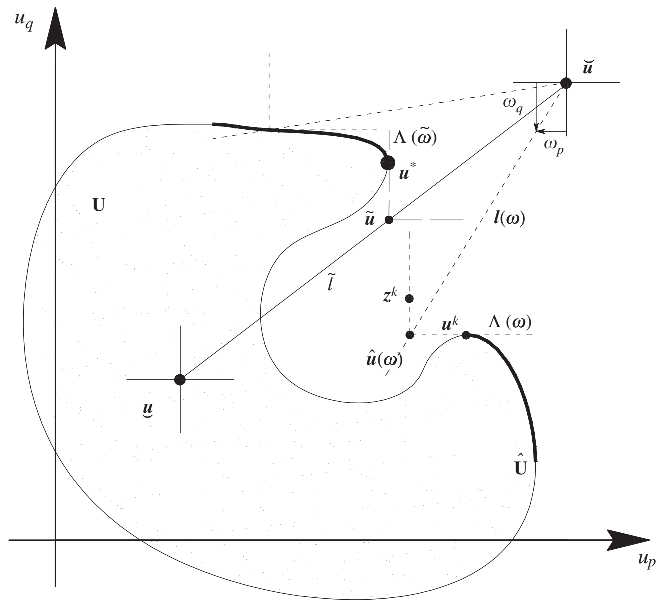

Fig. 2. Arbitrary stakeholder (p and q) utility space with distinguished points for decision-making.

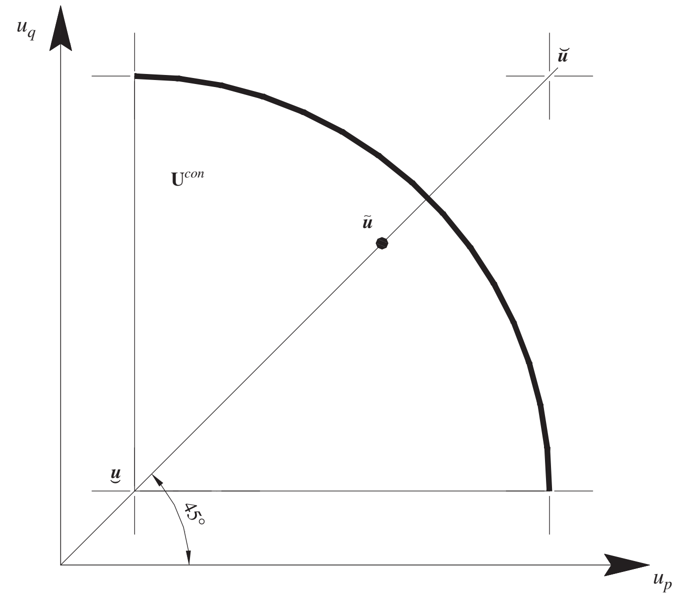

Fig. 3. Convex and symmetrical decision-making problem $\mathbf{U}^{con}$.

where weights $\boldsymbol{\omega}$ define the relative importance of stakeholders' preferences. Let $l(\boldsymbol{\omega})$ be an infinitely long line passing through the aspiration point $\breve{\boldsymbol{u}}$ and in the direction of the weighting vector $\boldsymbol{\omega}$. By varying this vector, the apex $\hat{\boldsymbol{u}}$, or the intersection of the cone $\boldsymbol{\Lambda}$ with the line l

$$\hat{\boldsymbol{u}}(\boldsymbol{\omega}) = \boldsymbol{\Lambda}(\boldsymbol{\omega}) \cap l(\boldsymbol{\omega}), \tag{8}$$

maps the entire Pareto front $\hat{\mathbf{U}}$ [32]. Furthermore, for any weighting vector $\boldsymbol{\omega}$, the apex $\hat{\boldsymbol{u}}$ is unique, i.e. it will identify only one design alternative. This is convenient since now every Pareto optimal alternative can be a member of the game **G**, meaning that it is eligible for selection. However, since $\boldsymbol{\Lambda}$ consists of hypothetical alternatives, and **U** can be non-convex, as is the case in Fig. 2, the apex $\hat{\boldsymbol{u}}$ might identify an unattainable alternative that does not belong to the set **U**.

Now, let every stakeholder j's available set of strategies in game **G** be a closed set $S_j = \{\mathbf{s}_j\}$ of some arbitrary i weight vectors $\mathbf{s}_j^{i_j} = \left(\boldsymbol{\omega}_1^{i_j}, \boldsymbol{\omega}_2^{i_j}, \ldots, \boldsymbol{\omega}_j^{i_j}, \ldots, \boldsymbol{\omega}_m^{i_j}\right)^{\mathrm{T}}$, and let stakeholders' utilities for the mixture of strategies $\mathbf{s}_1^{i_1} \times \cdots \times \mathbf{s}_j^{i_j} \times \cdots \times \mathbf{s}_m^{i_m}$ be determined with Eq. (8), such that the weighting $\boldsymbol{\omega} = \overline{\boldsymbol{\varpi}}$ of $\hat{\boldsymbol{u}}(\boldsymbol{\omega})$ is an average of weights ω_j^i,

$$\overline{\boldsymbol{\varpi}} = \left[\sum_j \frac{\boldsymbol{\omega}_1^{i_j}}{m}, \ldots, \sum_j \frac{\boldsymbol{\omega}_j^{i_j}}{m}, \ldots, \sum_j \frac{\boldsymbol{\omega}_m^{i_j}}{m}\right]^{\mathrm{T}}, \quad \forall j \in m. \tag{9}$$

The game **G** now permits the selection of any Pareto optimal design alternative with respect to the considered strength of stakeholder preferences addressed through the weighting factors. Nash Equilibrium, defined generally as

$$\tilde{u}_j(\mathbf{s}_1^* \times \cdots \times \mathbf{s}_j^* \times \cdots \times \mathbf{s}_m^*) = \max_{i_j} u_j(\mathbf{s}_1^* \times \cdots \times \mathbf{s}_j^{i_j} \times \cdots \times \mathbf{s}_m^*),$$
$$\forall j \in [1,m], \tag{10}$$

is the alternative with the maximum stakeholder j's utility for the best strategies of other stakeholders that yield them the maximum of their utilities. It is obviously concurrently maximally satisfying all stakeholder preferences, and as a solution of **G**, it is lying on the line connecting the reference points $\tilde{l} = l(\tilde{\boldsymbol{\omega}})$.[5] Analogically, the Nash equilibrium of **G**, denoted ahead as $\tilde{\boldsymbol{u}} = \hat{\boldsymbol{u}}(\tilde{\boldsymbol{\omega}})$, is always the alternative on the apex of the minimal weighted isometric *Chebyshev* cone, where the weighting factors can be determined with the following equation:

$$\tilde{\boldsymbol{\omega}}_j = \left\| \frac{\tilde{\boldsymbol{u}}_j - \underset{\sim}{\boldsymbol{u}}_j}{\breve{\boldsymbol{u}}_j - \underset{\sim}{\boldsymbol{u}}_j} \right\|, \quad \forall j \in m. \tag{11}$$

The $\|\cdot\|$ denotes normalization of the components since $\tilde{\boldsymbol{\omega}}$ is a unit vector.

In case that **U** is a convex symmetrical set as U^{con} in Fig. 3, Nash equilibrium of the game **G** will be symmetric. This means that the solution of **G** will always yield equal utilities to the stakeholders whenever it is possible to do so, thus clearly satisfying the axiom of anonymity, i.e. that it will maximally satisfy stakeholders in the competitive relationships.

3.3. The competitive optimum

Nash equilibrium of the game **G**, $\tilde{\boldsymbol{u}}$, according to the definition, besides MaSSCoR, satisfies also the first two fundamental conditions. Therefore, it gives a rational solution of the multi-stakeholder decision-making problem.

Realistic design selection problems involve certainly a finite number of alternatives to choose from. And even though such a discrete problem can be tackled well with the proposed game **G**, its Nash equilibrium, as we mentioned, can yield an unattainable solution. This means that there is no acceptable alternative on the line $\tilde{l}$ connecting the reference points. But, this also does not mean that there is no other alternative that satisfies the three conditions for selection. A strong Pareto optimal alternative closest to the aspiration point according to the augmented uniformly weighted Chebyshev metric $\lambda_a(\boldsymbol{u}, \tilde{\boldsymbol{\omega}})$ is such an alternative. This alternative is positively displaced from line $\tilde{l}$ for the same 'Chebyshev' metrics to the aspiration point for at least one stakeholder, while others do not accrue losses. Thus, it is better or equivalent to the alternative with the same Chebyshev metrics,

[5] Proof of this statement is given in the Appendix 1.

positioned on the line $\tilde{l}$. As addressed in Refs. [15,16], such a solution is named the *competitive optimum* (CO), and it can be mathematically defined with the following expression:

$$\boldsymbol{u}^* = \arg\left[\min_{\mathbf{x}\in\boldsymbol{\Omega}} \lambda_a(\boldsymbol{u},\tilde{\boldsymbol{\omega}}) \,|\, \lambda_a(\boldsymbol{u},\tilde{\boldsymbol{\omega}}) = \left\{\sum_{j=1}^{m} [\tilde{\boldsymbol{\omega}}_j(\check{u}_j - u_j)]^{\infty}\right\}^{1/\infty} + \rho_a \sum_{j=1}^{m} [\tilde{\boldsymbol{\omega}}_j(\check{u} - u_j)]\right] \tag{12}$$

where ρ_a is an arbitrary small constant, assuring that only a strong Pareto optimum has the minimal metrics. Competitive optimum is therefore a strongly Pareto optimal member of the minimal contour of the weighted Chebyshev metrics; see Fig. 2.

4. Case study: structural design of a crashworthy tanker

The case study aims to identify the crashworthy design of a hull structure of a 40 000 DWT tanker that maximally simultaneously satisfies stakeholder preferences. The considered case study is synthesized schematically in Fig. 4, where from a pool of design alternatives, with differing attributes, consequences are determined for the four shortlisted stakeholders mentioned in the beginning of the paper, i.e. the shipyard, shipowner, oil receiver and public. Consequences relate to risk reduction, i.e. safety benefits, and to commercial losses or the safety-induced costs, influencing in the end the preferences of the four stakeholders towards each of the considered alternatives as depicted in the figure. The linkages seen in Fig. 4 between the attributes, consequences and stakeholder are explained in the following sections.

4.1. The design alternatives

The observed tanker is 180 m long, with 32.2 m in breadth and 11.5 m of design draught. She has a typical product/chemical tanker internal subdivision, with the two longitudinal cofferdams, and a double hull. The main frame is seen in Fig. 5. Klanac et al. [17] performed the multi-objective optimization of the hull structure of this vessel with respect to three objectives: (i) to maximize crashworthiness, i.e. the capacity to absorb energy prior to the breach of the inner hull, E_{breach}, (ii) to minimize the overall hull mass, m_{HULL} and (iii) to minimize the mass of tank stainless steel plating, brand-named 'Duplex', m_{DUPLEX}. The three objectives are considered now as attributes within the context of safety (crashworthiness) and safety-induced costs (hull and duplex steel mass).

The optimization yielded 25 relevant design alternatives for this case study. Their values are given in Fig. 6. They span the three attributes in the range of 85 MJ for crashworthiness – from 5 to 90 MJ, 1600 t for the hull mass – from 7400 to 9000 t, and 130 t for the mass of stainless steel – from 2520 to 2650 t. The least crashworthy alternative is also the lightest alternative, while opposite is valid as well. The 25 alternatives in the attribute space depicts Fig. 7.

The alternatives are distinguished by the thickening of the side shell plating in the area assumed to be the most critical for ship collisions, amid the vessel's height, i.e. 7.5 m above the keel line. Raising thickness in the centre side shell is not decoupled from the surrounding structure due to the limitations in hull strength to normal service loads, namely the shear stresses. This increase in plating therefore needs to be balanced by the variations in surrounding strakes, which results in significant changes in all three attributes. A noticeable gap, caused by this effect, is thus

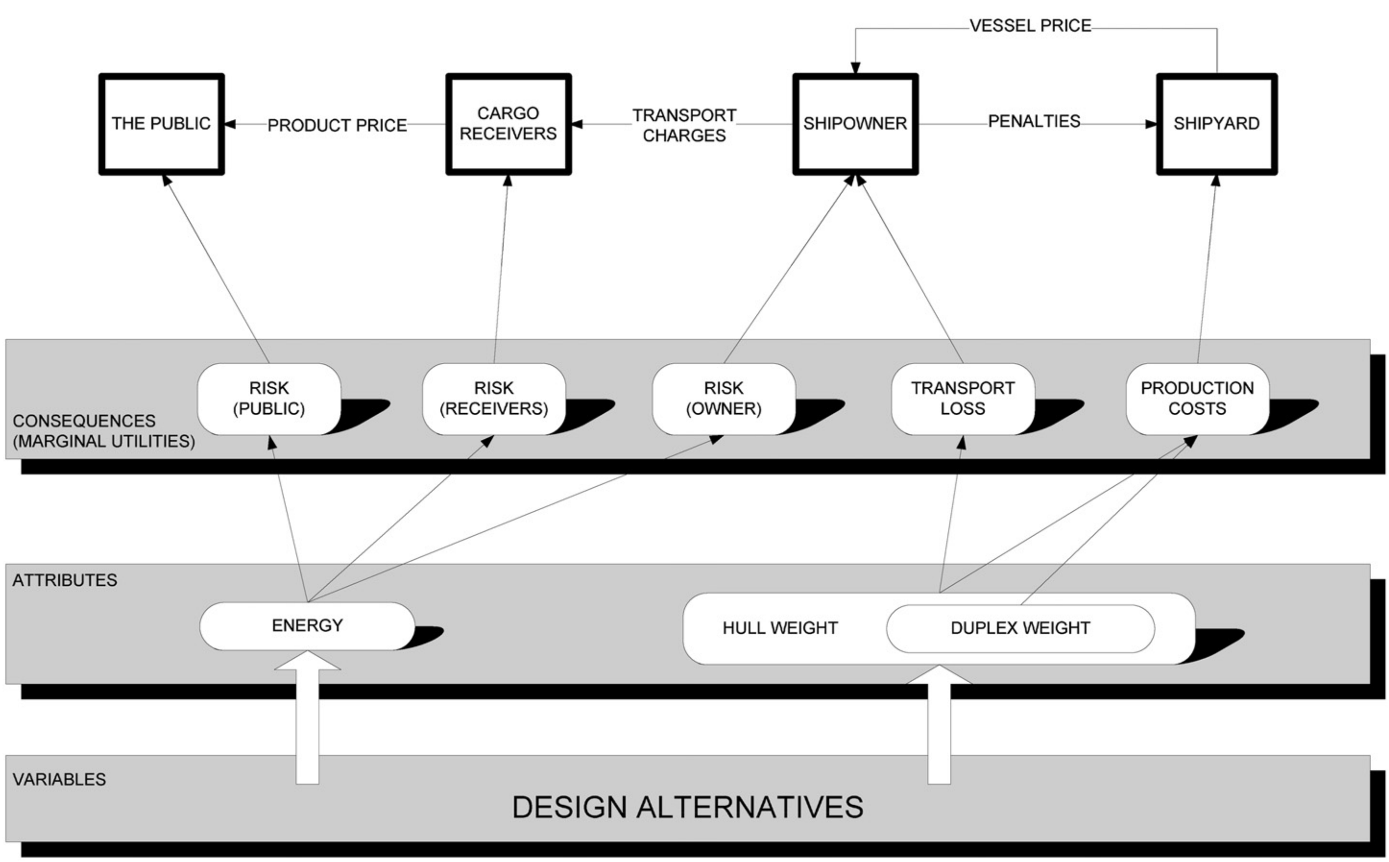

Fig. 4. The hierarchical structure of the case study decision-making problem.

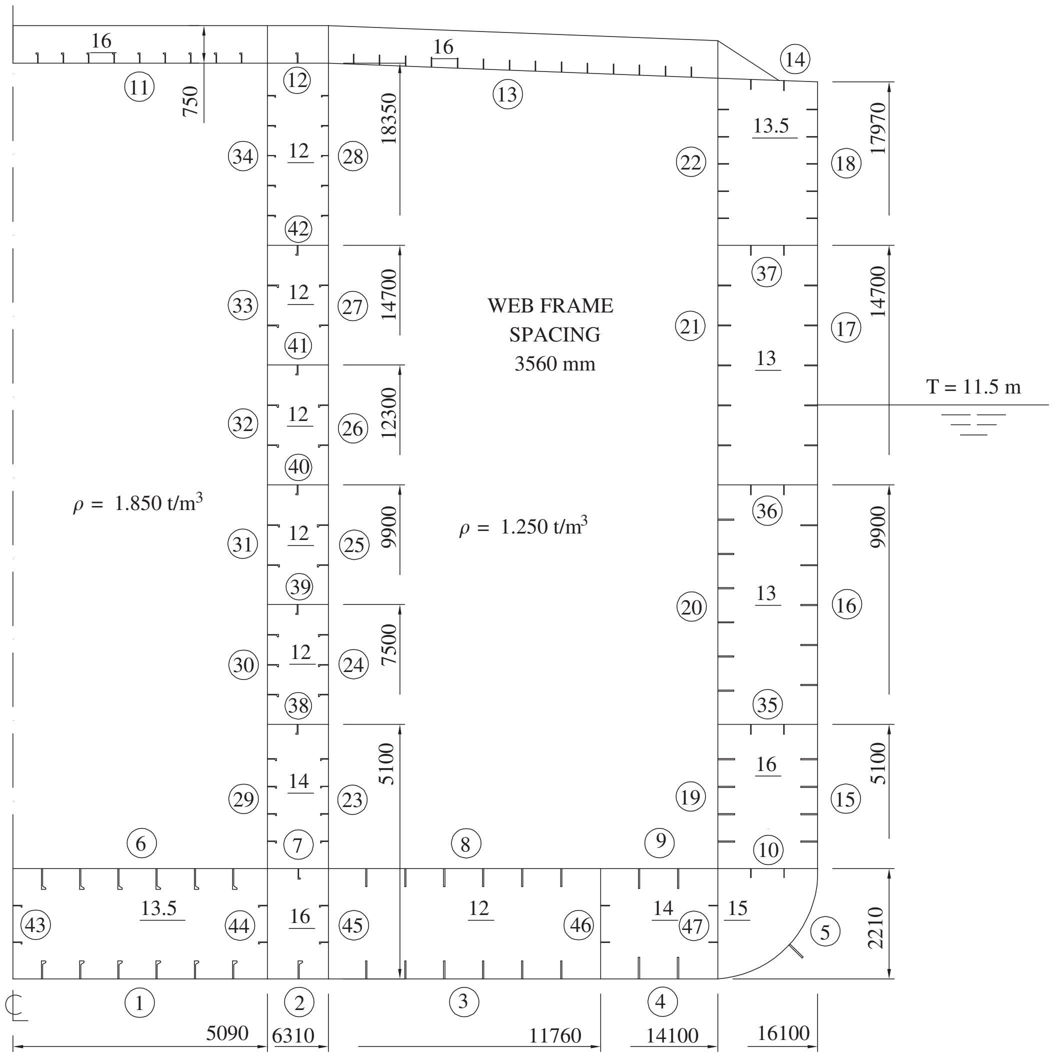

Fig. 5. Main frame section of a considered tanker with dimension in mm, indicated strake numbers (in circles) and scantlings of the transverse structures (underlined).

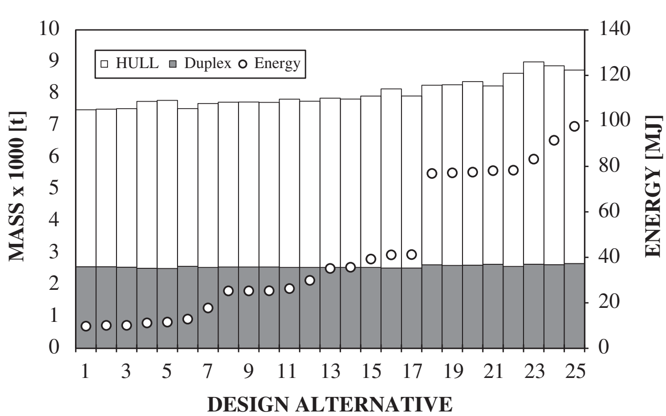

Fig. 6. Design alternatives and their attribute values.

visible in the Pareto frontier. The gap influences strongly on design selection as it causes a large, step-wise trade-off. We are for this reason facing effectively a choice to either make a limited investment into safety and reduce risk accordingly, or to make a considerable investment and significantly reduce risk. Options in-between are more-or-less infeasible.

4.2. The safety of design alternatives

To define safety of design alternatives we analyse their collision risk. In order for the analysis to be sensitive to the changes in structural design, we consider the following three aspects: (a) the analysis of the available deformation energy, (b) the analysis of crashworthiness of the struck ship design and (c) the analysis of collision consequences.

4.2.1. The available deformation energy

Based on the momentum conservation model for ship-to-ship collisions of Minorsky [33], Zhang [34] and Luetzen [35] determined the annual available deformation energy for the world traffic. In Ref. [36] it is shown that the annual probability distribution of the deformation energy can be well represented with *Gamma* distribution. Utilizing these results, the annual deformation energy for the observed vessel is determined accordingly with the mean of 60 MJ and standard deviation of 170 MJ.

4.2.2. The crashworthiness

A critical event in the analysis of collision consequences is the breach of inner hull. Here it is assumed to occur if the available

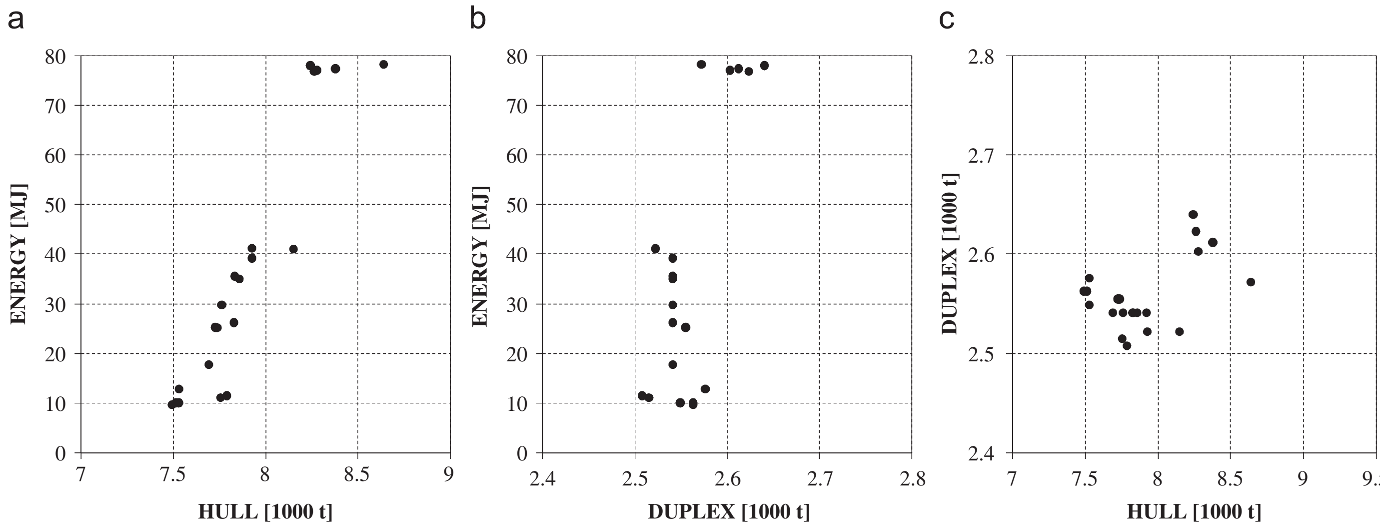

Fig. 7. Pareto optimal alternatives in the attribute space Y.

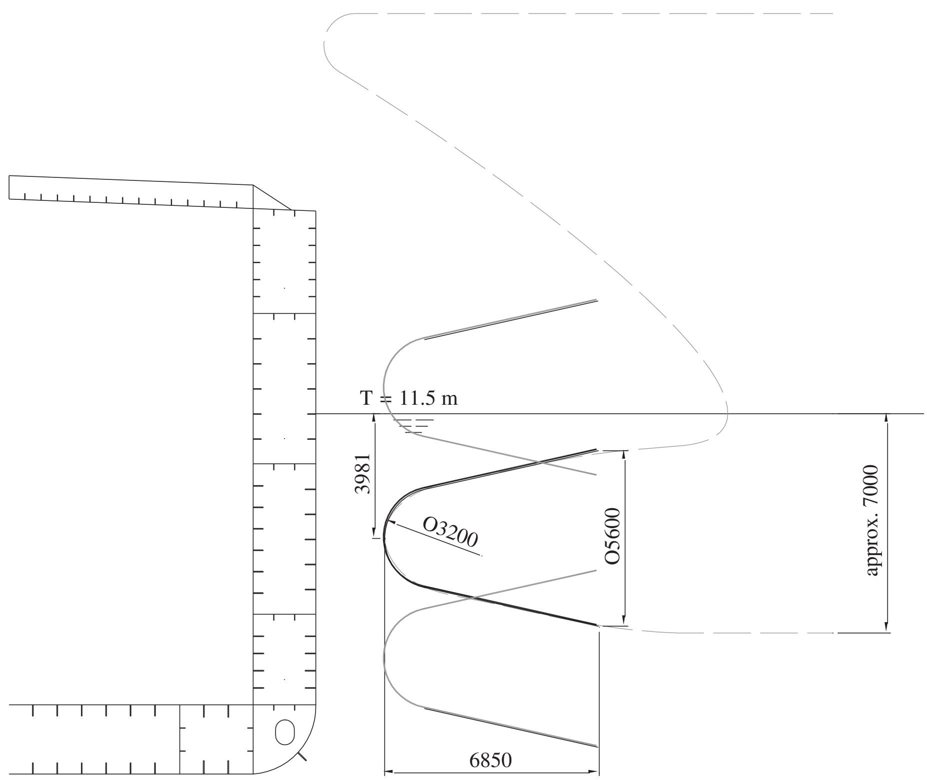

Fig. 8. Collision scenario (in actual scale) with indicated rigid bulb shape (bolded lines) used in FEM simulations and its accurate dimensions.

deformation energy in a collision E_{def} is higher than the capacity of the hull to absorb this energy E_{breach}. Numerical collision simulations for the observed vessel, reported in Ref. [17], had been conducted to establish this capacity. Simulations utilized LS-DYNA [37], a non-linear 'Finite Element Method' solver, and considered displacement controlled collisions between a rigid bulb and the tanker structure at the 90° angle amid two transverse bulkheads and between two web-frames. Following the recommendations for approval of crashworthy structures of Zhang et al. [38], as well as the results of several collision studies of similar ships, e.g. Refs. [39–41], the chosen collision scenario is a conservative estimate. Since the capacity of a hull to absorb collision energy depends significantly on the location of the initial contact, the capacity has been determined for a three characteristic contact zones always amid two stringers: (a) at the waterline, (b) at 4 m and (c) 7.85 m below the design waterline, as seen in Fig. 8.

Traffic statistics for the Baltic West [42] estimate that the tankers spend 40% of their voyages in the full ballast condition. Due to a lack of clear world-wide statistics, we adopt this number in this case study. Furthermore, we assume that in the remaining 60%, the observed tanker will, be at her full draught, i.e. fully laden. For this reason, and remembering the recommendations of Ref. [38], the distribution of location of the initial contact is considered to be uniform between the keel and waterline. If we assume then that the computed capacities to absorb energy for the three considered striking locations represent the capacities in

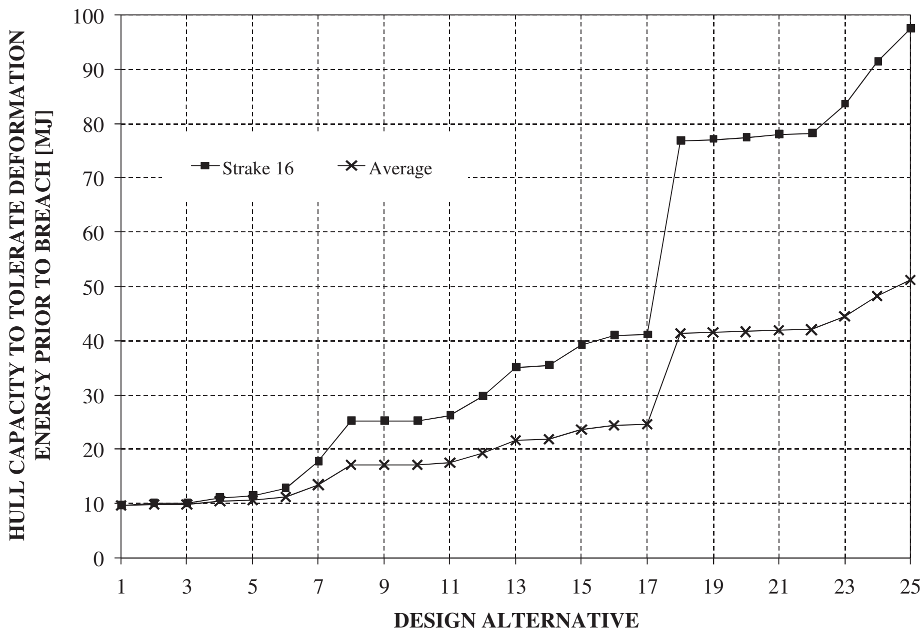

Fig. 9. The hull capacities to absorb collision energy prior to breach of inner hull.

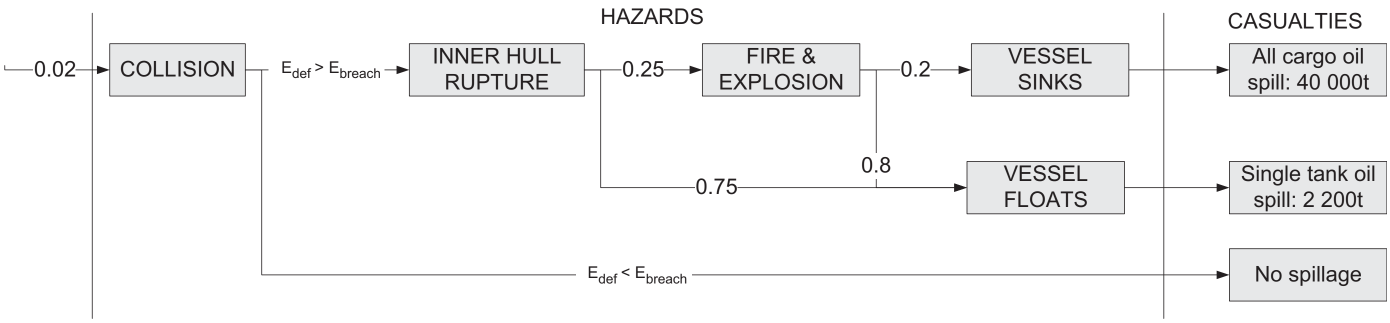

Fig. 10. Collision event tree.

the local areas along the height of the vessel, we can average the overall hull capacity to absorb collision energy prior to the breaching of its inner shell. The averaged values are given in Fig. 9, and are applied in the coming considerations.

4.2.3. *The collision consequences*

To evaluate the consequences of a collision, five hazards can be generally considered: (i) hull damage, (ii) inner hull breach, (iii) fire and explosion, (iv) loss of stability and (v) sinking. These hazards cause three types of serious casualties: (i) environmental damage, (ii) material damage and (iii) loss of life. In case of a tanker in collision, we are safe to assume that the most relevant casualty for all the maritime stakeholders is the environmental damage. Serious material loss for tankers usually leads to a spillage, which initiates environmental loss of a much higher magnitude, and for this reason material loss becomes less relevant. Loss of life on the other hand is never irrelevant, but it is rare and sporadic in case of tanker collisions; see data in Refs. [43–45]. It is usually triggered by fire and/or explosion. According to the same data, the evaluation of the risk of loss of life due to collision is unlikely to yield a confident conclusion. Furthermore, the loss of life is coupled with the environmental damage. Therefore, it has been decided not to consider the loss life in this study. The loss of stability due to flooding of the breached tank can also be assumed not to occur since the observed vessel satisfies the stability requirements of SOLAS [1], for a maximum presumed level of damage, i.e. that the cofferdams remain intact. Fig. 10 illustrates these considerations on hazards through an event tree. The probabilities presented are assumed according to Refs. [43–50].

Friis-Hansen and Ditlevsen [9] established a model to assess the environmental damage, i.e. the costs of oil spillage. Based on the data of recorded major spills [51], and on profiling of the risk at sea, a normal probability distribution of environmental damage costs c is defined depending on the expected volume of an oil spill μ. Using this model, the expected costs of the environmental damage can be determined for the two casualties: (i) a spillage of one tank of $\mu=2\,200$ t and a spillage of the whole cargo of $\mu=40\,000$ t. Probability distributions for the two casualties are presented in Fig. 11.

4.2.4. *Distribution of the risk*

Shipowner, oil receiver and local community share the costs of environmental damage. Under the international compensation conventions, *Civil Liability Convention 1992* (CLC92) and *International Oil Pollution Compensation Fund 1992* (IOPC92) [51], adopted by most of the maritime countries, the maximum compensations to be paid are limited for the shipowner, based on the vessel size,

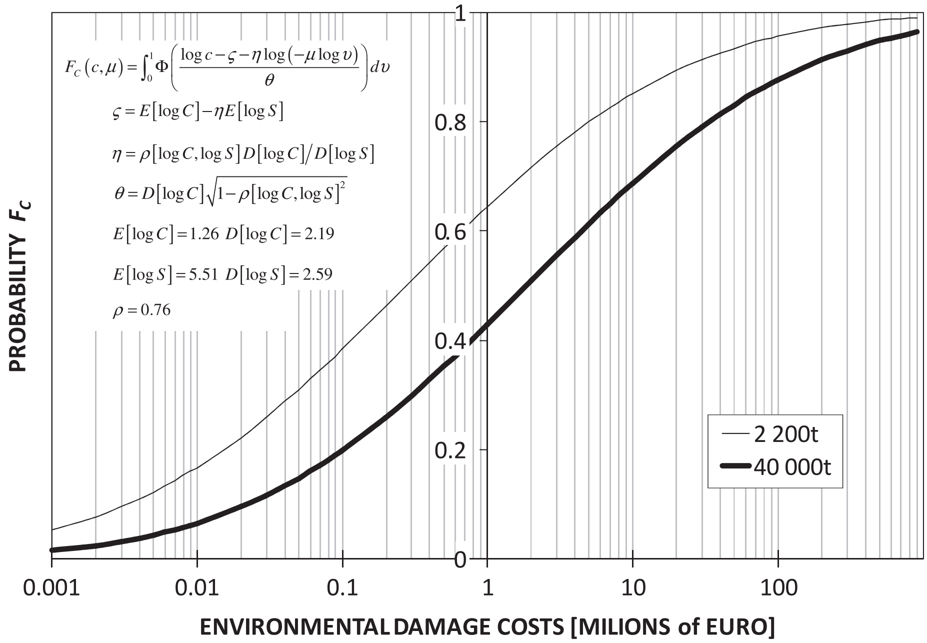

Fig. 11. Probability distribution of the environmental damage costs for single tank spillage (2 200 t) and for the spillage of the overall cargo (40 000 t); provided equations of Ref. [9] are used to calculate the probability distributions.

and for the oil receiver through the liability of the IOPC Fund, which they support. For the handy-max vessel of 40 000 DWT, or approx. 12 000 GT, such as the one we observe in the example study, the owner, through its insurer – a P&I club – is not entitled to pay more than 9 M€ according to CLC92. The IOPC92 fund, funded by the oil receivers, covers the remaining costs of up to 800 M€.[6] In case that the damages are higher than this limit, the remaining costs are covered by the local government obviously through the taxations. Combining now this information on limits of liability with the distribution of costs as specified in Ref. [9] and shown in Fig. 11, the expected cost for a collision involving a spillage can be determined for each of the three stakeholders, and for the two casualties. Table 1 presents the expected costs for the two casualties. Observing these expected costs and their certainty, it is easy to conclude that the owner and oil receivers are facing drastically smaller risks than the public, which evidently not only matches, but also justifies the persistent fear of spillage accidents in the public.

Annual environmental risk is computed finally for each design alternative and for each stakeholder facing this risk by integrating over the random variable of available deformation energy all collision consequences, and by multiplying this integral with the probability for collisions taken to be $p_{Coll}=0.02$ according to Ref. [35] and for a chance that tanker is fully laden $p_{laden}=0.6$. According to Eq. (1), the risk for each stakeholder is expressed as

$$u_{risk,j}=p_{Coll}\,p_{laden}\int_{E_{def}}\sum_i p_i(E_{def})C_{i,j}(E_{def})\,dE_{def}, \tag{13}$$

where the probabilities and consequences in the summation part of Eq. (13) can be specified according to the event tree. Thus:

$$\sum_i p_i(E_{def})C_{i,j}(E_{def}) = \begin{cases} 0, & \text{if } E_{def}<E_{breach} \\ p_{fire}\left[p_{loss}C_{total,j}+(1-p_{loss})C_{tank,j}\right]+(1-p_{fire})C_{tank,j}, & \text{if } E_{def}\ge E_{breach} \end{cases} \tag{14}$$

Table 1
The expected costs of environmental damage.

Stakeholder[a]	Expected costs in M€ of environmental damage for a collision involving a spillage the size of	
	One tank (2200 t)	All cargo (40 000 t)
Owner	1	1
Oil receivers	12	31
The public	70	550

[a] It is assumed that the Yard does not take part in costs distribution of environmental damage.

Alternatively to this financial risk $u_{risk,j}$, Eq. (14) can be applied to estimate the risk in terms of annual spilled volume u_{risk}^{volume}. The expected values for the cost of damage C are in that case simply exchanged for the expected size of an oil spill μ, disregarding obviously the stakeholder aspect. The obtained environmental risks are presented in Fig. 12.

4.3. The safety-induced costs

As depicted in Fig. 6, raising crashworthiness of the observed vessel inevitably increases the hull mass, which incites: (a) the added vessel's production costs due to the larger intake of material, and (b) the loss in transport efficiency due to the reduced cargo capacity.[7]

The following simplified model is assumed for the added production costs. The costs P are normalized relative to the lightest, non-crashworthy alternative, DA-1, which is assumed to represent a present-day standard design. To be consistent with the adopted evaluation of risk per annum, the production costs

[6] This compensation limit relates to the *Supplementary fund* option that has been, for the moment ratified in a limited number of countries only [51].

[7] In that case, main dimensions of the ship could be changed to accommodate for the loss, but this also opens other question and it is not always viable.

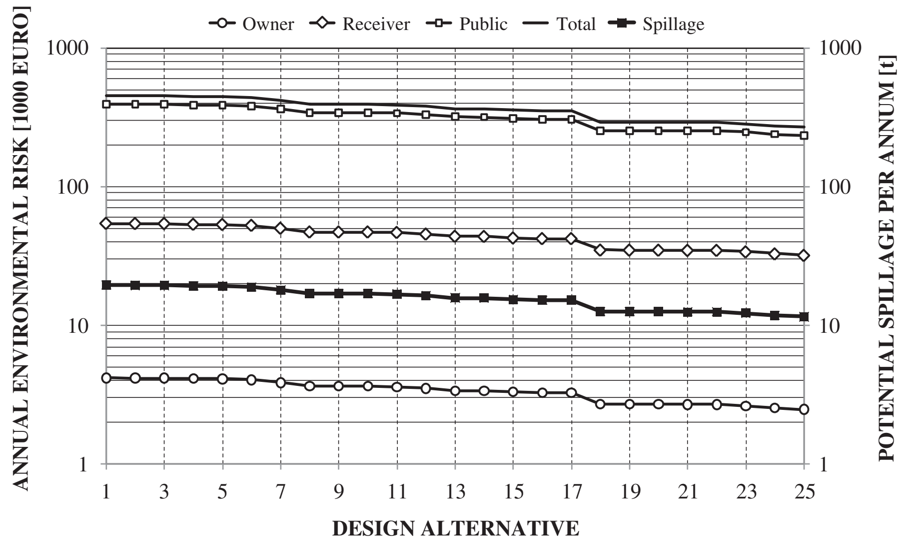

Fig. 12. Risk per annum of environmental damage in EUR and in spilled volume in tones (design alternatives sorted according to the rising crashworthiness).

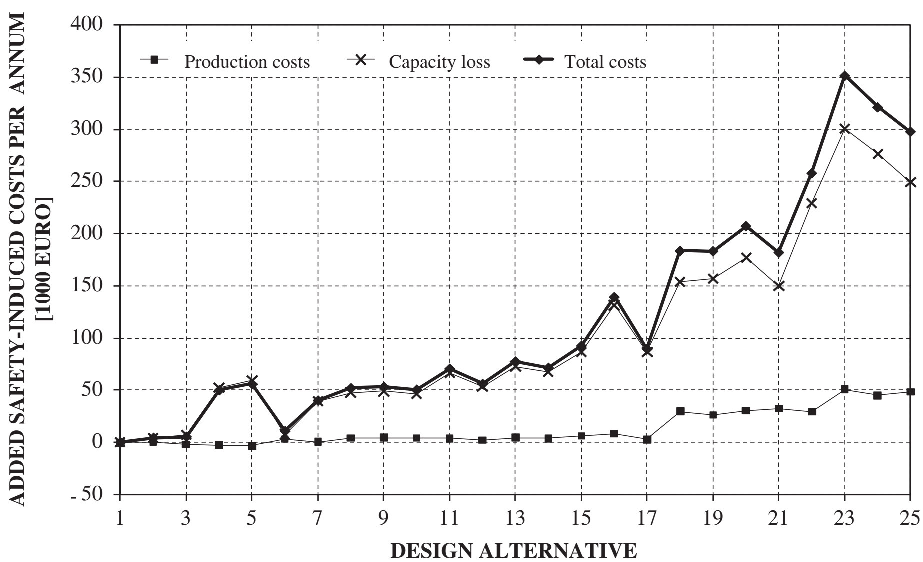

Fig. 13. The added safety-induced costs in comparison to the lightest and least crashworthy alternative DA-1.

are divided by the number of expected years of a vessel to be in service, *YIS*. Thus,

$$\Delta P_{prod} = \frac{c_{HTS}\Delta m_{HTS} + c_{Duplex}\Delta m_{Duplex}}{YIS}, \tag{15}$$

where, respectively, the production costs of ton of high tensile and of duplex steel are assumed to be $c_{HTS}=1200$ €/t and $c_{Duplex}=10\,500$ €/t, including both labour and material costs. Δm_{HTS} and Δm_{Duplex} are changes in masses of high tensile steel and duplex relative to the DA-1. *YIS* is taken to be 25 years.

Assuming the average daily charter rate of €20 000 per day, the loss of one ton of cargo capacity is taken as $c_{cargo}=200$ € annually. The annual cost of the capacity loss ΔP_{cargo} is given as

$$\Delta P_{cargo} = c_{cargo}\,\Delta m_{HULL}, \tag{16}$$

where Δm_{HULL} indicates the difference in total hull mass ($\Delta m_{HULL}=\Delta m_{HTS}+\Delta m_{Duplex}$) to the lightest alternatives DA-1. The computed added production cost and capacity loss are given in Fig. 13.

4.4. Distribution of the safety-induced costs

It can be expected that the additional safety-induced costs would be compensated amongst the stakeholders. For example, the added production costs are charged to the owner as the added ship price. Loss in the cargo capacity is on the other hand compensated through the penalties towards the yard and/or through the added freight rate to the oil receiver. Finally, the oil receiver raises the price of its products to the public. The amount that these compensations apply, or that stakeholder accepted them, is obviously uncertain. Precisely, they are a matter of

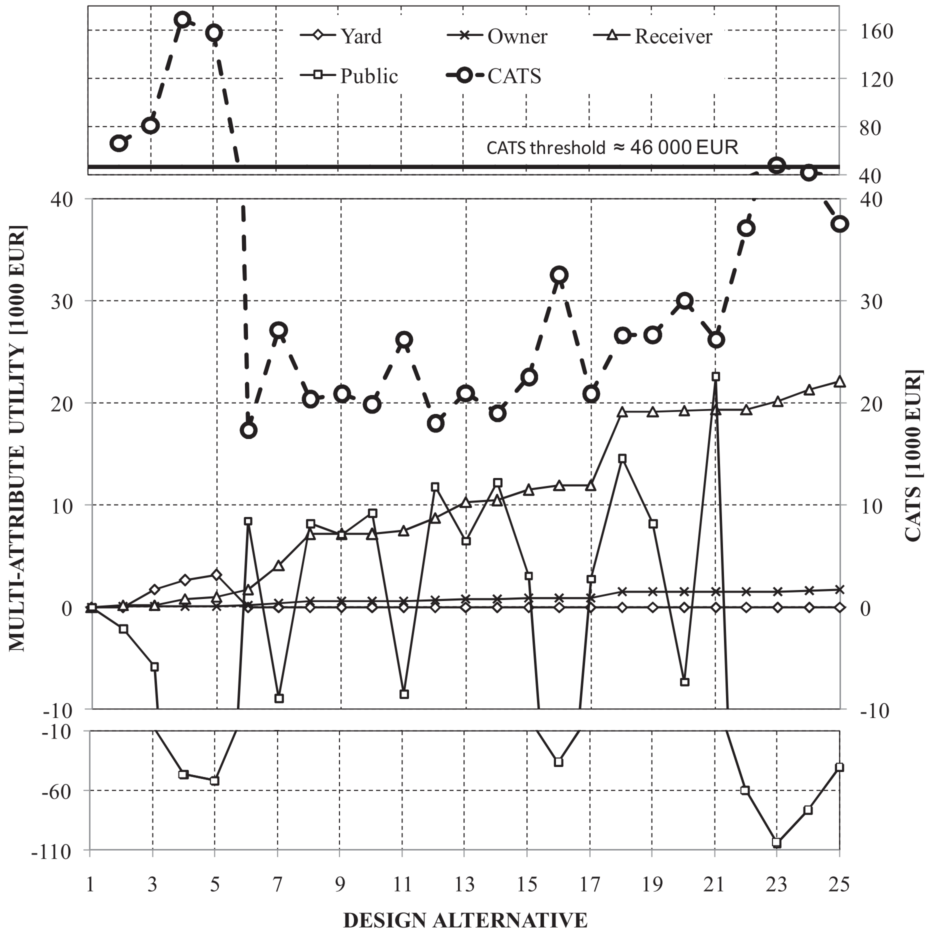

Fig. 14. Stakeholder multi-attribute utility values.

negotiations and market conditions. A general model can be nevertheless established, and the utilities of the safety-induced costs are for

(a) the yard as

$$\Delta u_{costs,yard} = p_{costs,yard}(\Delta P_{cargo} - \Delta P_{prod}) \tag{17}$$

(b) the owner as

$$\Delta u_{costs,owner} = p_{costs,owner}(1 - p_{costs,yard})(\Delta P_{cargo} - \Delta P_{prod}) \tag{18}$$

(c) the oil receivers as

$$\Delta u_{costs,receivers} = p_{costs,receivers}(1 - p_{costs,owner})(1 - p_{costs,yard}) \times (\Delta P_{cargo} - \Delta P_{prod}) \tag{19}$$

(d) the public

$$\Delta u_{costs,public} = p_{costs,public}(1 - p_{costs,receivers})(1 - p_{costs,owner}) \times (1 - p_{costs,yard})(\Delta P_{cargo} - \Delta P_{prod}) \tag{20}$$

where the utility of the stakeholder '$k+1$' is dependent on the costs ($\Delta P_{cargo} - \Delta P_{prod}$) that have not been accepted by the stakeholder 'k' and on the probability that these costs will be accepted. A special notation for the utility 'Δu' is applied since we consider relative values of costs.

Comparing the values in Figs. 12 and 13 we can conclude that for all stakeholders but public benefits of risk reduction are smaller than the induced costs. Obviously in this case it is hard to justify any acceptance of the added costs. If we suppose then that $p_{costs,yard}=0$, $p_{costs,owner}=0$, $p_{costs,receivers}=0$, $p_{costs,public}=1$, and that the probabilities of acceptance remain constant independent of the amount of the costs involved, we attain that the utility of the safety-induced costs for all the stakeholders but the public equal zero.

4.5. Design selection, verification and implications

Adopting the multi-attribute utility of Eq. (2), we can now easily establish, by subtracting from the benefits of risk reduction $\Delta u_{risk,j}$, the net-gain for raising vessel's crashworthiness for each of the stakeholders.[8]

$$u_j = \Delta u_{risk,j} - \Delta u_{costs,j} \tag{21}$$

The risk reduction is computed by comparing the reduced value of risk of any design alternative with the risk of design alternative DA-1. Fig. 14 presents the stakeholder multi-attribute utility values. All utility values are positive for every alternative and for all the stakeholders but for the public. The public's utilities are also changing widely as a consequence of large variations in safety-induced costs – related to the rise in hull mass, as seen in Fig. 13, which have all been transferred to them.

[8] The yard (j=yard) does not benefit from the reduction of environmental risk, but from the production costs savings only, i.e. when the ΔP_{prod} is only positive ΔP^{+}_{prod}, otherwise no benefits or costs exist for the yard. Hence, the multi-attribute utility of the yard is given as $u_{yard} = \Delta P^{+}_{prod} - u_{costs,yard}$.

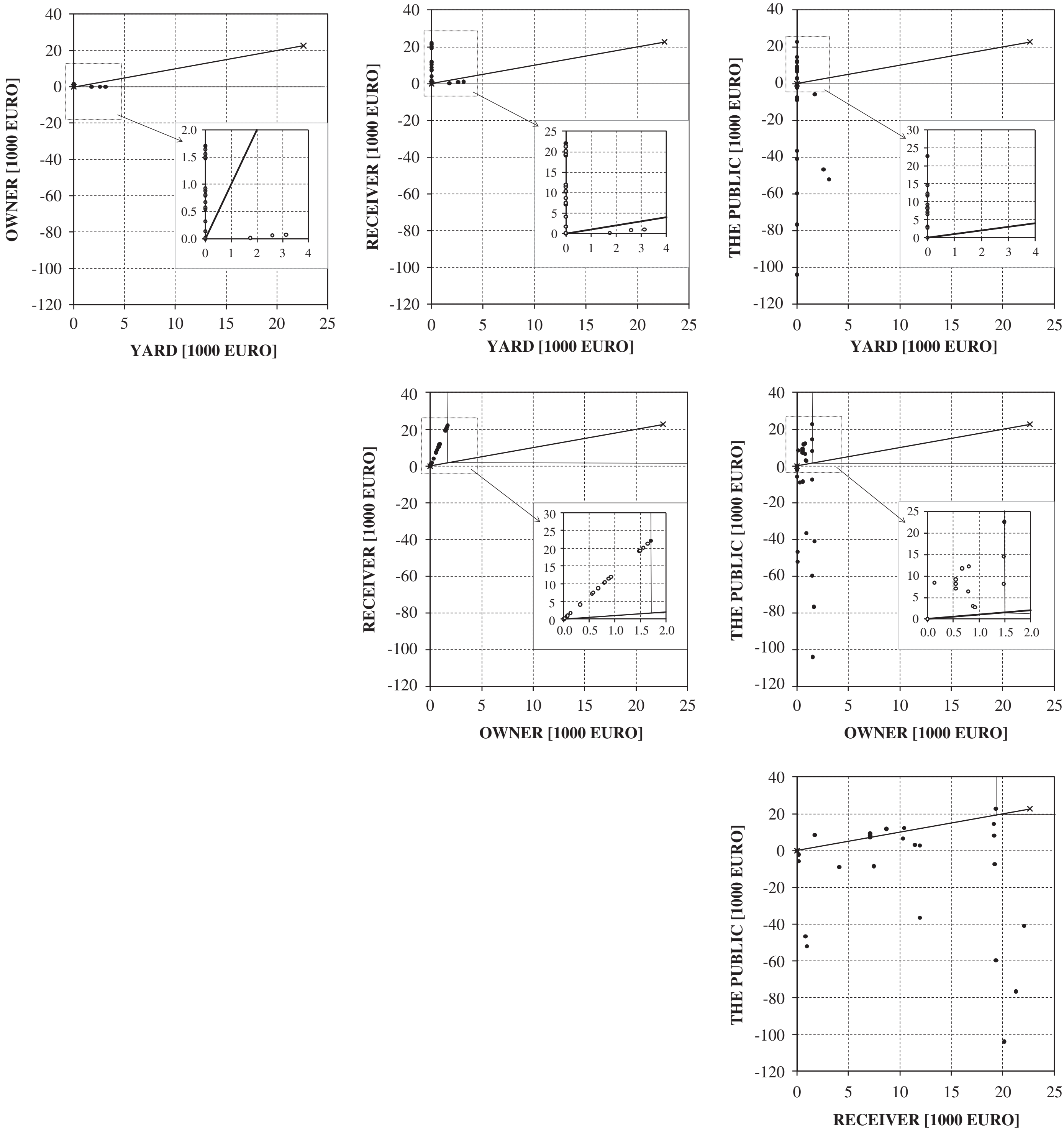

Fig. 15. Stakeholder utility space with indicated minimum Chebyshev metrics and the competitive optimum DA-21 (filled dot).

Observing the same utility values in the utility space of Fig. 15, we can notice that all 25 design alternatives are Pareto optimal. We can see also the trade-offs in the preferences between every pair of stakeholders, and conclude that the largest conflict exists between the yard and the public, which is reasonable since the yard does not partake in risk, and it cannot be expected to directly profit from safety improvements. On the other hand, the public takes the highest share of both.

Besides the stakeholder utilities, Fig. 14 presents also the CATS values of design alternatives. CATS, or the *Cost to Avert a Ton of Spillage*, is a ratio between the additional safety-induced costs and the averted volume of spillage $CATS=(\Delta P_{prod}+\Delta P_{\mathrm{cargo}})/\Delta u_{risk}^{volume}$ [52], and it is currently being used in the IMO as a benchmark value for the comparison of effectiveness of the risk control options [53], in this case being the design alternatives. A value of approx. 46 000 EUR (60 000 USD) is considered to be the threshold of efficiency [52]. Observing the values, we can conclude that several alternatives are inefficient according to this criterion as their CATS is above the threshold. Specifically, this refers to the DA-2 to -5 that have a very minor risk reduction, and

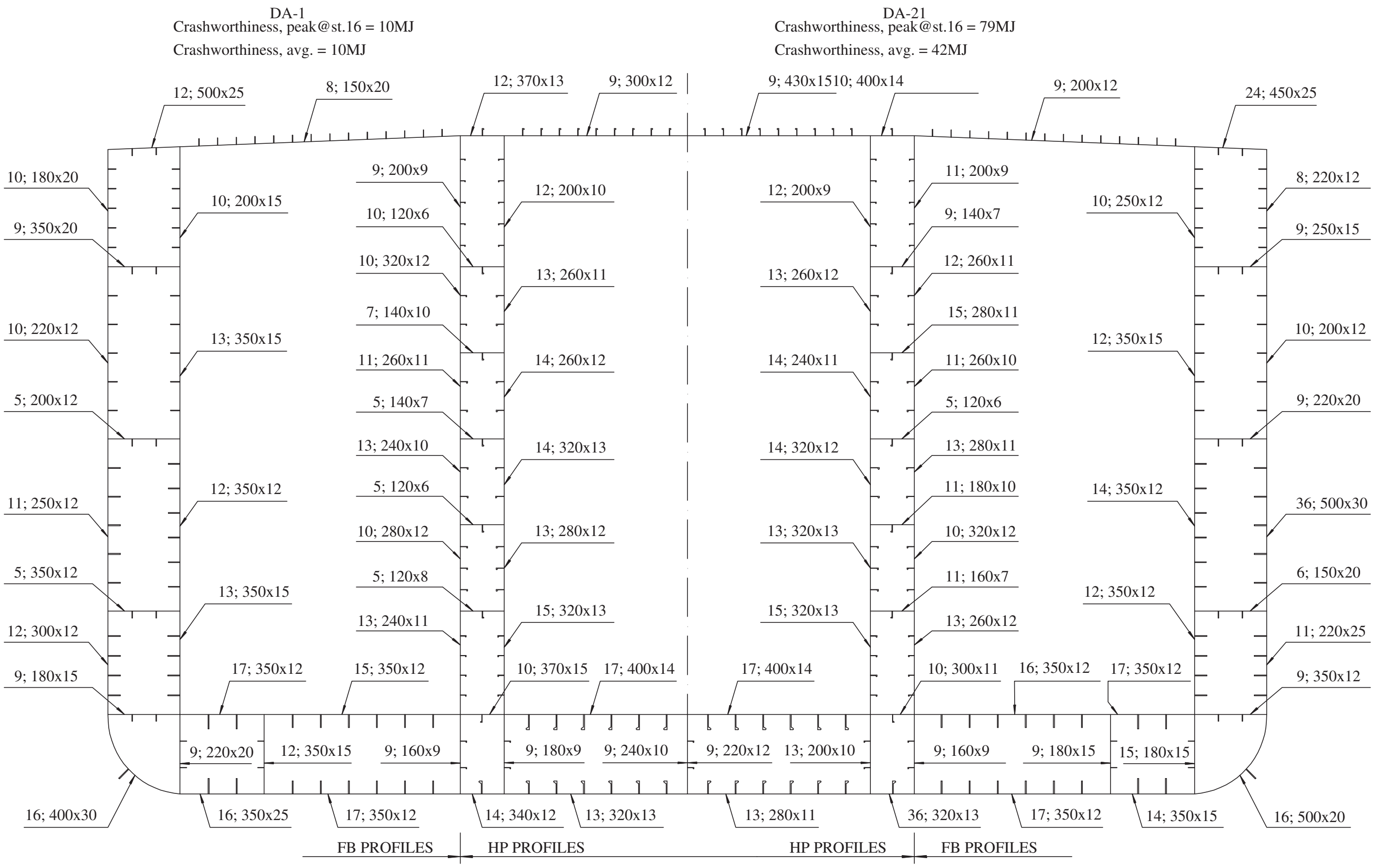

Fig. 16. Scantlings (strake plate thickness; stiffener height × stiffener thickness) of design alternatives DA-1 (left-hand-side) and DA-21 (right-hand-side).

to the DA-23, which is a very expensive alternative. Other alternatives have their CATS in a range mostly between 10 000 and 20 000 EUR.

To proceed with selecting the competitive optimum for the determined utility values, we need to elicit the reference points. Assuming that all stakeholders are equally important, we set up equal stakeholder utility values for the aspiration and for the reservation point. Concretely, we choose that the aspiration point values are that of the public's best possible net-gain for the considered set of alternatives. For the reservation values, we take – conservatively – the zero net-gain, i.e. the stakeholder utility has to be at least zero for the alternative to be considered acceptable. The reference points can be seen also in Fig. 15.

For this set of reference points, the competitive optimum is the design alternative DA-21.[9] Observing its structural characteristics in right-hand-side of Fig. 16, the DA-21 fosters strong local stiffening, i.e. thickening of the plating of strake 16. The plate thickness is increased to 36 mm, 25 mm more than for the least mass and least crashworthy alternative, DA-1, seen in the left-hand-side of Fig. 16. The crashworthiness of DA-21 is approximately eight times that of DA-1 if the vessel is collided at the critical location. The total mass of hull 750t heavier and 77t of this is the added mass of duplex.

The stakeholders can thus expect either a considerable risk reduction, or at least no losses, as is the case with the yard. All the costs induced by the increase in crashworthiness are transferred to the public since the public can expect the highest benefits from the reduction of risk. This implies that the public should accept higher costs of the goods being transported by the vessel in exchange for the reduced risk of pollution of the implemented more crashworthy structure. Furthermore, not only that there is an argument to opt for significant investments into safety, but also that all four stakeholders only benefit from this choice.

In comparison with other alternatives, DA-21 does not have the minimal CATS value; see again Fig. 14. The minimum value is actually found for the DA-6, even though a few other alternatives come close. DA-6, in comparison with DA-21, has a much lower risk reduction, so its high efficiency must emerge from low safety-induced costs. Obviously, the competitive optimum solution has a capacity to differentiate between the changes in safety and changes in safety-induced costs, whereas CATS simply levels the two.

To strengthen the arguments of DA-21 as the competitive optimum, this result can be tested against different set of reference points. If we choose for the reference points the maximum and minimum of the stakeholders' utilities from the set of considered alternatives, meaning that stakeholders are not anymore equal, we effectively simulate a design scenario where each stakeholder is equally satisfied with the maxima and minima of the attained attribute values. This means that stakeholders now value differently the expected financial gains. The competitive optimum in this scenario is again the alternative DA-21. Obviously such an outcome indicates certain robustness of the indicated design alternative, and this is especially useful if the input data is uncertain, especially relating to the reference points.

Furthermore, if we are to vary the probabilities to accept the safety-induced costs, given in Eqs. (17)–(20), we can analyse the influence of the assumed distribution of the safety-induced costs to the indicated competitive optimum. Since most of the

[9] A value of ρ_a=0.1 is considered in Eq. (12) to elicit the competitive optimum. The same value is applied for all the selections.

probability combinations are economically unsound, exploring them arbitrarily is senseless. But for the probabilities for which combination the competitive optimum has the smallest minimal Chebyshev metrics, specified in Eq. (12), the attained competitive optimum will be economically justified. Such a solution possesses the minimal of deviations from the aspiration point for all the possible economic scenarios. Moreover, the conflict between the stakeholders is minimal, and thus such an optimum would be the expected best solution of the problem.

If we apply this logic, the competitive optimum with the smallest minimal Chebyshev metrics, enumerated for all the combinations of probabilities, is again the DA-21. And as such, it is attained for both described sets of reference points. More importantly, it is attained for the initially considered values of probabilities, $p_{costs,yard}=0$, $p_{costs,owner}=0$, $p_{costs,receivers}=0$, $p_{costs,public}=1$. The DA-21 is thus the expected and preferred solution of this case study.

To conclude with respect to this outcome, the key argument to invest into the observed vessel's crashworthiness seems not to lie on the stakeholders that are immediately involved with design, i.e. the yard and the owner. It lies on a successful argumentation to the public to accept the higher costs of the petroleum products they purchase from the receivers. The public faces the highest risk of collision, but also has the highest benefit from the risk reduction. Should this benefit not have been considered in the presented selection, the indicated competitive optimum would be different. Concretely, if the public is excluded from the list of stakeholders, and their preferences are ignored, the competitive optimum would be the cheapest-to-produce and one of the least crashworthy alternatives, the DA-5, seen in Fig. 17. DA-5 is characterized by the least amount of installed stainless steel. If we now repeat the experiment to find the competitive optimum with the smallest minimal Chebyshev metrics as done above, the rational decision for the first three stakeholders would be still not to accept the safety-induced costs, i.e. the probabilities of Eqs. (17)–(19) would in this scenario continue to be nil. Now, as the costs cannot be anymore transferred to the public, the expected outcome is clear, and that is simply not to invest into crashworthiness and obviously remain at the minimum of acceptable limits of safety. This then shows how necessary it is, in order to justify improvements in safety beyond the minimum requirements, to consider the public and their preferences in parallel to other maritime stakeholders.

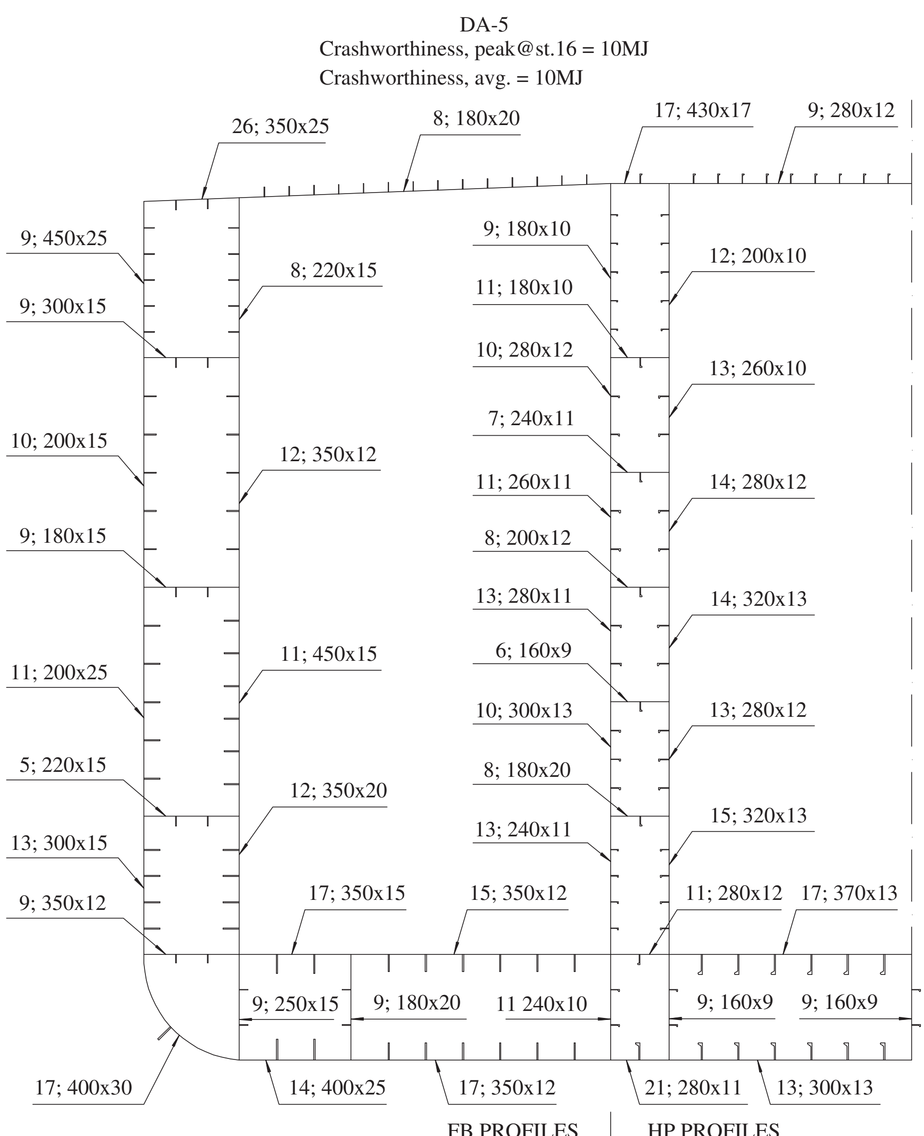

Fig. 17. Scantlings of the cheapest-to-produce alternative DA-5.

5. Conclusions

In this paper we sought to establish a method for design of marine structures with improved safety for environment. Theoretical contributions were also demonstrated with a simplified, but practical study on a 40 000 DWT product/chemical tanker safety in collision.

The method, based on the concepts of group decision-making can, for any number of stakeholders, determine the best design alternative that concurrently maximally satisfies all their preferences. Such an alternative, quoted as the competitive optimum, represents the fairest possible choice and it is the best compromise between the stakeholder preferences.

Applying the method to the practical study, and answering how much should the tanker crashworthiness be raised and how much should be invested in it, several implications were identified. From the pool of competitive, Pareto optimal design alternatives, one alternative with significant improvements in crashworthiness of the vessel has been outlined. This alternative did not incur any net losses to the stakeholders in comparison with the standard, present-day design. This also proved the capacity to reach the competitive designs that benefit all stakeholders in the maritime industry. A 40 000 DWT chemical/product carrier can therefore be realized as a safer 'crashworthy' vessel without a financial loss.

Nevertheless, these conclusions are not to be taken lightly or considered universal, first of all due to the adopted simplifications. Secondly, design selection was performed on the relative basis to the standard design, which is assumed to be satisfying the minimum of safety requirements. The real-life decisions, however, need to be made with real and not relative figures. Nonetheless, the extension of the proposed methodology to analyse real-life problems is direct, since it depends solely to more elaborate data acquisition.

The results attained by the proposed method, have been also compared with the industry standard CATS benchmark. The identified solution does not posses the minimal CATS value, even though it is below the threshold of acceptability. Actually, this discrepancy between the criteria of minimal CATS and competitive optimum is important, as it indicates their different treatment of safety and of the safety-induced costs.

Consequently, several steps should be performed in the future to further increase the understanding of the effects of the presented methodology: (i) through a series of interviews, confirm with stakeholders the assumed preferences and selected alternative as the rational solution, (ii) implement discounted utilities and further assess the value of the vessel with respect to safety and safety improvements, (iii) apply the methodology on different ships and for more particular navigational areas, (iv) consider different risk control options, such as the varying width of the double side, or the alternative cargo arrangement as proposed in the IMO study [53], and last but not least (v) gather more extensive data, such as unit production costs, vessel income and expenses in service, to be able to make more general conclusions.

Acknowledgements

This study was supported by the IMPROVE project, funded by the *European Union* (Contract nr. 031382-FP6 2005 Transport-4), and the *Technology Development Centre of Finland – TEKES*, including Finnish shipbuilding industry, through the projects *TÖRMÄKE* and *CONSTRUCT*. This help is here gratefully acknowledged.

Appendix A. Proof of position of Nash equilibrium

Proposition 1. *Nash equilibrium of the game* **G** *is always a member of line* $\tilde{l}$ *which connects the reference points.*

Before proceeding with the proof, we note that utilities can be linearly scaled without the loss in consistency, see e.g. Ref. [54]. Therefore, let us assume that **U** now represents strictly linearly normalized utility values of alternatives between the reference points normalized to **0** and **1**, $\mathbf{U} = \{\forall \boldsymbol{u} \in \mathbf{U}, 0 \le u_j \le 1\}$.

Lemma 1. *For any two similar apexes (or utility vectors in* **G***)* $\hat{\boldsymbol{u}}$ *and* $\hat{\boldsymbol{u}}'$ *having all except one component the same it is valid that* $\hat{u}'_j > \hat{u}_j$ *if* $\omega'_j > \omega_j$.

Proof. Suppose a line $l(\boldsymbol{\omega})$ marking any apex of a weighted Chebyshev metrics $\hat{\boldsymbol{u}}(\omega)$. The projection on the p–q plane of the utility space is given as $(\hat{u}_p, \hat{u}_q)$. From the similarities of triangles $\{1,(\hat{u}_p,\hat{u}_q),(1,\hat{u}_q)\}$ and $\{1,(\omega_p,\omega_q),(1,\omega_q)\}$:

$$\hat{u}_q = 1 - \frac{(1-\omega_p)(1-\hat{u}_q)}{1-\omega_p} \tag{A.1}$$

Therefore, the payoff in **G** is a strictly increasing function of a weight coefficient if other weight coefficients remain the same, which then concludes the proof. □

Then, the following corollary can be stated:

Corollary 1. $\lim_{\omega_j \to 1} \hat{\boldsymbol{u}}_j^* = 1$.

Lemma 2. *Strategy* $\mathbf{s}_j^* = (\omega_1^*, \omega_2^*, \ldots, \max_i \omega_j^i, \ldots, \omega_m^*)^{\mathrm{T}}$, *where* $\sum_j \omega_j^* = 1$ *, of a stakeholder j is the only strategy member of a rational reaction set* $\hat{\mathbf{S}}$.

Proof. Suppose any strategy vector $\mathbf{s}'_j \in \hat{\mathbf{S}}$, for which their scalar $\omega'_j < \max_i \omega_j^i$, to be a member of a rational reaction set. Hence, the payoff to a player j for any strategy $\mathbf{s}'_j$ should be at least $\boldsymbol{u}'_j > \hat{\boldsymbol{u}}_j^*$. This is then in contrary to Lemma 1 and Corollary 1, thus proving Lemma 2. □

Following Lemma 2, it is obvious that every stakeholder in **G** is best–off with the strategy $\mathbf{s}_j^*$, where $\omega_j \to 1$. Due to definition of game **G**, and following Eq. (9), the weighting factors for the Nash equilibrium are then uniform, thus completing the proof. □

In order to extend the validity of this proof to a general problem, where **U** is not normalized, the weighting factors, applied in the proof to determine the Nash equilibrium, have only to be multiplied with the inverse of Eq. (11).

References

[1] International Maritime Organization.International Convention for the Safety of Life at Sea (SOLAS), 1974. Available at: 〈http://www.imo.org/Conventions/contents.asp? topic_id=257&doc_id=647〉, accessed on 13 Oct 2009.
[2] International Maritime Organization. International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL). Available at: 〈http://www.imo.org/Conventions/contents.asp?doc_id=678&topic_id=258〉, accessed on 13 Oct 2009.
[3] Moore WH, Arai M, Besse P, Birmingham R, Bruenner E, Chen YK, et al. Design principles and criteria. In: Jang CD, Hong SY, editors. Procedings of the 17th international ship on offshore structures congress, Seoul; 2009. p. 587–688.
[4] Vatn J. A discussion of the acceptable risk problem. Reliability Engineering and System Safety 1998;61:11–9.
[5] Melchers RE. On the ALARP approach to risk management. Reliability Engineering and System Safety 2001;71:201–8.
[6] Aven T. Foundations of risk analysis. Chichester: Wiley & Sons; 2003.
[7] Skojng R, Ronold KO. Societal indicators and risk acceptance. In: Proceedings of the 17th international conference on offshore mechanics and Arctic engineering, 1998.

[8] Ditlevsen O. Decision modelling and acceptance criteria. Structural Safety 2003;25:165–91.
[9] Friis-Hansen P, Ditlevsen O. Nature preservation acceptance model applied to tanker oil spill simulations. Structural Safety 2003;25:1–34.
[10] Wang J, Yang JB, Sen P. Multi-person and multi-attribute design evaluations using evidential reasoning based on subjective safety and cost analyses. Reliability Engineering and System Safety 1996;52:113–28.
[11] Wang J, Kieran O. Offshore safety assessment and safety-based decision-making – the current status and future aspects. Journal of Offshore Mechanics and Arctic Engineering 2000;122:93–9.
[12] Rosqvist T, Tuominnen R. Qualification of formal safety assessment: an exploratory study. Safety Science 2004;42(2):99–120.
[13] French S, Bedford T, Atherton E. Supporting ALARP decision making by cost benefit analysis and multiattribute utility theory. Journal of Risk Research 2005;8(3):207–23.
[14] Rosqvist T. Stakeholder compensation model based on decision analysis. Journal of Multi-Criteria Decision Analysis 2003;12:219–23.
[15] Klanac A, Tabri K, Ehlers S, Nekic A. Multi-attribute design of crashworthy structures in the bi-stakeholder environment. In: Proceedings of international marine design conference – IMDC, Ann Arbor, 2006.
[16] Klanac A, Jalonen R, Varsta P. Multi-stakeholder decision-making in the risk-based design of a RO-PAX double bottom for grounding. Journal of Engineering for the Maritime Environment 2007;221(1):1–15.
[17] Klanac A, Ehlers S, Jelovica J. Optimization of crashworthy marine structures. Marine Structures 2009;22(4):670–90.
[18] Cho K-N, Arai M, Basu R, Besse P, Birmingham R, Bohlmann B, et al. Design principles and criteria. In: Proceedings of the 16th international ship and offshore structures congress. Southampton, 2006. p. 543–624.
[19] Bennett P. Mutual risk: P&I insurance clubs and maritime safety and environmental performance. Marine Policy 2001;25:13–21.
[20] Pöyhönen M. POLSSS: surveying stakeholders about acceptability of risks and system changes. Safety Science 2000;35:123–37.
[21] Slovic P. Perception of risk. Science 1987;236(4799):280–5.
[22] von Neumann J, Morgenstern O. Theory of games and economic behaviour. Princeton: Princeton University Press; 1953.
[23] Keeney RL, Raiffa H. Decisions with multiple objectives: preferences and value tradeoffs. New York: John Wiley & Sons; 1976.
[24] Arrow KJ. Social choice and individual values. New York: Cowles Foundation and Wiley; 1951.
[25] Hazelrigg GA. The implications of Arrow's impossibility theorem on approaches to optimal engineering design. Journal of Mechanical Design 1996;118(2):161–4.
[26] Miettinen K. Nonlinear multi-objective optimization. Norwell: Kluwer Academic Publishers; 1999.
[27] Wierzbicki A. The use of reference objectives in multiobjective optimization. In: Fandel G, Gal T, editors. Multiple objective decision making — theory and application. Berlin Heidelberg New York: Springer; 1980. p. 468–86.
[28] IMO. Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process. International maritime organization, Marine Safety Committee, MSC/Circ.1023, MEPC/Circ.392, 2002.
[29] Deutsch M. A theory of co-operation and competition. Human Relations 1949;**7**:129–52.
[30] May KOA. Set of independent necessary and sufficient conditions for simple majority decisions. Econometrica 1952;20:680–4.
[31] Nash JF. Non-cooperative games, PhD dissertation, Princeton University, 1950.
[32] Bowman Jr VJ. On the relationship of the tchebycheff norm and the efficient frontier of multiple-criteria objectives. In: Thieriez H, Zionts S, editors. Multiple-Criteria Decision Making. New York: Springer-Verlag; 1976. p. 76–85.
[33] Minorsky VU. An analysis of ship collision with reference to protection of nuclear powered plant. Journal of Ship Research 1959;3(2):1–4.
[34] Zhang S. The mechanics of ship collisions. PhD thesis, Technical University of Denmark, Department of Naval Architecture and Offshore Engineering. Lyngby, 1999.
[35] Luetzen M. Ship collision damage. PhD thesis. Technical University of Denmark, Lyngby, 2001.
[36] Ritvanen H. A crashworthy ship: comparative risk analysis of AFRAMAX – tanker side structures, Master thesis, Helsinki University of Technology, Department of Mechanical Engineering, Ship Laboratory, 2006.
[37] Hallquist JO. LS-DYNA. Keyword User's Manual, Version 971. Livermore: Livermore Software Technology Corporation, 2007.
[38] Zhang L, Egge ED, Bruhms H. Approval procedure concept for alternative arrangements. In: Proceedings of the third international conference on collision and grounding of ships. Japan, 2004. p. 87–97.
[39] Ehlers S, Klanac A, Tabri K. Increased safety of a tanker and a RO-PAX vessel by implementing a novel sandwich structure. In: Proceedings of the fourth international conference on collision and grounding of ships. Hamburg, 2007. p. 109–115.
[40] Konter A, Broekhuijsen J, Vredeveldt A. A quantitative assessment of the factors contributing to the accuracy of ship collision predictions with the finite element method. In: Proceedings of the third international conference on collision and grounding of ships. Izu, 2004. p. 17–26.
[41] Ozguc O, Das PK, Barltrop N. A comparative study on the structural integrity of single and double side skin bulk carriers under collision damage. Marerials and Structures 2005;18(7–8):511–47.
[42] International Maritime Organization. Routeing of ships, ship reporting and related matters: Assessment of the traffic in the Baltic Sea West. NAV51/INF 2005; Available at: 〈http://www.sjofartsverket.se/upload/3986/565568070-199949298-15-282226%20ARON.pdf〉, accessed on: 11 Oct 2009.
[43] International Maritime Organization. Casualty statistics and investigations: Very serious and serious casualties for the year 1999. FSI.3/Circ.2, 2001; Available at: 〈http://www.imo.org/includes/blastDataOnly.asp/data_id%3D5397/2.pdf〉, accessed on: 4 Aug 2008.
[44] International Maritime Organization. Casualty statistics and investigations: very serious and serious casualties for the year 2000. FSI.3/Circ.3, 2002; Available at: 〈http://www.imo.org/includes/blastDataOnly.asp/data_id%3D5118/3.pdf〉, accessed on: 4 Aug 2008.
[45] International Maritime Organization. Casualty statistics and investigations: very serious and serious casualties for the year 2001. FSI.3/Circ.4, 2004; Available at: 〈http://www.imo.org/includes/blastDataOnly.asp/data_id%3D8934/4.pdf〉, accessed on: 4 Aug 2008.
[46] International Maritime Organization. Casualty statistics and investigations: very serious and serious casualties for the year 2002. FSI.3/Circ.5, 2005; Available at: 〈http://www.imo.org/includes/blastDataOnly.asp/data_id%3D11539/5.pdf〉, accessed on: 4 Aug 2008.
[47] International Maritime Organization. Casualty statistics and investigations: very serious and serious casualties for the year 2003. FSI.3/Circ.6, 2005; Available at: 〈http://www.imo.org/includes/blastDataOnly.asp/data_id%3D11540/6.pdf〉, accessed on: 4 Aug 2008.
[48] Tuovinen J. Statistical analysis of ship collision. TKK master thesis. Espoo, 2006.
[49] Papanikolaou A, Eliopoulou E, Alissafaki A, Aksu A, Tuzcu C, Delautre S, et al. Critical review of AFRAMAX tankers incidents. In: Proceedings of the 3rd international conference on marine science and technology for environmental sustainability ENSUS. Newcastle upon Tyne, 2005.
[50] Grey CJ. The cost of oil spills from tankers. In: Proceedings of the international oil spill conference, 1999. Available at: 〈http://www.itopf.com/_assets/spilcost.pdf〉, accessed on 11 Oct 2009.
[51] IPIECA/ITOPF. Oil spill compensation: a guide to the international conventions on liability and compensation for oil pollution damage. A joint IPIECA/ITOPF publication. Available on: 〈http://www.ipieca.org/activities/oilspill/downloads/publications/reports/english/Compensation.pdf〉, accessed on 11 Oct 2009.
[52] Vanem E, Endresen O, Skjong R. "Cost-Effectiveness crieteria for marine oil spill preventive measures. Reliability Engineering and System Safety 2008;93:1354–68.
[53] International maritime organization. FORMAL SAFETY ASSESSMENT, FSA – crude oil tankers, Submitted by Denmark, MEPC58/INF.2, 2008.
[54] Yu PL. A class of solutions for group decision problems. Management Science 1973;19(8):936–46.