RISK BASED-GOAL BASED SHIP HULL FORM DESIGN

Çağan Birant Pekküçük
İstanbu Teknik Üniversitesi | pekkucukc@itu.edu.tr

ABSTRACT

Risk based design has become a necessity in many work ares today. Since the safety factor is a vital consideration especially for big industries which include ship building industry, it has been gaining more and more importance every day. Also there has been various methods and techniques which are on lifelong development, contributing to the safe and reliable design options.

Since the hull form is a core subtitle of ship design, it becomes an interconnection point of many other main design parts of ship, such as stability, manoeuvrability, strength and seakeeping. Thinking on stability base, one of the main precaution which should be taken in case of accidents is a subdivision of a vessel since it determines the survivability degree. Also the avoidance of accident and precautions which should be taken for materializing the accident should be taken into consideration.

In this paper, risk-based and goal-based design will be defined briefly and the stability focus for this subtitle will be investigated referring to an existing case study.

Keywords: Risk, Goal, Analysis, Collision, FSA, Stability

1. Introduction

In recent years risk-based design gained more importance in ship design. In parallel discussion started at the International Maritime Organisation (IMO) on the development of regulations based on risk-based methods, named Goal-Based Standards Safety Level Approach. Risk based methods require more engineering effort by introducing new criterias to be considered into design process. Therefore some stakeholders are reluctant to accept this innovation because of uncertainties concerning design classification and approval.

In this study, risk based design and goal based standards will be investigated and an existing case study for passenger ro-ro vessels' damaged stability case due to collision will be presented as a sub-heading to hull form design to examplify the risk based approach to a design process and consolidate the philosophy of the method.

2. Risk Based Design

As mentioned in the introduction, methods of risk and reliability analyses gain more and more acceptance and importance as decision support tools in engineering applications. The integration of these methods into the design process leads to risk-based design.

In general risk-based design is a design process with an additional design variable Rdesign and the additional design requirement:

$$Rdesign \leq Racceptable$$

where Rdesign is the expected loss, for instance loss of life, damage to environment or property, and Racceptable is the threshold set by the approval authority.

To apply the method, basic requirement is an engineering analysis based on science and engineering practise consisting of:

- Casualty scenario development based on a hazard identification including a ranking of hazards
- Selection of hazards
- Quantitative analysis of the design casualty scenarios, and
- Evaluation of the alternative design

Obviously this is the process of risk analysis. Therefore, alternative design is regarded as a special form of risk-based design that requires a risk analysis for two designs - a reference design complying with prescriptive rules and regulations, and a novel design challenging some or all of these requirements.

3. Goal Based Standards

The concept of goal-based ship construction standards was introduced in IMO at the eighty-ninth session of the Council in November 2002 through a joint proposal from the Governments of Bahamas and Greece, suggesting that: *"IMO should play a larger role in determining the standards to which new ships are built…"*, which has been traditionally the responsibility of classification societies and shipyards.

Prescriptive regulations tend to be a representation of past experience and, as such, become less and less relevant over time and can hold back ship designers, who are technically innovative, from being able to properly address future design challenges. As a result, safety regulations need to be frequently updated to keep pace with lessons learned and the latest technologies. Example below demonstrates the difference between goal-based and prescriptive regulations:

● **Goal-based**: "People shall be prevented from falling over the edge of a cliff."
● **Prescription**: "You shall install a 1 meter high rail at the edge of the cliff."

After in-depth discussions within the Maritime Safety Committee (MSC) and its ad hoc Working Group on Goal-Based Standards (GBS) over several years, the Committee, in May 2005, agreed the IMO goal-based standards are:

- broad, over-arching safety, environmental and/or security standards that ships are required to meet during their lifecycle;
-the required level to be achieved by the requirements applied by class societies and other recognized organizations, Administrations and IMO;
-clear, demonstrable, verifiable, long standing, implementable and achievable, irrespective of ship design and technology; and
-specific enough in order not to be open to differing interpretations.

3.1 Methodology

In May 2006, MSC 81 agreed to limit the scope of the GBS work initially to bulk carriers and oil tankers and consider expansion to other ship types and areas of safety at a later time. For GBS, in general, the following five-tier system was agreed:

Tier I – Goals
Tier II – Functional requirements
Tier III – Verification of conformity
Tier IV – Rules and regulations for ship design and construction
Tier V – Industry practices and standards

Goals are High-Level objectives to be met. Functional requirements refer to the criteria to be satisfied in order to conform to the goals. Procedures for verifying that the rules and regulations for ship design and construction conform to the goals and functional requirements is Verification of conformity. Detailed requirements developed by IMO, national Administrations and/or recognized organizations and applied by national Administrations and/or recognized organizations acting on their behalf to the design and construction of a ship in order to conform to the goals and functional requirements refer to Tier-4, while Industry standards, codes of practice and safety and quality systems for shipbuilding, ship operation, maintenance, training, manning, etc., which may be incorporated into, or referenced in, the rules and regulations for the design and construction of a ship refers to Tier-5.
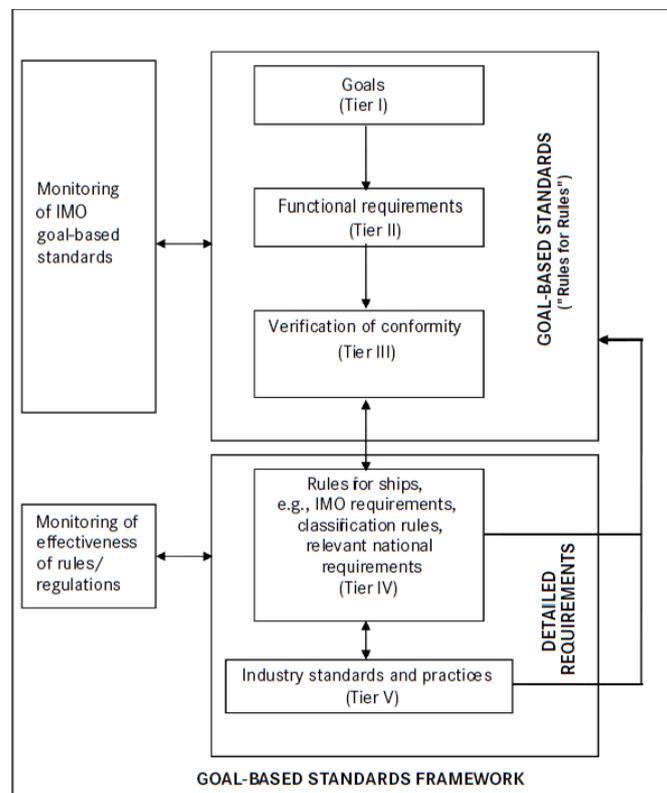

Figure-1. Goal Based Standards Framework.

3.2 Safety Level Approach

The GBS Safety Level Approach is based on application of risk-based methods for justifying regulations and rules. This approach was named safety level approach in order to expressing that risk will be reduced to acceptable level. This approach is not finally discussed at IMO and details how safety level will be specified were not agreed, i.e. whether explicit or implicit, global or separately for functions.

In order to structure the functional requirements, six safety areas were distinguished:

● Safety of crew
● Safety of passengers
● Safety of third parties
● Safety (protection) of environment
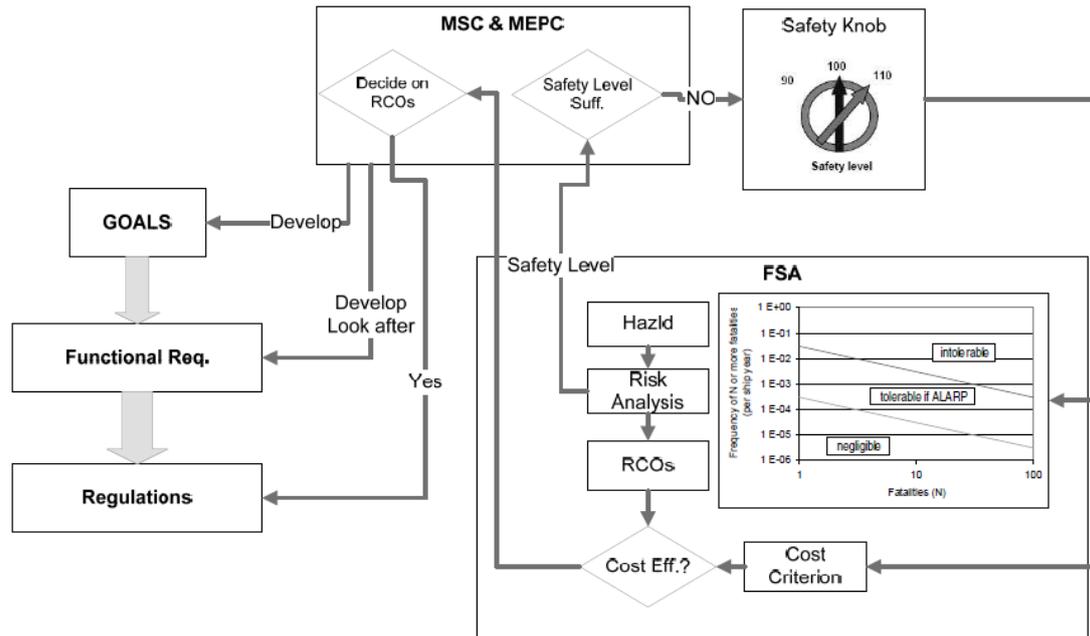● Safety of ship
● Safety of cargo

Figure 2. Safety Level Approach and Formal Safety Assesment.

For these safety areas functional requirements should be specified in GBS. The IMO discussion on SLA provides a lot proposals and information addressing single aspects, such as how to determine the current safety level (including determination of relevant input data), whether explicit safety level or ALARP, how to monitor IMO instruments with respect to the achieved safety level, or examples for risk determination.

3.3 Prescriptive Approach

Formally considered, the Safety Level Approach and the prescriptive approach are two different code formats of the GBS formulation. They can be compared to the well known working stress design (WSD) and load and resistance factor design / partial safety factor (LRFD/PSF) formats, respectively, in current design codes. Another example of the prescriptive approach is the International Goal-Based Ship Construction Standards for Bulk Carriers and Oil Tankers. This means that, in principle, both approaches are possible according to the Generic Guidelines for Developing IMO Goal Based Standards, *IMO* (2011). Furthermore also prescriptive formulations can contain requirements based on a SLA or on results of risk and reliability analyses. Thus the difference between (a) GBS based on SLA, and (b) prescriptive approach, should be confined to a different formulation of the functional requirements (Tier II) and in a different methodology for the verification process (Tier III).

Figure-3 compares the two approaches for some functional requirements included in the current GBS for bulk carriers and oil tankers.

Functional requirement	SLA	prescriptive
General remark *1*	Target Safety levels can be defined, based on FSA(s)	Safety level implicit, empirical, due to experience
General remark *2*	Proactive rule development possible	Proactive development very difficult usually reactive adaptation of rules
General remark *3*	More open to new technological development	Limited to known, existing design solutions
1 Design life	Could be open to owner's decision	Is fixed
2 Environmental conditions	In accordance with the selected design life probabilities of exceedance could be defined. Environmental conditions may be ship-type or ship-size specific	Based on North Atlantic environmental conditions, but conditions in other areas could be worse, depending on ship type and length
3 Deformation and failure modes	Could be equal to the prescriptive approach	Definition of failure modes that has to be considered (covered) by the rule formulations
4 Ultimate strength	A target level for failure probability for local parts (stiffened panels) as well as for the hull girder could be set	Currently it is open to discussion what is meant by "adequate ultimate strength"
5 Safety margins	Safety margins or target safety levels / failure probabilities could be developed based on e.g. FSA	Currently it is open to discussion what is meant by "suitable safety margins"
6 Residual strength	More quantifiable requirements like target failure probabilities could be introduced	Currently it is open to discussion what is meant by "sufficient strength" in some requirements by SOLAS

Figure 3.

4. Application

In this study, a method/procedure for establishing risk levels corresponding to the collision that may occur during operation and for decision making considering available risk control options (RCOs), which influence ship costs and performance, in order to quantify trade-offs and perform optimisation among the RCOs within a multi-criteria environment accounting for other design constraints and objectives will be described by referring to an existing study.

Having the focus of the study on damaged stability, causes which may lead to damage on the operation or at berth should be investigated and clarified. The scenarios shown in Fig. 4 are meant to provide the "structural links" to be used for the development of the risk-based design framework.
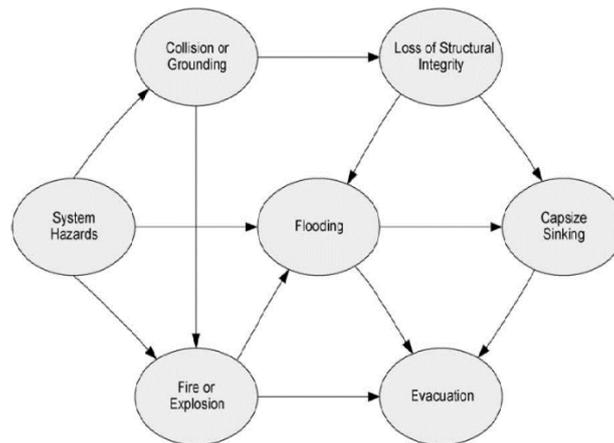

Figure 4. Structural links between events.

4.1 Collision

Collision can be defined as a ship striking or being struck by any self propelled ship whilst at sea whether the ship is in transit or anchored and excludes collisions with any underwater vessel/wreck and self propelled oil installations.

The collision events are among the most common ship accidents and continuous efforts have been made to prevent this event or mitigate the associated consequences. However, collisions are likely to happen in the future and therefore, tools for the analysis are continuously being developed and/or refined.

4.2 Damage Survivability

Maritime transport in general represents an efficient and environment-friendly mode of transport, which has led to technological developments represented by the technical evolution and development of new, innovative ship designs and intermodal systems. Though, human activities bring certain risks which can be related with human life, property, environment, in passenger Ro-Ro vessel operations. These risks, if not considered carefully and taken precautions, can lead to unacceptably large potential for loss of life and loss of the vessel.
The desired goal is to identify appropriate arrangements and layouts for passenger Ro-Ro vessels, by considering specific safety and techno-economic targets. The various characteristics/parameters to be considered are grouped in the following:

• *Hull-related parameters*, for example, principal dimensions, ratios and coefficients, flare, height of the main vehicle deck, shear, camber, presence of a ducktail, etc.

• *Internal layouts and arrangements*, i.e. possible layouts below (for example, pure transverse subdivision, combination of transverse and longitudinal subdivision, presence of a lower hold) and above the main vehicle deck (for example, presence of centre and/or side casings, transverse or longitudinal bulkheads, combinations).

The various systems of the vessel can be analysed using classical risk analysis techniques, such as Fault Tree Analysis and Failure Modes and Effect Analysis. A risk-based operational procedure that is applied onboard can also be considered as a ship system and analysed using the same techniques. Human effects and interaction can also be modelled within this analysis.

4.3 Criteria for design

The design criteria to be fulfilled should correspond to acceptable levels of risk, as well as to established techno-economic criteria which are normally applied in contemporary design practice. In this respect, three types of criteria can be distinguished as in the following.

Risk Acceptance Criteria

There are no established explicit risk acceptance criteria to date, however, there is a certain consistency in the criteria used in various risk analysis studies submitted to the International Maritime Organisation (IMO). The following originate from a document submitted to IMO by Norway [6], which are further elaborated upon in a recent document produced as part of the activities of the SAFEDOR project [7,8]. A criterion for risk acceptance is compatible to the form that the risk is presented.

For passenger ships, the following are complementary forms of risk presentation:

● *Damage risk*: The risk experienced by a vessel for defined levels of damage. This may be expressed as the frequency of "total loss" per ship year, or as the frequency of "serious casualties" per ship year.

● *Individual risk*: The risk experienced by an individual person. It can be expressed as:

    - A risk of death per year for a specific individual (passenger or crew member);
    - A Fatal Accident Rate (FAR), which is defined as the number of fatalities per 100 million person-hours at sea.

● *Societal risk*: The risk experienced by the whole group of people exposed to a hazard. It can be expressed as:

    - The Annual Fatality Rate (AFR), which is defined as the long-term average number of deaths per ship year;
    - The F–N diagram, which relates the frequency and number of fatalities in accidents.

For individual risk, the following boundaries between unacceptable, tolerable and broadly acceptable risk are suggested by the UK's Health and Safety Executive in [11]:

Boundary between broadly acceptable and tolerable risk	10^-6 per year
Maximum tolerable risk for workers (e.g. crew members)	10^-3 per year
Maximum tolerable risk for public (e.g. passengers)	10^-4 per year

In [6,8] it is suggested to use stricter criteria by one order of magnitude for the target individual risks for new ships, as follows:

Target individual risk for workers (e.g. crew members)	10^-4 per year
Target individual risk for public (e.g. passengers)	10^-5 per year

Societal risks are usually represented on an F–N diagram, where the number of fatalities N is plotted against the cumulative frequency F of incidents with N or more fatalities on a log-log scale. The F–N criteria lines between the intolerable, ALARP and negligible risk regions are currently debated, especially with reference to passenger ships. Figure below presents the criteria lines for passenger Ro-Ro vessels, as proposed in [6,8].
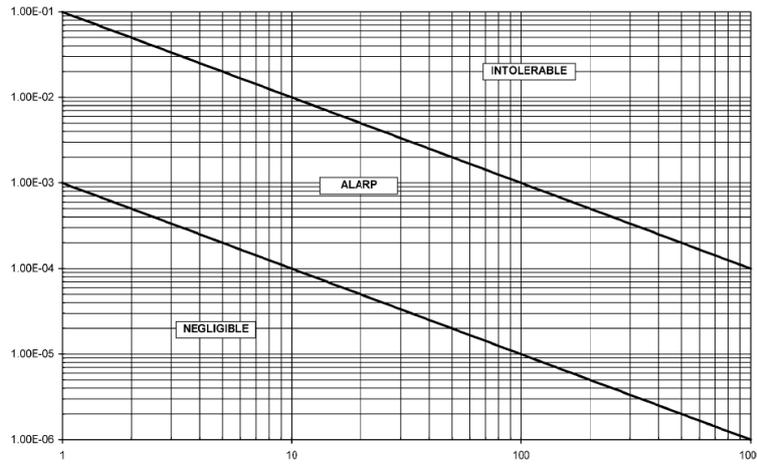

Figure 5.

Techno-Economic Design Criteria

Typical technical and economic design criteria include the subjects below:
• The requirements for deadweight (number of crew and passengers, private cars and trucks).
• The requirement for speed to be fulfilled at minimum required installed power.
• Passenger comfort (metacentric height GM and accelerations).
• Techno-economic performance as calculated by standard procedures, such as Net Present Value (NPV) or Required Freight Rate (RFR).

Cost Effectiveness

Cost-benefit analysis is a well-known selection technique, which is used when societal costs and benefits are required to be taken into account in evaluating different alternatives. The assessment is based on the comparison of the benefit gained by the implementation of each alternative, expressed in monetary terms, with the implied cost of implementing the alternative. The alternative is considered to be cost effective when the benefit outweighs the cost.

For this purpose, the Cost of Averting a Fatality (CAF) criterion is used. Estimates to demonstrate whether a risk control option (RCO) is reasonably practicable or not. The definition is as follows:

$$Gross\ CAF = \frac{\Delta C}{\Delta R}, \qquad Net\ CAF = \frac{\Delta C - \Delta B}{\Delta R},$$

where: ΔC is the overall cost of the RCO; ΔB is the economic benefit resulting from the implementation of the RCO; ΔR is the risk reduction, measured as the number of fatalities averted offered by the RCO.

4.4 Case Study

The focus of the study is the determination of the number of transverse bulkheads required for effective subdivision of a conventional passenger Ro-Ro vessel, accounting for social and techno-economic benefits, together with considerations of collision preventive measures and evacuability.

An existing passenger Ro-Ro vessel was used as the example ship with the following main dimensions:

Lbp	156,45m
B	156,45m
D (main veichle deck)	8,9m
T (Centre casing on the main veichle deck)	6,5m

For the prediction of the overall frequency for collision incidents for this vessel, 3.71×10^{-2} per ship year is taken [10]. Figure 6 shows the event tree for this case [3].
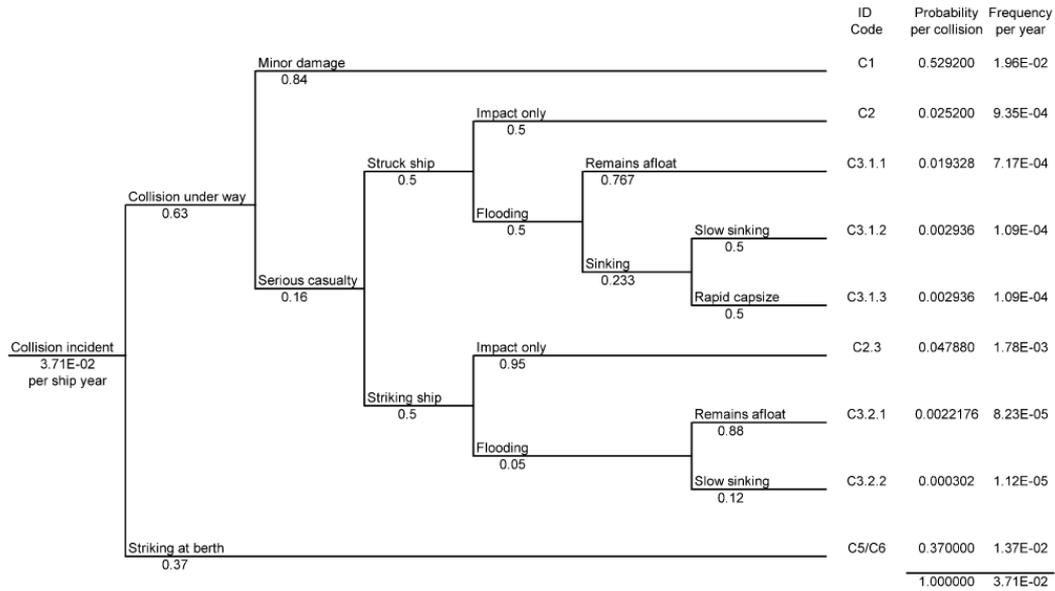
Figure 6.

This event tree has been developed as part of the activities of the Joint North-West European Project on the Safety of Passenger Ro-Ro vessels [10], with its branch probabilities recently updated as part of the activities of the SAFEDOR project [7], using available accident data.

Risk Control Options

The following have been considered for risk control options:

      • *Subdivision***:** Varying number of transverse bulkheads.

      • *Collision avoidance***:** Crew collision avoidance training or the presence of a second watch officer on the bridge of the vessel or both.

      • *Evacuation***:** An alternative accommodation layout.

Risk and Cost-Effectiveness Analysis

The risk analysis for subdivision and evacuability was based on the application of available first-principles tools and techniques, whilst for collision available expert judgement from the literature was used.

Subdivision considerations

A damage survivability analysis considering varying number of transverse bulkheads installed below the main vehicle deck has been carried out. The results of the Attained Subdivision Index A obtained using the new SOLAS harmonized probabilistic rules [12] are shown in figure-7 for her current maximum operational condition and main vehicle deck height.

Number of transverse bulkheads	8	10	12	14	16
Lane metres available	884	867	849	832	815
Weight of bulkheads (tonnes)	163	204	244	285	326
RFR ($ per lorry)	204	204.6	205.2	205.8	206.4
RFR ($ per lane metre)	13.6	13.64	13.68	13.72	13.76
Subdivision Index A	0.607	0.659	0.689	0.738	0.767
Frequencies					
Slow sinking (per ship year)	1.84E−04	1.59E−04	1.45E−04	1.22E−04	1.09E−04
Rapid capsize (per ship year)	1.84E−04	1.59E−04	1.45E−04	1.22E−04	1.09E−04
Potential Loss of Life (PLL)					
Slow sinking (per ship year)	5.52E−03	4.77E−03	4.35E−03	3.66E−03	3.27E−03
Rapid capsize (per ship year)	1.99E−01	1.72E−01	1.57E−01	1.32E−01	1.18E−01
Overall risk (per ship year)	2.04E−01	1.76E−01	1.61E−01	1.35E−01	1.21E−01
Cost Data					
Cost of additional steelwork ($)		63,248	119,998	174,600	227,868
Depreciated (25 years, 6%)		4,948	9,387	13,658	17,825
Lost revenue, per year ($)		61,380	123,120	185,220	247,680
Total Cost, ΔC ($)		66,328	132,507	198,878	265,505
Δ PLL					
Slow sinking (per ship year)		7.50E−04	1.17E−03	1.86E−03	2.25E−03
Rapid capsize (per ship year)		2.70E−02	4.21E−02	6.70E−02	8.10E−02
Overall risk (per ship year)		2.78E−02	4.33E−02	6.88E−02	8.33E−02
Gross CAF					
Gross CAF – slow sinking ($ m)		88.4	113.3	106.9	118.0
Gross CAF – rapid capsize ($ m)		2.46	3.15	2.97	3.28
Gross CAF – overall ($ m)		2.39	3.06	2.89	3.19

Figure 7.

The calculations presented in Table 4.2 indicate that the alternative comprising 14 transverse bulkheads achieves the best balance between risk reduction (ΔPLL) and cost effectiveness (Gross CAF) over the range of the considered variation, which can be clearly seen by the decrease of Gross caf at bulkhead number 14 through increasing number of bulkheads.

Considerations of collision preventive measures

Measures for prevention of collisions, reducing the frequency of collisions, include a wide range of alternatives which may be implemented. A number of these are contained in various IMO conventions and regulations, such as the Collision Avoidance Regulations or the STCW (watch keeping and navigation). The effect of this kind of measures on the frequency of accidents and the corresponding fatality rates is difficult to quantify, since it is mainly based on expert judgment.

For the purpose of this case study, a 20% frequency reduction will be considered related to crew training for collision avoidance, and a 10% frequency reduction will be considered for the presence of a second officer at the bridge during navigation. The percentages derive from [10] and correspond to the reductions on the frequency levels when the above mentioned measures are implemented. The annual present value of collision avoidance training is taken as $50,000, whilst the cost of a second officer is considered to have an annual present value of $110,000. Figure 8 contains the relevant calculations for a subdivision arrangement comprising 14 transverse bulkheads.

	Alternative number of bulkheads	Fatalities reduction (Subdivision)	Fatalities reduction (Training)	Fatalities reduction (Officer)	Fatalities reduction (Both)
Remain afloat					
Slow sinking	14	1.86E−03	2.23E−03	2.05E−03	2.42E−03
Rapid capsize		6.70E−02	8.04E−02	7.37E−02	8.70E−02
Total fatal		6.88E−02	8.26E−02	7.57E−02	8.95E−02
Additional cost ($)		198,878	248,878	308,878	358,878
	Alternative number of bulkheads	Gross CAF (Subdivision) ($ m)	Gross CAF (Training) ($ m)	Gross CAF (Officer) ($ m)	Gross CAF (Both) ($ m)
Remain afloat					
Slow sinking	14	106.9	111.5	151.0	148.4
Rapid capsize		2.97	3.10	4.19	4.12
Total fatal		2.89	3.01	4.08	4.01

Figure 8.

These calculations clearly indicate that crew training for collision avoidance is a cost-effective measure, whilst the presence of a second officer on the bridge is by no means cost-effective. Implementation of both measures may be recommended, if further reduction of the frequency of collisions is deemed necessary.

Considerations of evacuability

For evacuation of Ro-Ro vessels, the time available to evacuate passengers and crew is likely to be the big unknown (although it may be predicted by computer simulations and controlled through active decision support/active flooding to remain afloat in a stable condition). *Herald of Free Enterprise* capsized in a few minutes, *Estonia* in less than 1½ hours, the Greek ferry *Express Samina* went down in about

40 minutes, while *Titanic* took 2 hours 40 minutes to sink. In several accidents where fire has broken out onboard, the vessel involved survived (remaining afloat) for many hours or even days. However, people have been injured or lost their lives, often due to toxic smoke inhalation (e.g. *Scandinavian Star*, *Sun Vista*)

The term *Evacuability* is defined to be the probability of an environment being completely evacuated no later than a given time elapsed after the alarm went off, in a given state of the environment and a given state of initial distribution of people onboard. With this formalism a sound rule may be proposed, e.g., *Evacuability (60 min, entire ship- worst anticipated conditions-, worst passenger distribution) > 0.99* [14]. Figure 9 illustrates the derived probability density functions for the total evacuation times for the original accommodation layout (Case B) and an alternative layout that provides considerable improvement in the evacuation time (Case A) [3]. The improvement offered by Case A is that all assembly and embarkation stations are considered located on the same accommodation deck, rather than having assembly stations located in two different accommodation decks as in Case B [15]. Figure 10 presents the risk calculations carried out for the accommodation layout of Case A [3].
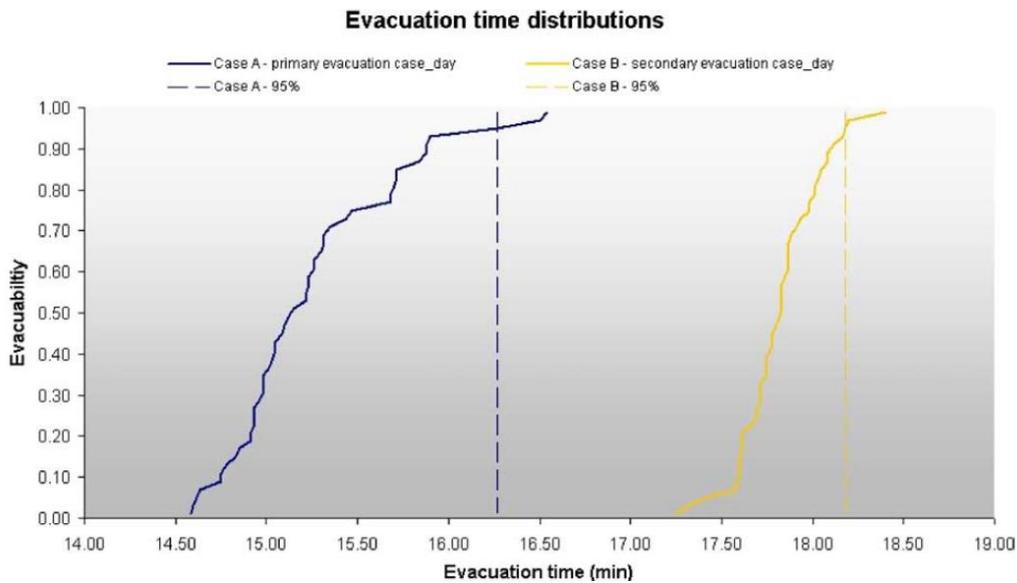

Figure 9.

Number of transverse bulkheads	8	10	12	14	16
Potential Loss of Life (PLL)					
Slow sinking (per ship year)	5.52E−03	4.77E−03	4.35E−03	3.66E−03	3.27E−03
Rapid capsize (per ship year)	1.66E−01	1.43E−01	1.31E−01	1.10E−01	9.81E−02
Overall risk (per ship year)	1.71E−01	1.48E−01	1.35E−01	1.13E−01	1.01E−01
Cost data					
Total cost, ΔC ($)		66,328	132,507	198,878	265,505
Δ PLL					
Slow sinking (per ship year)		7.50E−04	1.17E−03	1.86E−03	2.25E−03
Rapid capsize (per ship year)		2.25E−02	3.51E−02	5.58E−02	6.75E−02
Overall risk (per ship year)		2.33E−02	3.63E−02	5.77E−02	6.98E−02
Gross CAF					
Gross CAF – slow sinking ($ m)		88.4	113.3	106.9	118.0
Gross CAF – rapid capsize ($ m)		2.95	3.78	3.56	3.93
Gross CAF – overall ($ m)		2.85	3.65	3.45	3.81

Figure 10.

5. Conclusions

In this paper risk based design and goal based standards have been investigated as importance-gaining players in the ship building industry and an existing case study has been presented to illustrate the application of risk based methods to specific cases by setting goals, identifying hazards, constructing risk control options, making the analyses by considering cost effectiveness and practicability. Risk based design brings more effort to the design stage, but also provides an important scope called 'safety' , which is especially vital for processes that include very high potential risks within and big industries like ship construction.

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