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Design for Safety: Development and Application of a Formalised Methodology

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Abstract

The paper describes a formalisation of a *Design for Safety* methodology in an integrated environment, outlines early developments of a software tool, and presents the results of an application of the methodology to a case study. The approach adopted attempts to link safety performance prediction through the utilisation of appropriate technical tools, safety assessment deriving from risk-based methodologies and disparate design activities and issues. Blackboard systems have been utilised as the platform in the development of the integrated design environment, allowing safety assessment to become an integral part of the design process. Finally, the case study addresses the application of the developed methodology to three different arrangements of a conventional passenger Ro-Ro vessel, with the aim to demonstrate the validity of the process and methodology adopted. The findings are presented and discussed, and recommendations given for the way forward.

Keywords: design for safety, integrated design environments, blackboard systems

1 Introduction

Safety is a broad concept and understanding of what it actually means tends to vary widely depending on the context and the individual. From a philosophical point of view the need of human beings for safety and security is fundamental. As a result humans become deeply involved with events and phenomena which can have a long or short-term impact on life, property and the environment. Deep feelings are aroused by the controversy over safety, especially when technology fails us and human lives are lost or when ships disappear in the knowledge that simple precautions could have greatly reduced loss of life such as in the recent well-published Ro-Ro accidents. Such emotions, however, can weigh heavily on how rationally and systematically maritime safety is approached, from any of technological, operational and managerial points of view. After investing for decades in ships' hardware for the purposes of increased returns, emphasis must now be shifted towards the human element (humanware) and the organisation and management (software) before a marked improvement of safety can be achieved. With human regard for the environment at an all time high, maritime safety has to be further extended to account for environmental issues, as

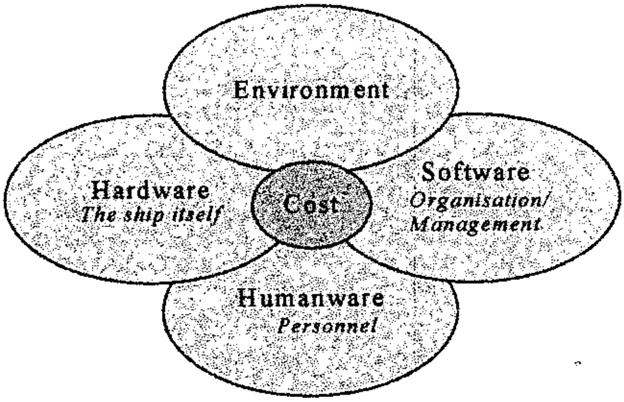

Figure 1: Elements of maritime safety

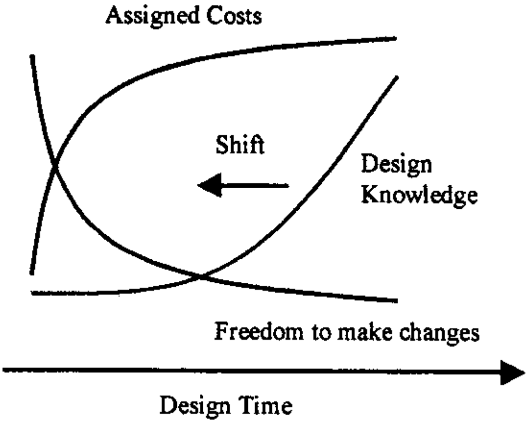

Figure 2: Elements of the design process

shown in Figure 1. In this respect, the following definition is now deemed appropriate:

"hip safety is the quality that reflects a state of acceptable[1] risk concerning humanware, hardware, software and the environment".

This broadening of safety necessitates changes in attitude and the adoption of a new approach capable of striking a balance between all the elements involved cost-effectively and throughout the life cycle of the vessel. The implications deriving from this are many, bringing to surface a plethora of challenges:

- A change in attitude must come first and, hence, the role of education must be pivotal in this process.
- An approach to safety must be based on a comprehensive assessment of the risks involved and risk mitigation measures and must utilise routinely cost-benefit analyses to aid decision making, for safety costs money, particularly poor safety!
- Safety improvement necessitates investment in people.

Approaching safety this way must derive from a logical framework and offer the means to take into consideration both the operating environment and the hazards specific to the vessel in question(Vassalos 1999). With Ro-Ro vessels, for example, one of the tasks should be to quantify the probability of damage with water ingress in a given service area and, another, to quantify the consequences of damage by identifying and analysing all the important factors using probabilistic methods. In this case, however, even though it is self-evident that the risks involved can be minimised by reducing either the probability of damage or the consequences of damage, or both, there is a level beyond which consequences cannot be tolerated. Reducing the probability of damage alone will not suffice. It will be necessary, therefore, to address key questions, seeking answers concerning definition of acceptable risks, definition and management of maximum tolerable consequences and procedures for dealing with residual risks.

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[1] In terms of societal perception and economic considerations

Table 1: Approaches to Ship Safety

"Conventional"	"New"
Reactive	Pro-active
Prescriptive	Goal-setting
Regulation	Self-regulation
Deterministic	Probabilistic (risk-based)
Conformance-based	Performance-based
Compulsory	Safety Culture
Discipline-oriented (sectorial)	Total (integrated)
Experiential	First principles (calculation/simulation)
Hardware focus	Balance of safety elements
Short-term	Life-cycle
Irrational (subjective/emotional/political)	Rational (scientific/cost-benefit analysis)

2 Safety in ship design

Approaches to ship safety are in a transitional state, reflecting the evident shift on the treatment of ship safety from design periphery to a core design factor and from a post-design consideration to a through-life design imperative. A review of the relevant methodologies is given in (Papanikolaou and Konovessis 1999). Conventional approaches are under scrutiny and potential new approaches come under the microscope as the shipping industry is forced to respond positively. Table 1 summarises the various 'conventional' and 'new' approaches to shipping safety.

However, safety in design is still treated haphazardly by designers in the way that safety conformance is rule-based and not an integrated part of the design process. In this respect, safety is excluded from the creative design phase and measures are taken as an afterthought or as a post-design compliance with regulations. To deal with this problem a new philosophy has been adopted through the theme *Design for Safety*, which aims to integrate safety cost-effectively in the ship design process.

In general, ship design is characterised by the fact that some of the most important decisions regarding the ship are taken at the early stages of the process where later design actions are inevitably restricted by the set frame of earlier decisions allowing for little possibility to positively affect cost and performance. Figure 2 illustrates this situation.

As the design process proceeds, the knowledge on the design object increases, whilst the freedom to make changes decreases due to the large costs associated with these changes. There is evidently a need for knowledge feedback to the early stages of the design process where the assigned costs are lower and the freedom to make changes are greater.

The philosophy adopted is illustrated in Figure 3, which aims to facilitate the development of a formalised *Design for Safety* methodology by linking:

- safety performance prediction through the utilisation of appropriate technical tools
- safety assessment deriving from risk-based methodologies
- disparate design activities and issues

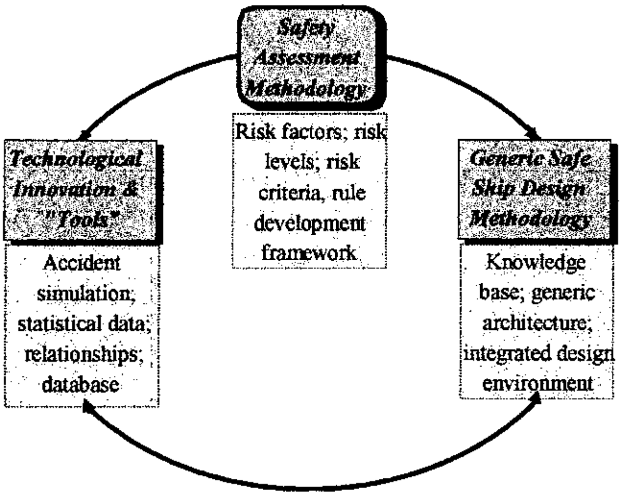

Figure 3: Design for safety philosophy

The underlying theme is that safety assessment will enable safe-ship-designing to be formalised as a process within an iterative procedure that allows a two-way dynamic link between tools and design, where design constraints are defined or filtered by the process of safety assessment. The procedure, on the one hand, gathers and assimilates technical information, prioritises safety issues, identifies practical and cost-effective safeguards and sets requirements and constraints for the design process. On the other hand it provides feedback from the design process to stimulate validation and refinement of the tools, in the light of the experience gained from simulation, implementation, and/or practical applications.

3 A methodology in an integrated design environment

A top-down approach is advocated, governed by high-level events and their frequencies and consequences, in order to design for safety. There is literature on design for safety describing it as a bottom-up approach focusing on component failure and system reliability. However, the latter approach cannot address safety in the early design phases as an integral part of the design process in line with traditional naval architecture disciplines, such as resistance and general arrangement, but is rather targeted in the detail design phase. The bottom-up approach focuses on design for reliability rather than the *Design for Safety* approach described here.

The relationships between risk reduction measures and ship performance must be established in the early design phases, as keeping this relationship outside the design process will only result in local optimisation of safety. The effects of risk reducing design features on resistance, seakeeping, loading/unloading, stability, etc. should be determined by utilising relevant tools in the design process. This aspect is fundamental in the design for safety philosophy. A ship is a compromise between many conflicting parameters and past research has managed to integrate most naval architect issues very well, e.g. stability and hydrodynamics. It is argued that this is not the case for safety and research is needed to both identify relationships with other naval architecture issues and implement this knowledge in the design process. Safety may then develop from being an afterthought to becoming an integral part in the design process.

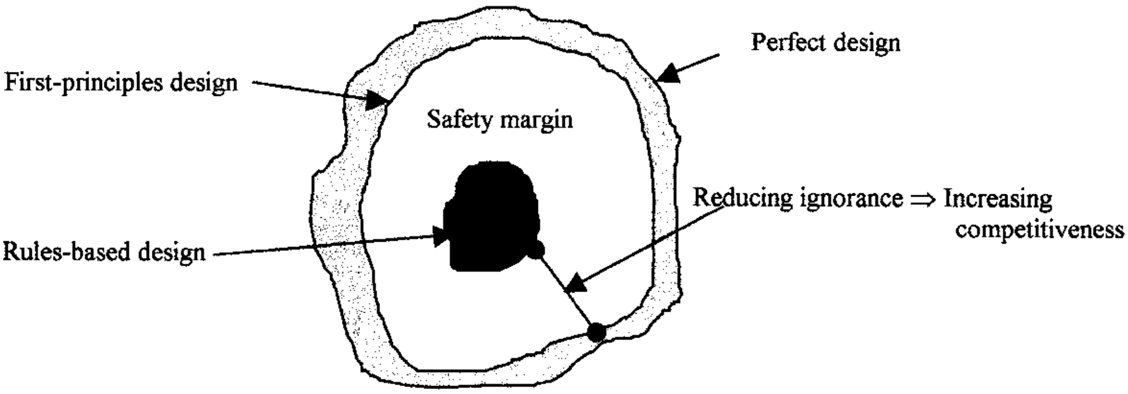

Figure 4: Relationship between safety, costs, and design constraints

A chief concern in integrating safety in the design process, particularly when claiming that this must be done in a way that safety "drives" design relates to the presumption that any investment on safety does not compromise returns. This concept is ill-based. Figure 4 illustrates the relationship between economic and technical issues in a safe ship design process. The outer boundary corresponds to a design solution that achieves a perfect balance among all safety and cost criteria and constraints, which is presently unattainable. Today's practice is represented by the inner boundary, whilst it is argued that a safety-effective and cost-effective solution could be achieved by adopting first-principles-based design. The enhanced awareness on safety-related issues and the improved appreciation of how safety and cost interrelate and interact is slowly beginning to drive home the simple fact that scientific approaches to dealing with safety is the key to increasing competitiveness.

3.1 The safety assessment process

An accident is the result of several undesired events where the seriousness of the accident is a compound set of technical failures, operating errors, fundamental design errors, and management errors. The removal of any contributing links, or causes, may be sufficient to prevent accidents. The chain of events leading to a catastrophic accident for Ro-Ro ships is illustrated in Figure 5.

There are two types of technical safeguards. One safeguard prevents accidents from happening and the other mitigates the effects of accidents. They are treated separately as their contributions to risk reduction are distinct and not comparable. The difference between these two concepts is that by preventing risks the probability, or frequency, of accident occurrence is reduced, whilst by mitigating risks the consequence of the accident is reduced.

On this background, a safety assessment process is established as illustrated in Figure 6. This process is an integral part of a larger *Design for Safety* methodology and targets optimised design of safe, cost-efficient Ro-Ro ships. The safety assessment framework accommodates the various definitions of hazard and risk assessment and their numerical approach, known as quantitative risk assessment(QRA). The merit function of the framework is based on a cost-benefit analysis(CBA)

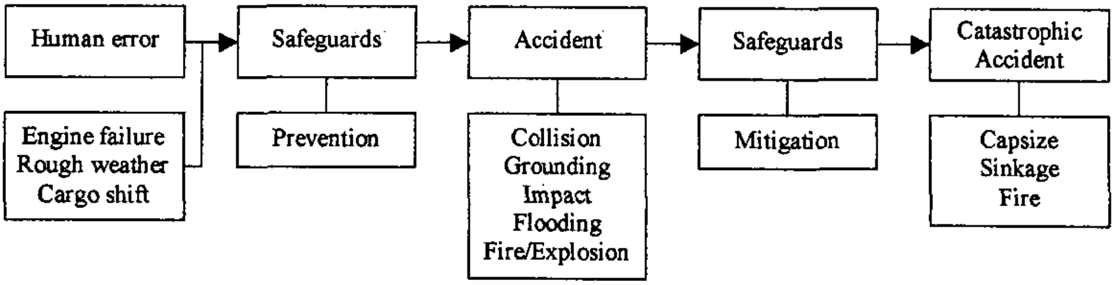

Figure 5: Chain of Events

comparing the costs of manufacturing and operating the proposed safety measures with the benefits of enhanced operational safety. Combined, these components establish the safety assessment process. The main difficulty in this approach is to quantify the benefits of the safety features.

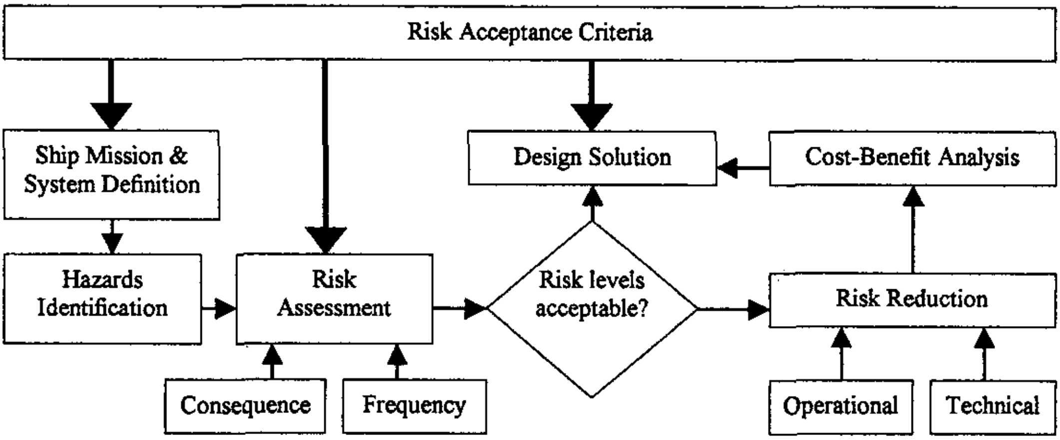

Figure 6: Safety Assessment Process

3.2 A design for safety methodology

The *Design for Safety* methodology, illustrated in Figure 7 (Oestvik 1999), is an iterative process where a solution is sought that is safe, performance and cost-effective aiming at optimal solutions using a top-down approach. Input required is a ship design, which is developed using information modelling techniques.

Risk analysis is performed for the design concept and the resulting quantified risk level is controlled against the risk acceptance criteria. Risk reduction measures, or design features, are considered when a ship fails to meet risk acceptance criteria. There is a general distinction between risk reduction and mitigation means and both must be considered in order to develop an optimal design. On the basis of applying risk reduction measures 'new ship designs' are developed and the effects of the changes are again evaluated against risk acceptance criteria. Designs that are considered to be safe are put forward in the procedure and cost-benefit analysis of the risk reduction measures are performed. Using ICAF(Inverted Cost of Averting a Fatality) criteria the new design solutions are evaluated based on their cost-benefit performance and economic viable design solutions are put forward in the process. The safe and cost-effective design solutions are thereafter assessed for their effect on other performance factors, such as seakeeping, cargo capacity, turnaround time, etc. The resulting solutions of this process are weighted and the best design is put forward in the design process for further development.

The procedure has potential to accommodate multiple accident events, where the effects from the various event-driven design configurations are assessed. In such a scenario, event-driven design features may be conflicting necessitating the use of decision support models in order to derive the best overall design configuration.

3.3 An integrated design environment architecture (IDEA)

An Integrated Design Environment Architecture(IDEA) provides the designer with a means to assess the technical and analytical characteristics of the design using relevant tools. The IDEA must be formalized indicating that entities, attributes and relationships for the relevant issues are generic. This allows information to dynamically change, for altering design input and innovations can be readily implemented. The design information is stored in object-oriented knowledge bases, which are updated independently as required. A control and management function is needed to accommodate these issues. The design for safety procedure outlined in the foregoing has been accommodated in an IDEA using blackboard systems as the platform. An IDEA is illustrated in Figure 8, having a central blackboard to control and manage the overall ship design process applying the appropriate knowledge bases, tools and methodologies.

3.4 Blackboard systems

Blackboard systems(BBS) are regarded as a part of the Artificial Intelligence family and originated with the Hearsay project in the USA twenty years ago(Nill 1986a, Nill 1986b). BBS constitute the fundamental assumption of design co-ordination, a formalisation within concurrent engineering. Design co-ordination emphasises that tasks must not necessarily be carried out concurrently, but rather in such fashion as to achieve optimum performance. Design co-ordination is defined as a high level concept of the planning, scheduling, representation, decision-making and control of product development with respect to time, tasks, resource utilisation and design aspects(Duffy et al 1995).

The philosophy of blackboard systems is to opportunistically piece together a solution on the blackboard by using external knowledge sources, which are working co-operatively and are activated by a control mechanism, be it human or software programs, applying the right knowledge at the right time(Corkill 1991).

In this respect, various sources of knowledge participate in forming and modifying the emerging solution by knowledge sources contributing opportunistically when called upon. Furthermore, as steps are taken toward the solution, the processing commitments are minimised since the solution is built incrementally and steps of forward chaining can be arbitrarily interleaved with steps of backward chaining. Blackboard systems are particularly effective for incremental solution generation, which is typical for the ship design process, where the knowledge sources contribute to the solution as appropriate, outperforming a problem solver that uses the traditional ship design approach to generate a solution.

3.5 An integrated design for safety environment

Current ship design practice is a design-check (trial-and-error) procedure, which is insufficient as it keeps safety considerations outside the creative design process and make amendments afterwards in order to satisfy rules and regulations. This work integrates safety assessment in the design process allowing for design of safe, cost-efficient ships in an iterative procedure. The vehicle for this integration is an integrated design environment utilising the outlined blackboard system applications. A prototype ship design blackboard system has also been developed, as reported in (Oestvik et al 1999).

A blackboard system has been developed accommodating the Design for Safety procedure described in the foregoing. The Design for Safety process has been embedded in an integrated environment, using blackboard systems(BBS) as the platform in order to function as a decision support tool for a designer. The blackboard system program specification is outlined in Table 2, which was the basis for the developments.

The integrated *Design for Safety* environment, illustrated in Figure 9, accommodates a methodological assessment of relationships between safety, cost, and design features adopting a top-down approach by assessing hazards and risks at the event level, i.e. for collision, grounding, impact, flooding, and fire/explosion. Furthermore, the IDEA accommodates the identification of risk prevention and mitigation measures, cost-benefit quantification of design features/safeguards, assessment of ship performance effects and provides decision support in order to design safe, cost-efficient ships fulfilling the operational themes in an iterative procedure.

4 Application

The case study addresses the application of the developed methodology, with the aim to demonstrate the validity of the process adopted. It mainly draws from the area of *Design for Survivability*, a field of particular importance within the broad spectrum of ship safety. The application focuses on collision incidents and possible outcomes, by carrying out a study of safety-critical design features using damage stability and survivability calculations and criteria as the means to obtain the benefits on risk reductions and concludes with the selection of the more appropriate alternative through design trade-offs between different safety and cost-effectiveness or performance measures.

An existing passenger Ro-Ro vessel, of typical size and layout for the Northwest European routes, has been used as the example ship. The vessel has been built at the early 1980s and complies with the SOLAS 74 two-compartment damage stability standard. The three upgrading alternatives considered are providing marginal compliance to the SOLAS 90 two-compartment standard. The particulars of the alternatives are as follows:

- **Sponson alternative (S)**: Sponson fitted at the midship area of the ship with length of 51.75 m. width of 0.7 m and of conventional configuration (vertical extent from below waterline to a depth above the car deck level).

- **Transverse bulkheads alternative (B)**: Four transverse bulkheads of 4 m height have been considered installed on the car deck.
- **Combination alternative (C)**: Two transverse bulkheads of 4 m height have been considered installed on the car deck (at the same locations with the aft and fore bulkheads of the previous alternative), together with the fitting of a sponson at the midship area of the ship with length of 31.5 m, width of 0.8 m and of conventional configuration.

Hazard identification and analysis of the associated risks have not been performed for the case study. Instead, generic figures for collision incidents obtained from the safety assessment in the Joint North West European Project have been used. These figures are obtained from relevant accidental data, theoretical models and expert judgements, and are therefore applicable in the main for this study. More specifically, the event tree for collision outcomes contained in (Spouge 1996) is used. The event tree is reproduced in the Appendix. The considered final outcomes for a collision incident have been associated with their potential to cause a number of fatalities or no fatalities at all. In this respect, a categorisation of the final outcomes that can potentially cause minor, considerable, or major number of fatalities is possible. In Table 3 the aggregation of the frequencies per ship year relevant to the final outcomes of a collision incident is shown.

Damage stability calculations have been carried out for the existing vessel and the three upgrading alternatives for one-, two- and three-compartment damages cases, assuming B/5 inboard penetration for all the cases (standard SOLAS notation). Elements of the probabilistic framework developed during the Joint North West European Project have been utilized(Rusaas et al 1996) for the aggregation of results to form comparable measures of safety levels achieved by the different alternatives considered.

The Attained Index is considered as follows:

$$A_i^* = \sum_{l}^{i} p_i^* \times s_i^* \tag{1}$$

with i=1,2,3 and

$$p_i^* = \int_{1/L-\varepsilon}^{1/L+\varepsilon} f(x)dx \tag{2}$$

the probability that a compartment or combination of compartments are being flooded, with l the flooded compartment(s) length, f(x) the distribution for damage length used in the Joint North West European Project, and ε a small positive number. In the current context, this probability is used as a weight that a certain damage will occur. Finally,

$$s_i^* = \sqrt[4]{GZ_{max} \times Range \times Area} \tag{3}$$

with GZ_{max}, positive range of and area under the GZ curve corresponding to the actual attained values of the damage case in question. In the current context, this factor is not expressing a probability, but a figure which when aggregated will express the full benefit offered by an alternative.

Table 4 contains the calculated increments on the attained indices of the three upgrading alternatives (S, B and C) against the existing ship's corresponding indices. The results clearly suggest that the installation of transverse bulkheads on the Ro-Ro deck is the best solution from safety enhancement point of view.

These increments can be directly applied to calculate the benefits and residual risks for the three alternatives, based on the original risk levels contained in Table 3. It is assumed therefore, that the risk levels in Table 3 correspond to the existing ship configuration. Furthermore, a correspondence mapping is possible if we consider that one-compartment damage cases relate to incidents involving minor number of fatalities, and one- and two-compartment damage cases, and one-, two- and three-compartment damage cases relate to considerable and major number of fatalities respectively. Table 5 contains the benefits and the residual risk levels for the three alternatives.

The risk levels contained in this table can be compared against societal risk criteria, applicable to passenger Ro-Ro vessels. Such criteria have been proposed as part of the work of the safety assessment study of the Joint NW European Project, in the form of the F-N curve. As it can be seen from Figure 10 the original level of risks for the existing ship is generally high in the ALARP region, even in the intolerable risk region for minor number of fatalities, which coincides with the general observation for the level or risks for existing passenger Ro-Ro ferries.

In order to calculate the ICAF, a cost model has been developed appropriate for the problem. It takes into account the cost associated with procurement and installation or fitting of the devices (a period of 15 years of remaining operational life with a 5% discount rate have been assumed), and the effects on payload, manning, maintenance and fuel consumption. Table 6 contains the comparisons of the different alternatives with respect to the calculated ICAF. These results now suggest that accounting for costs incurred following the installation of safety enhancing devices, the sponson solution is the clear favourite.

Measures costing less than £2m per fatality averted are considered cost-effective and should be adopted. Measures costing more than £50m are not considered cost-effective and will not normally be adopted. Measures having a cost in the range between £2m and £50m must be carefully evaluated according to their benefits, which is the case for all three alternatives considered. In order to decide on the alternative to consider for the upgrading of the vessel, trade-offs between safety measures and cost-effectiveness or performance indicators are necessary. Safety measures can be expressed with the levels of residual risks or the benefits obtained (Table 5). Cost-effectiveness can be expressed with the annual cost or the calculated ICAF as contained in Table 6. A performance indicator can be obtained through the considerations of Table 7. The ranking of the alternatives is achieved when considering the five areas (resistance, manoeuvring, loading time, survivability in waves and capacity) and the effect expressed on the scale 1 to 3, with the notation that the higher the figure the more effective the alternative is. The ranking is based on judgements and on the actual performance of the vessel. No weighting among the areas has been considered, in order to maintain the generic nature of the application. In this respect, the highest possible score for a design is 15.

The trade-offs contained in Table 8 prove that the alternative that utilises a combination of bulkheads and sponson can be considered as the best solution to the problem. This result coincides with the decision taken by most of the owners/operators that have already undertaken upgrading of their vessels.

5 Conclusion

A formalised *Design for Safety* methodology has been described with particular reference paid to the essential elements necessary for the required endeavours to be met. Safety assessment should become an integral part of the ship design process. An appropriate integrated environment has been defined and the vehicle to act as the platform for the development has been identified, through a detailed account of the benefits that blackboard systems technology can offer to ship design. Based on the above, initial software tools development has been briefly described. Finally, a case study has proven the validity of the methodology adopted, in a process that technical elements of safety (i.e. damage survivability in waves) have been considered in parallel with the classical ship design tasks.

The approach adopted developing the *Design for Safety* methodology can be made generic to accommodate other issues. The approach describes the current situation for the topic in question (reality), the development and utilization of information models and integrated design environments resulting in an overall methodology for future application in industry/academia.

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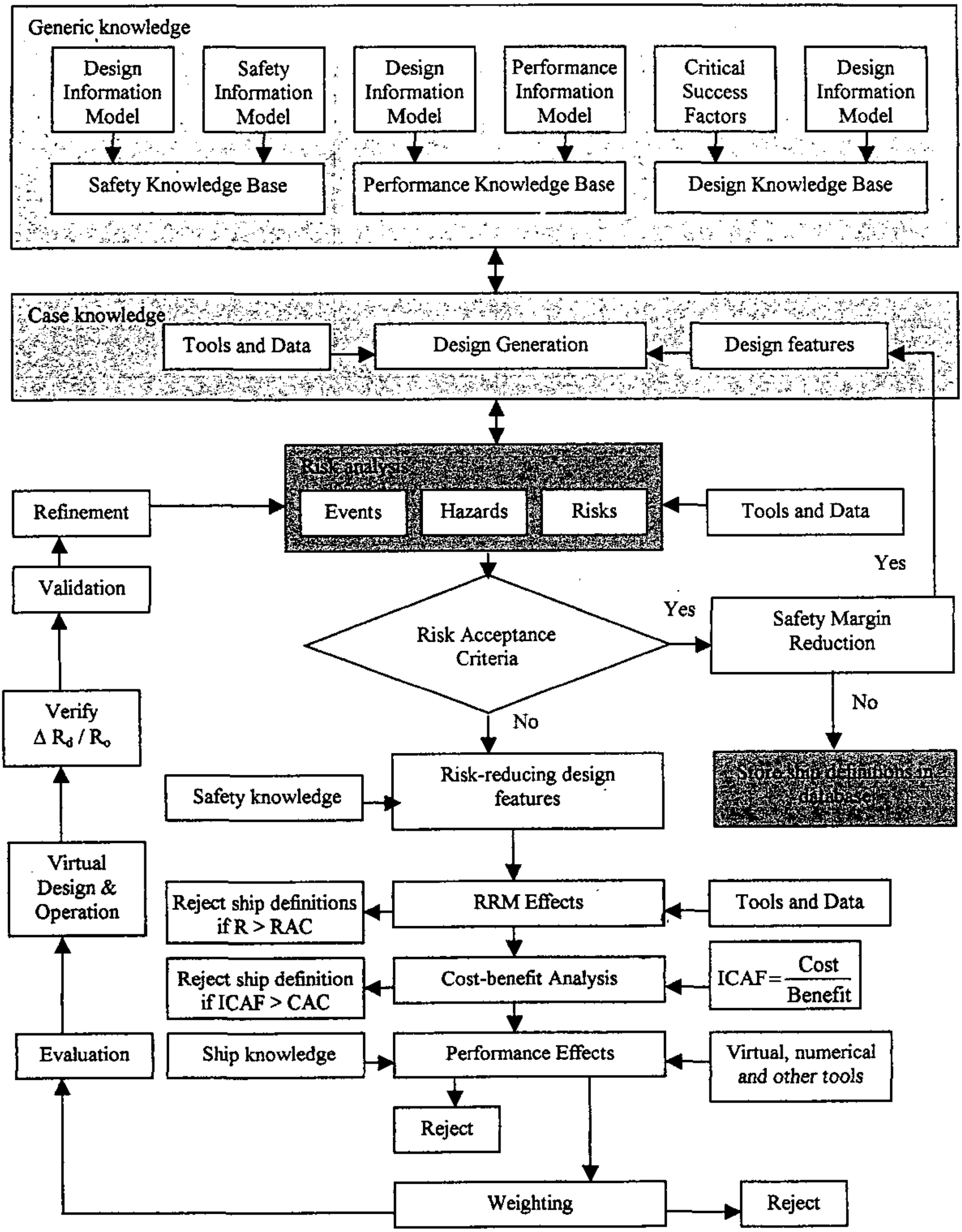

Figure 7: Generic design for safety methodology

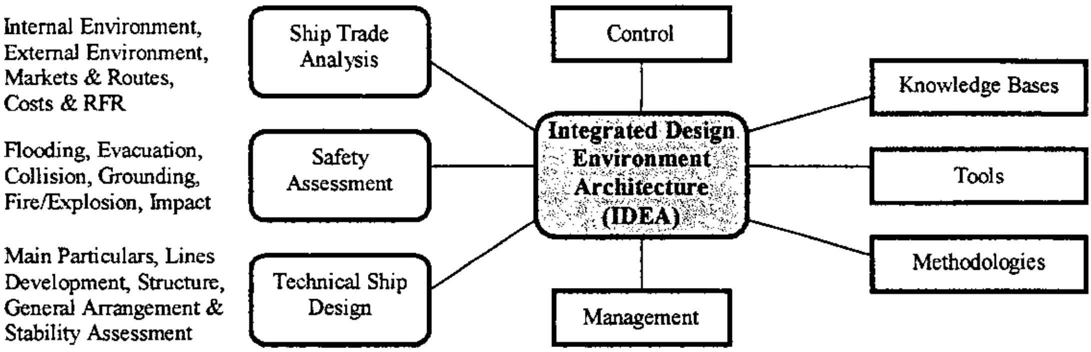

Figure 8: An Integrated Design Environment

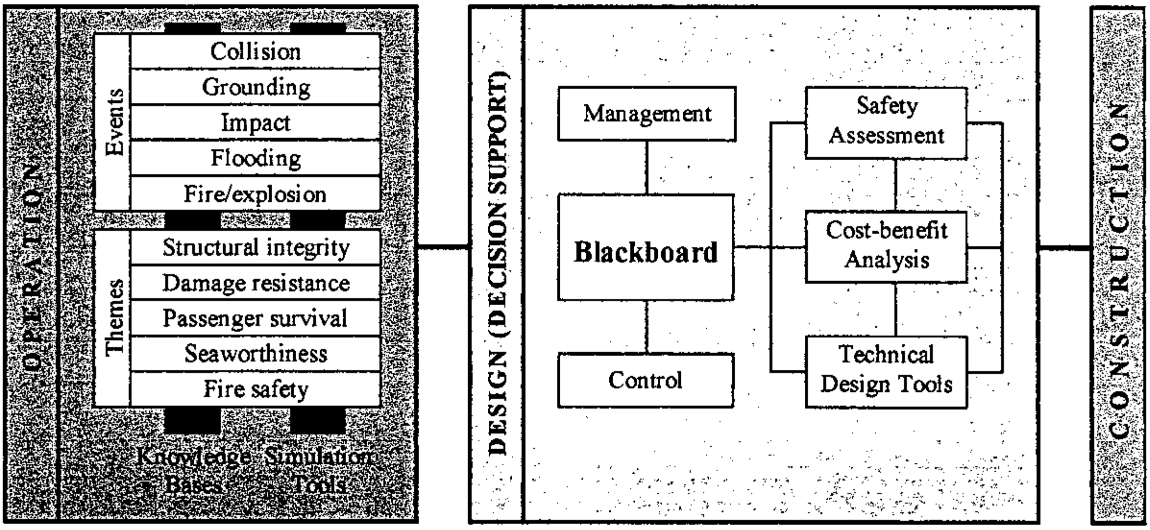

Figure 9: An Integrated Design for Safety Environment

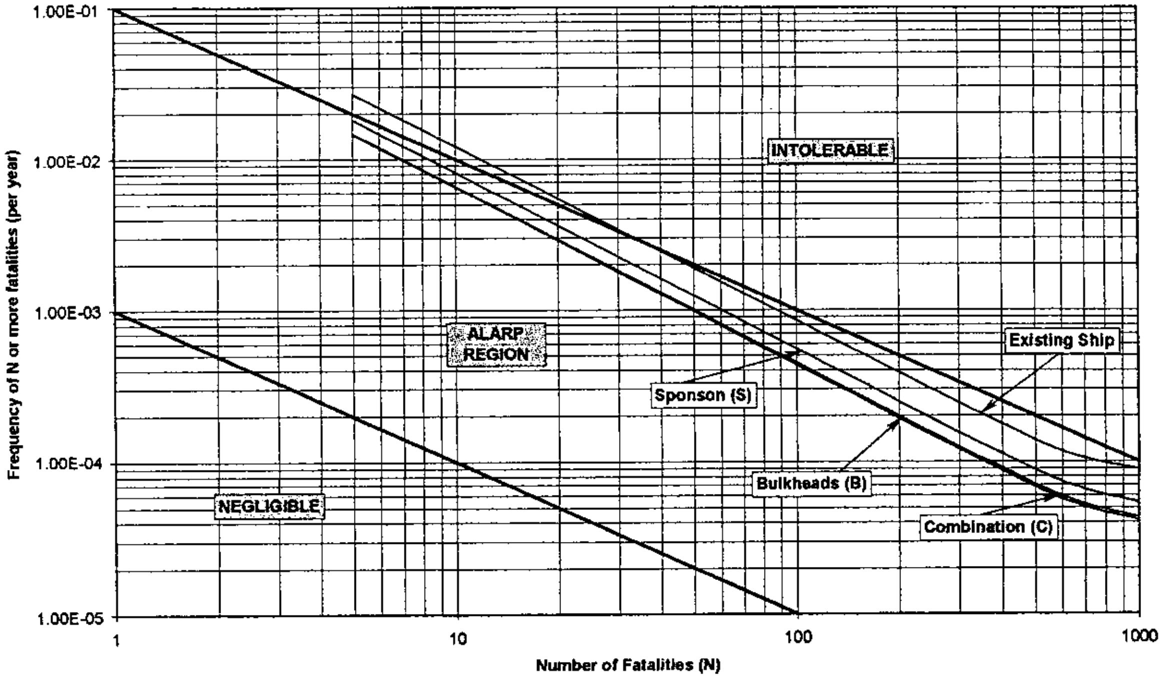

Figure 10: F-N Curve for the Existing Ship and the Three Upgrading Alternatives

Table 2: Blackboard System Specification

	KS	**Task**	**Work comments**
10	Start	Start program	Introduce user to program
20	Ship type and configuration	Identify ship type and import ship configurations	Identify ship type on the blackboard
30	Events	Select events	Select events for assessment for the ship type in question
40	Hazard	Identify event-specific hazards	Identify event-specific hazards using databases or hazard identification techniques (if data do not exist)
50	Frequency	Identify event frequency	Identify overall event frequency using databases or fault tree techniques.
60	Consequence	Identify consequences of events	Identify consequences of events using databases or event tree techniques.
70	Design Risk	Identify probability of fatal events	Identify probability of fatal incidents for designs using databases or event tree techniques
80	RAC	Check risk acceptance criteria	Use databases to check risk for ship design configuration vs. fatal event criteria - when r < rac then store ship definition in database and go to 160, when r > rac then proceed
90	Risk Reduction	Reduce risks	Identify preventive and mitigating design features (rrm) to reduce risks for specific hazards and events using a safety knowledge base
100	Design Generation	Generate new ship designs	Implement rrm on unsafe design configuration resulting in a number of new ship design configurations for the considered events
110	RRM Effects	Identify effects	Determine the effects of rrm on risk using programs or databases and assess effects on other events
120	RAC	Check risk acceptance criteria	Use databases to check risk for rrm ship design configuration vs. fatal event criteria - when r < rac then proceed, when r > rac then reject rrm design
130	Cost-Benefit	Determine ICAF ratio	Determine ICAF ratio for safe rrm design configuration - when ICAF<CAC then store in database, when ICAF > CAC then reject
140	Ship performance effects	Safety and performance relationship	Identify relationship between rrm designs and design performance using virtual and numerical tools or data – when performance is OK proceed, otherwise reject design
160	Weighting	Weight event-based design configurations	Weight event-based design configurations and identify the best configuration based on route characteristics
170	Virtual design and final selection	Design virtual ships and select final ship design configuration	Build up virtual representations of the remaining ship design configurations and select final design configuration to be put forward to virtual operation
180	Virtual operation	Identify operational hazards and risk	Identify operational hazards and risks for ship configuration in virtual ship system
200	Refinement	Refine tools	Compare risk used in design process with operational risk (go to 70 to refine design risk); when no refinement needed then proceed
210	Finish	End program	Terminate program or go to 10

Table 3: Final outcomes of collision incidents(frequencies per 1000 ship year)

Incidents involving	**ID Codes for Final Outcomes**	**Frequencies**
No Fatalities	C2.1, C3.1.1, C2.3, C3.2.1, C5/C6	3.9916
Minor Number of Fatalities	C1, C2.2, C4.1, C4.3	26.8212
Considerable Number of Fatalities	C3.1.2, C4.2, C3.2.2, C4.4	0.1398
Major Number of Fatalities	C3.1.3, C4.5	0.08991
Total		**31.04251**

Table 4: Attained indices of upgrading alternatives

Alternative	A_1^*	A_2^*	A_3^*
Sponson(S)	32.7%	36.5%	38.9%
Bulkheads(B)	45.5%	51.3%	53.4%
Combination(C)	44.7%	49.1%	51.9%

Table 5: Benefits and residual risks for the three alternatives (frequencies per 1000 ship year)

Incidents involving	**Existing Ship**		**Sponson Alternative(S)**		**Bulkheads Alternative(B)**		**Combination Alternative(C)**	
	Benefit	Risk	Benefit	Risk	Benefit	Risk	Benefit	Risk
No Fatalities		3.992		3.992		3.992		3.992
Minor Number		26.821	8.744	18.077	12.177	14.644	11.989	14.832
Considerable		0.139	0.051	0.088	0.071	0.068	0.068	0.071
Major Number		0.089	0.035	0.054	0.048	0.041	0.046	0.043
Total		**31.041**	**8.83**	**22.211**	**12.296**	**18.745**	**12.103**	**18.938**

Table 6: Comparison of alternatives with respect to ICAF

Alternative	**Benefit**	**Cost (£ per Year)**	**ICAF (£m per Fatality Averted)**
Sponson (S)	8.83×10^{-3}	240,000	27
Bulkheads (B)	12.296×10^{-3}	605,000	49
Combination (C)	12.103×10^{-3}	408,000	34

Table 7: Performance indicators

Design Aspect	**Sponson Alternative(S)**	**Bulkheads Alternative(B)**	**Combination Alternative(C)**
Resistance	1	3	2
Manoeuvring	1	3	2
Loading Time	3	1	2
Survivability	1	2	3
Capacity	3	1	2
Total	**9**	**10**	**11**

Table 8: Design Trade-offs

Trade-offs	**Sponson Alternative(S)**	**Bulkheads Alternative(B)**	**Combination Alternative(C)**
Safety(Risk Benefit) Vs. Performance	$(8.83 \times 10^{-3}, 9)$ $(0.718, 0.6)$ 0.489	$(12.296 \times 10^{-3}, 10)$ $(1, 0.667)$ 0.333	$(12.103 \times 10^{-3}, 11)$ $(0.984, 0.733)$ $\mathbf{0.267}$
Safety(Residual Risk) Vs. Performance	$(22.211 \times 10^{-3}, 9)$ $(0.844, 0.6)$ 0.429	$(18.745 \times 10^{-3}, 10)$ $(1, 0.667)$ 0.333	$(18.938 \times 10^{-3}, 11)$ $(0.989, 0.733)$ $\mathbf{0.267}$
Safety(Risk Benefit) Vs. Cost-Effectiveness (Cost per Year)	$(8.83 \times 10^{-3}, 240000)$ $(0.718, 1)$ $\mathbf{0.282}$	$(12.296 \times 10^{-3}, 605000)$ $(1, 0.397)$ 0.603	$(12.103 \times 10^{-3}, 408000)$ $(0.984, 0.588)$ 0.412
Safety(Risk Benefit) Vs. Cost-Effectiveness (ICAF)	$(22.211 \times 10^{-3}, 27)$ $(0.718, 1)$ $\mathbf{0.156}$	$(18.745 \times 10^{-3}, 49)$ $(1, 0.397)$ 0.449	$(18.938 \times 10^{-3}, 34)$ $(0.984, 0.588)$ 0.206
Performance Vs. Cost-Effectiveness (Cost per Year)	$(9, 240000)$ $(0.6, 1)$ $\mathbf{0.4}$	$(10, 605000)$ $(0.667, 0.397)$ 0.689	$(11, 408000)$ $(0.733, 0.588)$ 0.491
Performance Vs. Cost-Effectiveness (Cost per Year)	$(9, 27)$ $(0.6, 1)$ 0.4	$(10, 49)$ $(0.667, 0.551)$ 0.559	$(11, 34)$ $(0.733, 0.794)$ $\mathbf{0.337}$

Explanation: The values in the first line for each trade-off are the actual values attained by the alternative. In the second line the corresponding relative values are contained whereas (1, 1) is the ultimate best design. Finally, the distance from the point (1, 1) is calculated. The alternative that is closer to point (1, 1) for each trade-off is highlighted in bold.

APPENDIX

Final Outcomes for Collision Incidents [Spouge, 1996]