

Risk-based design-realising the triple-a navy

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ABSTRACT

"Design for Safety" refers to a design paradigm introducing safety in design as another objective. This requires explicit consideration and quantification of safety, which is equivalent to evaluating risk during the design process; hence the term "Risk-Based Design". The essential advance attributable to Risk-Based Design is the holistic, explicit, rational and cost-effective treatment of safety, without which optimal design solutions are not feasible. This is achieved on the basis of principles that support multi-discipline design optimisation and promote the use of knowledge in all forms. More specifically:

- A formalised procedure to measure safety consistently (risk analysis / risk assessment / risk management).
- Flexibility to allow trade-offs between Performance, Earnings, Risk and Costs; hence focus on life-cycle issues.
- Integration of such procedure in the design process (integrated design environment) with focus on holistic optimisation.

The "Design for Safety" philosophy and the ensuing formalised methodology, "Risk-Based Design (RBD)" were introduced in commercial shipping as a design paradigm in the 1990s to help bestow safety as a design objective and a life-cycle imperative. This was meant to ensure that rendering safety a measurable (performance-based) design objective, through using first-principles tools, would incentivise industry to seek cost-effective safety solutions, in response to rising societal expectations. It turned out that removing rules-imposed (largely-conservative) constraints and the adoption of a performance-based approach has had much more profound effects than originally anticipated, the full impact of which is yet to be delivered. This is particularly true for knowledge-intensive and safety-critical ships, such as naval vessels and the giants of the cruise ship industry being built today, where the need for technological innovation creates unprecedented safety challenges that cannot be sustained by prescriptive-regulation-based safety.

Drawing from the implementation of Risk-Based Design in the cruise ship industry, this paper presents and discusses the process of implementation and impact, demonstrating that all pre-requisite scientific and technological developments are in place for Risk-Based Design to be fully implemented in the naval sector as the platform to deliver active, adaptive and affordable vessels.

Keywords: Design for Safety; Risk-Based Design (RBD); Safety Measurement and Verification; Life-Cycle Risk management

INTRODUCTION

Safety permeates all physical and temporal boundaries and as such it is the most influential factor in ship design and operation. Conversely, all human activity in a "risky" environment, such as the sea and in a fiercely competitive, tight-margins industry, such as the marine industry within a fast-changing, technology-intense world, is fraught with wide-ranging problems that tend to undermine safety. This calls for a "safety system" that is generic and flexible for ease of adaptation to change, holistic for ease of transcending complexity and sustainable for ease of gaining wider acceptance and support, thus providing a foundation for continuous improvement. Such requirements demonstrate the deficiencies of the current safety system (prescriptive) and the challenges that lie ahead. This is particularly true for knowledge-intensive and safety-critical ships, such as naval vessels and the giants of the cruise ship industry being built today, where the need for innovation creates unprecedented safety challenges that cannot be sustained by prescriptive-regulation-based safety. The reason for this is simple: traditional approaches to safety (rules-based) are experiential and with change happening faster than experience is gained, the "safety system" is unsustainable. This realisation helps explain the need for changing the way safety is treated in the maritime and naval sectors. The need to change the way safety is being dealt with is forcing the realisation that the maritime industry is a "risk industry", thus necessitating the adoption of risk-based approaches to maritime safety. This, in turn, is paving the way to drastic evolutionary changes in ship design and operation, more specifically to the development and implementation of Risk-Based Design (RBD) as the formal design methodology treating safety as a design objective rather than a constraint. The biggest impact has been at the International Maritime Organization (IMO) and by IMO: Safety Level, Alternative Design and Arrangements, Goal-Based Standards, Safe Return to Post, to name but a few unprecedented legislative instruments. The adoption of these marks the beginning of contemporary safety, catalysing an impact that is still being delivered.

Albeit maturity of the underlying concepts, tools and techniques still remains a quest, there is tangible evidence of existing capability for implementation to the knowledge intensive cruise ship design as well as of the benefits being derived, particularly in facilitating multi-objective design optimisation with safety as one of these objectives. It is with this in mind and considering the recent climate of declining defence budgets and increasing ship costs, leading to rapidly decreasing number of ships in most western navies, that this paper advocates the use of a truly holistic approach for a safety-critical platform as the only vehicle to counter potential decrease in capability through innovation in the ship design process, namely the use of Risk-Based Design methodology.

DESIGN FOR SAFETY: RISK-BASED DESIGN

By defining *safety* as *the state of acceptable risk* (Vassalos, 1999), the duality "safety and risk" becomes easier to apprehend and this facilitates understanding of all the ensuing concepts. In this respect, "Design for Safety" refers to a design paradigm introducing safety in design as another objective. This requires explicit consideration and quantification of safety, which is equivalent to evaluating risk during the design process; hence the term Risk-Based Design. Discussions at IMO over Goal-Based Standards have given rise to another term "Safety Level", a wrong choice of terminology but it was meant to designate the through-life level of acceptable risk associated with a particular ship concept and, as such, becoming the new guiding philosophy to attaining safety cost-effectively. What this entails, however, is no mean task; it is nothing less than being able to quantify the life-cycle risk of a vessel by considering all "passive" (design) and "active" (operational) safety measures and to do so during the concept design stage under extremely tight cost and time constraints. Application of RBD is biased towards design concepts with high levels of innovation, hence design risk. The essential advance attributable to RBD is the holistic, explicit, rational and cost-effective treatment of safety. To achieve this, the following principles have been put forward (Vassalos, 2008):

1. A consistent measure of safety must be employed (risk) and a formalised procedure of its quantification adopted (risk analysis). For this to be workable, considering the complexity of what constitutes safety, a top-down approach is required with clear focus on major accident categories and Key Safety Performance Indicators (e.g., A-Index for damage stability and similar indices for fire, systems availability, evacuability, etc.)), all such performances captured with knowledge intensive models to enable fast and accurate safety performance evaluation and to facilitate optimisation studies.
2. Formal procedures for risk quantification, risk assessment and risk management, used in the marine industry include the Formal Safety Assessment (IMO FSA 2002) for generic risk assessment (at ship fleet level) and in support of the rule making process and the Safety Case of the Health and Safety Executive (HSE Safety Case 2005) for use in specific design/measures, among others. The right-hand-side of Fig 1 illustrates the elements of a typical "safety assessment process".
3. Such procedure must be integrated in the design process to allow for trade-offs between safety and other design factors by utilising overlaps between performance, life-cycle cost considerations, functional requirements and safety. The interfaces between the ship design process and the safety assessment procedure are illustrated in Fig 1. Consequently, additional information on safety performance and risk will be available for design decision-making and design optimisation.
4. Considering the level of computations that might be necessary to address all pertinent safety concerns and the effect of safety-related design changes on the overall design performance, a different handling of the design process is required. Namely, to allow for trade-offs between safety and other design objectives through overlaps at parameter level, the latter will also need to be addressed through the use of parametric models and access to fast, accurate and knowledge-intensive tools as well as access to databases (past designs, incident /accident data, etc.). Furthermore, the need for integration of all the tools and data under one umbrella (Integrated Design Environment) to facilitate data and process management is paramount. Risk-based Design is by its very nature akin to holistic optimisation and use of formal optimisation and data analysis techniques essential to achieving optimum design solutions whilst ensuring cost-effective safety.

The aforementioned RBD principles are reflected in the following high-level definition: *RBD is a formalized methodology that integrates systematically risk assessment in the design process with prevention/reduction of risk embedded as a design objective, alongside "conventional" design objectives*. Put differently, safety rules give way to safety objectives, giving rise to additional functional requirements and design criteria and to the need for first-principles tools for **verification of "safety performance"**, in the absence of experiential knowledge. Key to understanding RBD is the integration of risk assessment in the design process and decision-making towards achieving the overall design goals but also as part of a parallel (concurrent) iteration within the safety assessment procedure to meet safety-related goals/objectives as depicted by the high-level framework of Fig 1. In relation to design decision-making, in the same way of using explicit ship performance evaluation criteria (design criteria) and economic "targets" (owner's requirements), there is a need to define safety performance evaluation criteria and risk acceptance criteria. The latter could be related to safety performance criteria, so that safety performance could be used in the design iterations, alongside or even instead of explicit risk acceptance criteria. As a result, key design aspects of the initial baseline designs (watertight subdivision, structural design, internal layout, main vertical zones, bridge layout, materials,

major ship systems, including safety systems, etc.) can be optimised from the point of view of ship performance, cost implications, potential earnings whilst ensuring that the safety level (as quantified) is appropriate and commensurate with acceptable and quantified risk levels (provided that such do exist).

Another key aspect to Risk-Based Design is that any ship design decision will be well-informed and will lead to design concepts that are technically sound (at least to a level commensurate with state-of-the-art), fit for purpose, and last but not least, with a known level of safety that is more likely (than by following rules) to meet contemporary safety expectations.

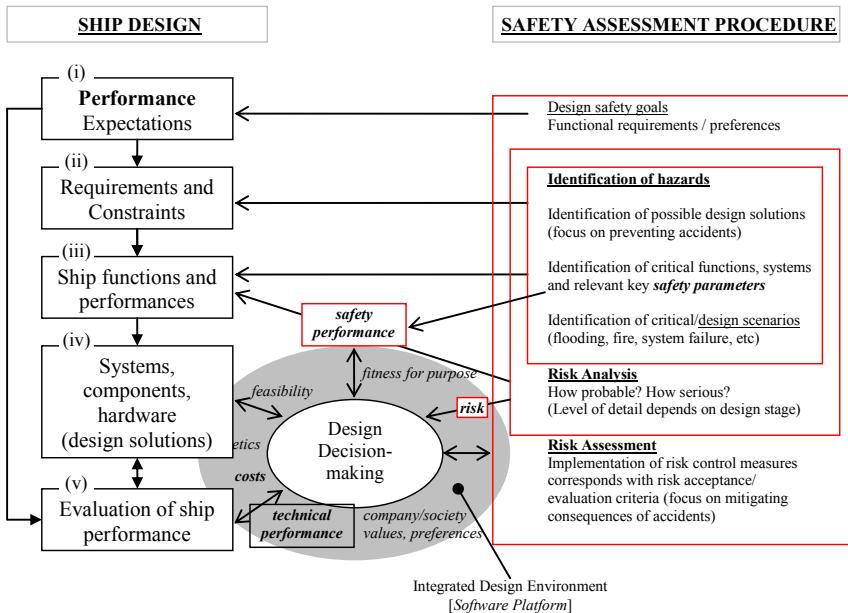


Fig 1 A High Level Framework for Risk-Based Design

LIFE-CYCLE SAFETY (RISK) MANAGEMENT (LCRM)

Concept and needs

Every time there is an accident in the marine industry exposing gaps in design and operation, societal outcry follows, leading to new rules that target design improvements to address damage limitation post-accident. Any such improvements focus mainly on newbuildings, which comprise a small minority of the existing fleet. Therefore, state-of-the-art knowledge is often wasted, scratching only the surface of the problem and leaving thousands of ships with severe vulnerabilities, that is almost certain to lead to further (unacceptably high) loss of life, property and damage to the environment. The time is ripe, however, to review critically maritime safety and lay the foundations for a modern, sustainable system. Key to this is adopting a life-cycle approach for effective risk management. A formal process should address risk at the design stage (risk reduction/mitigation), in operation (managing residual risk) and, ultimately, in emergencies (crisis management), ensuring in all cases a tolerable level of risk. Traditionally, however, safety is addressed as a fundamental design problem focussing on design measures for safety improvement. Operational /active measures (in normal operations and during emergencies) to address safety have not been pursued in a similar fashion in a way that provides measurable and hence auditable safety improvement. Considering the above, a life-cycle perspective offers a framework for a holistic approach to risk management, focusing on life cycle and encompassing all feasible risk control options, accounting for these based on cost-effectiveness. This assumes that the risk reduction potential of all such measures is known and this is where there is a big gap that needs to be overcome before such a process can be institutionalised. Moreover, while it is clear that the overall safety impact of new technologies and solutions becoming available through applied research and innovation needs to be quantified, it must be acknowledged that no agreed methodology exists for this purpose except for the feedback loop described in the IMO GBS Guidelines. IMO has identified the Safety-Level Approach under the Goal-Based Standards (GBS-SLA) as the future approach to improve maritime safety (aiming for a truly Risk-Based Regulatory Framework).

In this respect and in order to industrialise the measurement and management of risk over the life-cycle of the vessel, it is important that the performance of the applied risk control options is continuously monitored so that inherent uncertainties are quantified, a better understanding on the safety level is obtained and the retrieved feedback can ensure that the vessel is built to meet her intended purpose. Furthermore, by encompassing the interaction of

human, organisational, technological and software aspects, the emphasis is given on realising how the risk control options contribute to efficient risk management implementation. Hence, with such an holistic approach, it is assured that objective information is collected so that safety is expressed with numbers (i.e. safety index), it is not isolated between design and operation and the decisions are based on a transparent as well as traceable base. This change of paradigm will be attained only by setting and demonstrating the effect of continuous safety improvement through data, which is perceived as the cornerstone of life-cycle risk management. An essential element in institutionalising the process is the development and adoption by IMO of a life-cycle risk management regulatory framework to expedite assignment of credit for any measure and means of risk reduction. Pursuing the realisation of the full potential of life-cycle risk management, it is expected that during the process, issues with respect to data collection and methodology, monitoring systems, sensors, models, tools, etc. may be identified, thus requiring resolution through specifically targeted research, as shown in Fig 2.

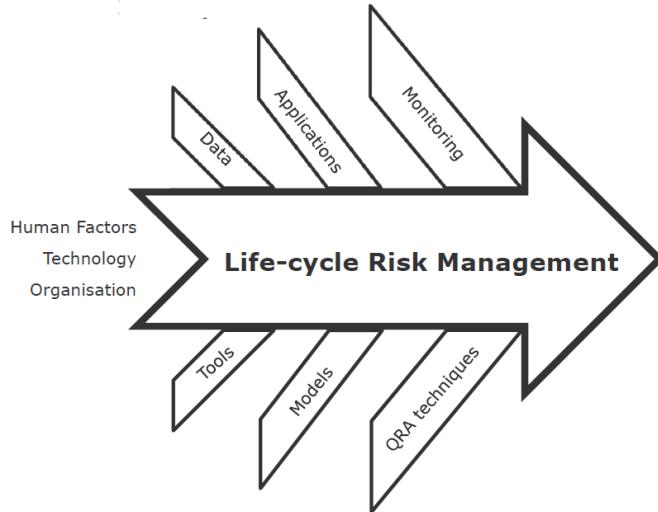


Fig 2 Illustration of the Chevron approach to LCRM

Underpinned research and development

The goal is to contribute to safer waterborne operations through development and implementation of a Life-Cycle Risk Management approach, accounting rationally and formally for all cost-effective active and passive measures of risk reduction and leading to cost-effective safety improvements for new and existing ships and offshore units as well as to promote safety culture and the regulatory framework. The recently established European research association "Vessels for the Future" targets safer shipping as one key area for future research, development and innovation. They promote a long-term objective to reduce risk of crew onboard ships built in Europe by 90% in 2050 compared to 2010. Technology focus areas for implementation towards 2025 have been published addressing the above and shown here in Fig 3.

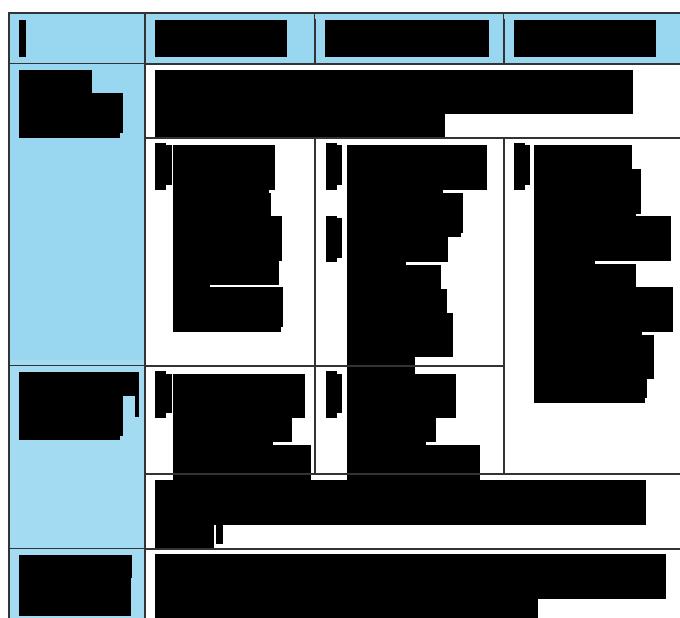


Fig 3 EU Research Targets for Safer Shipping (VftF Strategic Research Agenda)

RISK-BASED DESIGN IMPLEMENTATION AND LCRM

Generalised methodology

This thinking is largely in line with the above-mentioned Safety Case and FSA approaches and more latterly the Guidelines on Alternative Design and Arrangements (MSC\Circ.1002, 1212) with the focus clearly on safety performance verification. The Safety Case approach to safety management is more ship-specific rather than ship type specific as in the case of the FSA. As such, it is treated as a "living instrument", starting with the first concept of design and spanning the whole life cycle of the vessel. It starts with a suite of safety claims. As the design develops, the claims can be reinforced with arguments. When the design is finalized, the arguments can be verified with evidence. At the design stage, the evidence consists of results of relevant design safety verification activities (e.g., engineering analysis, model tests, etc.). These results are used to assess the risk level and verify that adequate measures are taken into account to ensure that residual risks (to be managed operationally) are acceptable. This is illustrated in Fig 4.

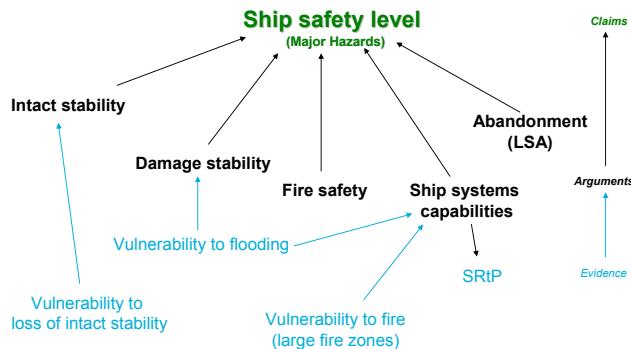


Fig 4 Safety Level Estimation during Concept Design Stage of Passenger Ships

The focus on dealing with residual risks, naturally leads to the need for a SMS (Safety Management System), outlining the organization and procedures required to maintain a tolerable level of safety throughout the life of the vessel. This has to be aligned with the ISM (International Safety Management) Code implemented onboard. The formal process facilitates measurement of safety performance, which contributes to the process of continuous improvement. Pertinent activities include aspects of onboard and shore-based Safety Centres, monitoring systems and emergency decision-support for crisis management. Ultimately, all these feed into future newbuildings specification.

Design phase: safety level (total risk) estimation

A common way of presenting graphically the chance of a loss (risk) in terms of fatalities is by using the so-called F-N diagram, the plot of cumulative frequency of N or more fatalities, together with related criteria, Fig 5, (IMO MSC85 2009). In addition, some form of aggregate information is used, such as the expected number of fatalities E(N), often referred to as the Potential Loss of Life, PLL. This is outlined next.

Risk model

$$Risk_{PLL} \equiv E(N) \equiv \sum_{i=1}^{N_{max}} F_N(i) \quad (1)$$

Where N_{max} the maximum number of persons onboard and the FN curve is given as:

$$F_N(N) = \sum_{i=N}^{N_{max}} fr_N(i) \quad (2)$$

The frequency $fr_N(N)$ of occurrence of exactly N fatalities per ship year is modelled as follows:

$$fr_N(N) = \sum_{j=1}^{n_{hz}} fr_{hz}(hz_j) \cdot pr_N(N|hz_j) \quad (3)$$

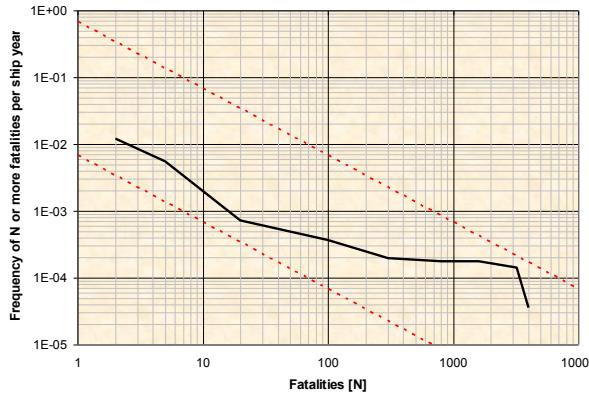


Fig 5 FSA Cruise Ships – Societal Risk

Where, n_{hz} is the number of loss scenarios considered, and hz_j represents a loss scenario, identifiable by any of the principal hazards. Furthermore, $fr_{hz}(hz_j)$ is the frequency of occurrence of scenario hz_j per ship year, and $pr_N(N|hz_j)$ is the probability of occurrence of exactly N fatalities, given that loss scenario hz_j has occurred. Table 1 shows estimates for the annual frequencies of occurrence for flooding- and fire-related hazards derived from statistics, (Jasionowski and Vassalos, 2006).

Table 1 Principal hazards

j	<i>Principal hazards, hz_j</i>	<i>Average historical frequency of occurrence, $fr_{hz}(hz_j)$</i>
1	Collision and flooding	1.48E-3, (cruise ships)
2	Fire	0.92E-2, (cruise ships)
3	Intact Stability Loss	
4	Systems Failure	
	... etc	

Research effort is currently being expended to derive these from first principles. With passenger ships, flooding- and fire-related scenarios comprise over 90% of the risk (regarding loss of life) and almost 100% of all the events leading to decisions to abandon ship. Therefore, it would be possible to estimate the total risk (safety level) of a passenger vessel by addressing these two principal hazards alone in a consistent manner and framework, allowing for their contribution to risk to be formally combined as indicated in Fig 4 and in Equation (3).

The specific design implementation highlighted here relates to the largest cruise ship ever built during the concept development phase, under the name Project Genesis, having the general particulars depicted in Fig 6 and Table 2 below.

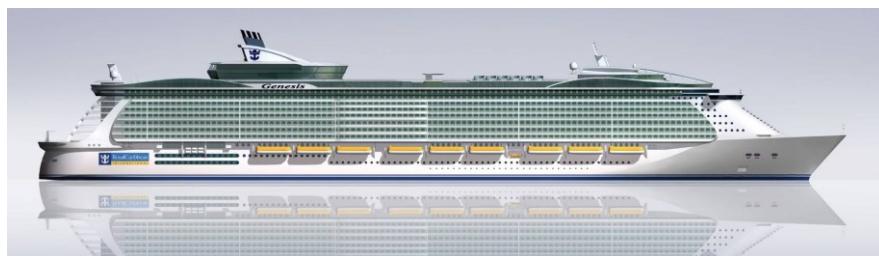


Fig 6 Project Genesis

Table 2 Project Genesis Main particulars

Length	361 m
Breadth	47 m
Draught	9.15 m
Gross Tonnage	225,000
Air Draught	72 - 65 m
Number of Guests	5,400
Number of Crew	2,166
LSA Capacity	8,460

As this vessel represents a step change in the size of mega-ships, including some unique, innovative features, focusing on safety and adopting a risk-based design methodology came naturally; in fact the initiative was entirely that of the owner. The task in hand was no less than proving that Genesis is not only the largest ship ever built but also the safest and do so during the concept design stage commensurate with all other design goals and functional requirements. The procedure adopted to achieve this is briefly described in the following under four pertinent headings:

Flooding survivability analysis

For undertaking this analysis a complex geometric model was developed comprising 717 compartments and 1,160 openings, as depicted in Fig 7.

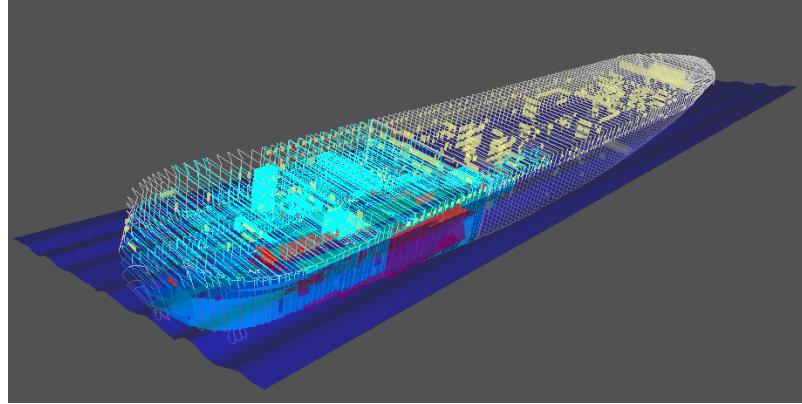


Fig 7 Flooding Analysis Model for Project Genesis

Frequency Analysis ($f_{rh}(hz_1)$): Even though analysis targeted both collision and grounding related flooding, only collision is addressed here to allow comparisons between Project Genesis and the rest of the world cruise fleet. As records of 111 ship years of statistics, obtained from the owner, showed zero occurrences of flooding incidents, the frequency of 1.48E-3 per ship year (1 event every 571 ship years), deriving from statistics of the existing cruise ships, Table 1, was used instead.

Consequence Analysis $pr_N(N|hz_1)$: The comprehensive risk model described in (Vassalos, 2008) requires two parameters to be estimated: the first is the time required for orderly evacuation of passengers and crew in any given event, derived from numerical simulations using advanced evacuation simulation software (Vassalos et al., 2003); the second is the time to capsize/sink, which is evaluated by sampling the random variables comprising loading conditions, sea states and damage characteristics (location, length, height, penetration according to the damage statistics adopted in the probabilistic rules) using Monte Carlo sampling and each damage scenario is simulated using explicit dynamic flooding simulation by PROTEUS3, (Jasionowski, 2005). The investigation involves a case by case explicit dynamic flooding simulation accounting for transient- cross- and progressive-flooding, impact of multi-free surfaces, watertight and semi-watertight doors. 342 collision scenarios were used resulting in an absolute sampling error for the cumulative probability of time to capsize of the order of 4%-5%. A typical set up of Monte Carlo simulations is shown in Fig 8 (generic) and Fig 9 for Project Genesis collision studies. A comprehensive experimental programme was also set up to verify the numerical simulations, offering corroborative evidence and hence confidence in the derived results, which are presented in Fig 10 as an F-N curve together with results from the FSA on cruise ships (IMO MSC 85, 2009).

The results clearly demonstrate the superior flooding survivability characteristics of Project Genesis.

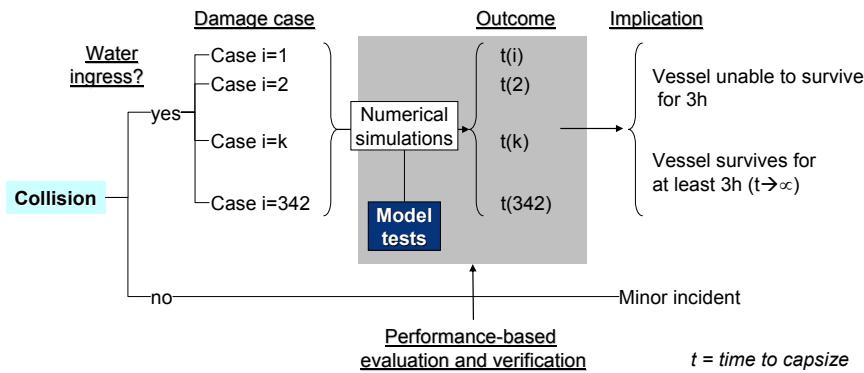


Fig 8 Monte Carlo Simulation – Collision

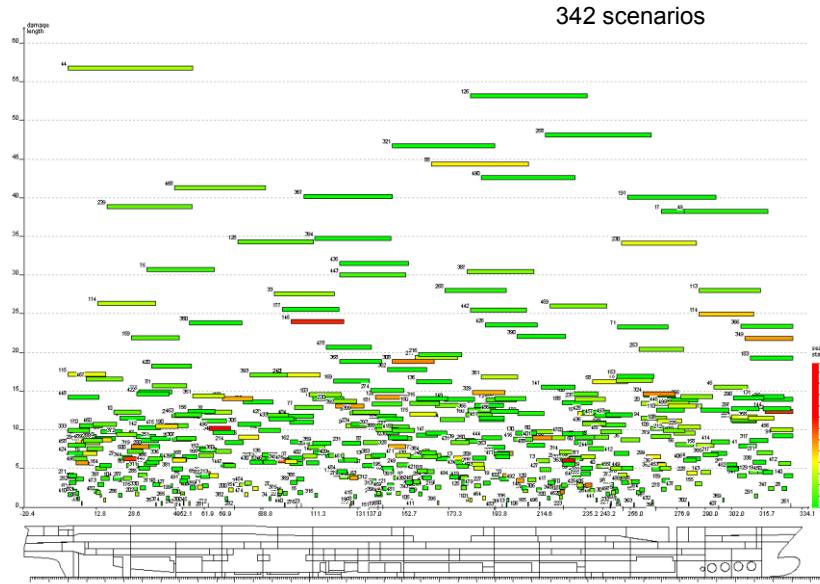


Fig 9 Monte Carlo Simulation Set up – Collision

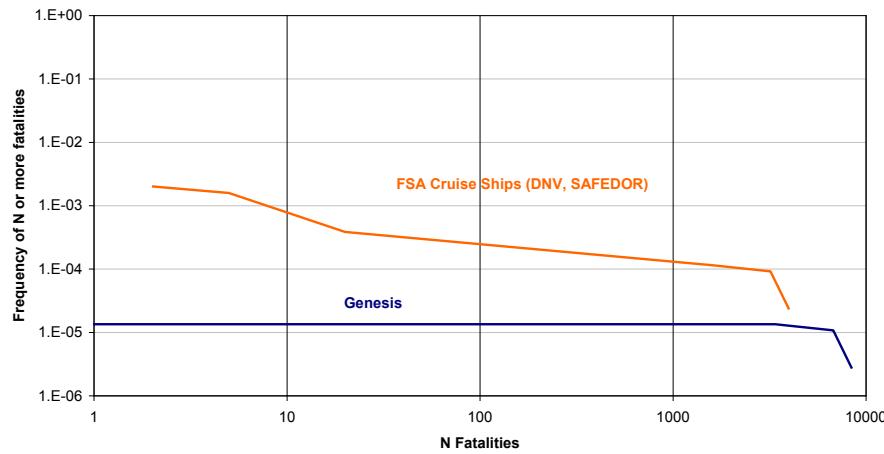


Fig 10 Societal Risk – Collision Accidents

Fire safety analysis

A full description of the risk model developed for fire safety analysis can be found in (Vassalos, 2008). The general set up is illustrated in Fig11 next. The ship has 144 fire zones, 80 in excess of SOLAS.

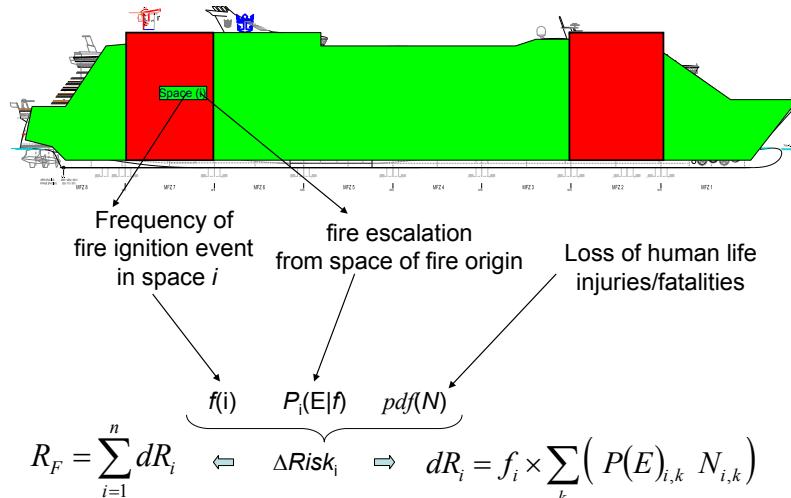


Fig 11 Fire Risk Model Illustration

Frequency Analysis $fr_{hz}(hz_j)$: A fire incidents database was provided by the owner containing 577 fire incidents (including near-misses) in 111 ship years of records. This was used to derive a simple numerical model for fire occurrence in any given space onboard the ship based on frequency per unit area for each type of space.

Consequence Analysis $pr_N(N|hz_j)$: Empirical data was used to develop design fires for each type of space onboard and fire dynamics calculations to estimate the time evolution of the fire in both enclosed and external spaces. Similar to flooding cases, escape time simulations were also undertaken to estimate impact on occupants. A total of 8,326 fire scenarios were evaluated in 144 fire zones (8 main vertical zones and 18 decks) for night and day occupancy cases. The results are presented in Fig 12 as societal risk, together again with results from the FSA on cruise ships. The superior fire safety characteristics of project Genesis are clear to see.

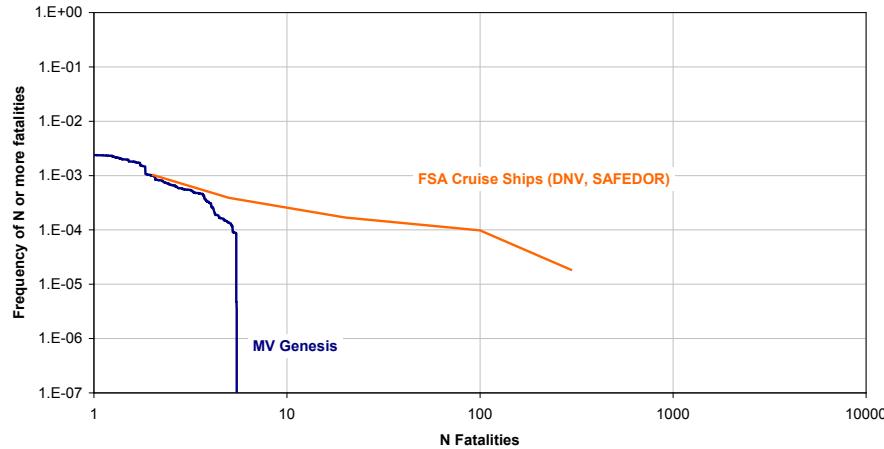


Fig 12 Societal Risk – Fire and Explosion Accidents

With flooding and fire modelled consistently using the same framework, the risk contributions from each hazard can be combined, thus giving what constitutes (almost) the total risk for Project Genesis, as shown in Fig 13 together with the corresponding result from the IMO cruise ship FSA.

In addition to the foregoing considerations a number of specific regulatory and other safety issues were considered as outlined briefly in the following.

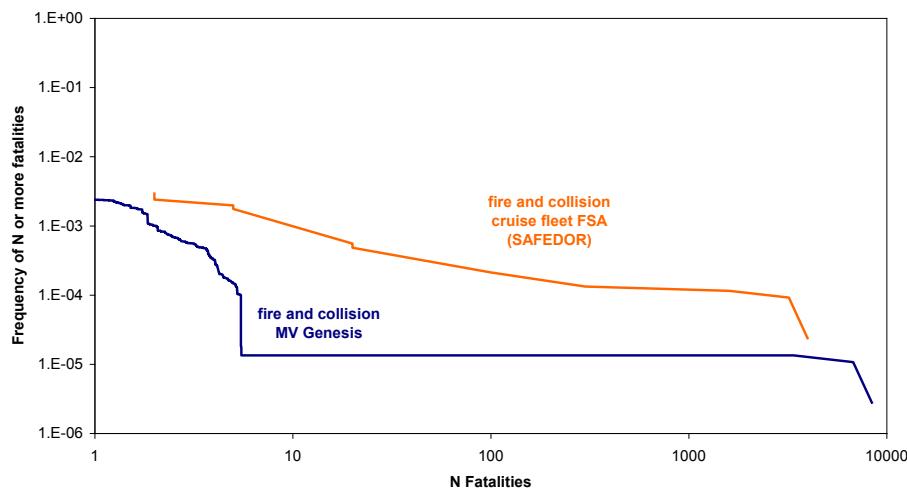


Fig 13 Societal Risk – Project Genesis Vs Existing Fleet

Alternative Designs (Equivalent Safety)

- Large fire zones, average 1,950 m² designed to SOLAS Ch. II-2 Reg. 17 and Guideline MSC/Circ. 1002
- Openings in main fire bulkheads with A-60 roller shutters (Royal Promenade)
- Fire breaks on open areas between split superstructure
- LSA: Enhanced functionality large lifeboats – Rescue Vessels (18 life boats for 370 persons each); 4 MES Stations for 450 persons each.

Dynamic Behaviour at Sea

- Extensive model tests with full-scale verification, including: life boat tests; weather criteria tests; wave excitation measurements on rigid and segmented models; parametric rolling; behaviour in F/Q seas; manoeuvring calculations / simulations and model tests.

Safe Return to Port

- Systems related to propulsion, covering also steering and manoeuvring capability (+ fire, flooding, navigation)
- Systems related to comfort

Additional Safety and Security Features

- Dedicated Safety Centre within bridge
- Improved focus on navigation
- Improved ability to manage safety and security incidents
- Dynamic Positioning
- Improved systems for emergency mustering
- Comprehensive digital CCTV system

Operational phase: management of residual risk

Having achieved the goal of designing a safe ship cost-effectively and to go beyond all new and emerging safety requirements by utilizing all available knowledge and technology, the question that came naturally to the fore is whether this extensive knowledge acquired during the design phase could be used to manage operational / accidental risk over the life-cycle of the vessel. More importantly, the goal post could be set even higher, namely to target optimum balance between safety and operational efficiency. Tackling such questions and concerns as watertight doors, ballasting/de-ballasting, damage control and so on led to the development of iStand (illustrated in Fig 14), a Decision Support System (DSS) installed onboard the first ship of the Genesis series with the following general features – in addition to being a standard onboard loading computer:

1. *Real time sensors and hardware integration (link to ship's SMS)*: tank levels, draughts, door states, water ingress alarms, wind and waves. Any change in ship loading or internal architecture is being continuously monitored.
2. *Vulnerability log*: Global and local ship vulnerability to flooding - monitoring the flooding-related risk onboard to any changes in related ship or environmental parameters. Vulnerability to fire is undergoing development.
3. *Criticality assessment*: survival time, escape and evacuation time (crisis management)
4. *Corrective action search*: evaluation of the impact of corrective actions. Ballast system availability.
5. *Essential systems availability post-flooding*: verification of compliance with Safe Return to Port requirements.

The DSS developed comprises a very powerful computer with a massive database encapsulating all the features of Safe Return to Port Requirements and linked to sensors capable of monitoring all the elements that could affect ship vulnerability.

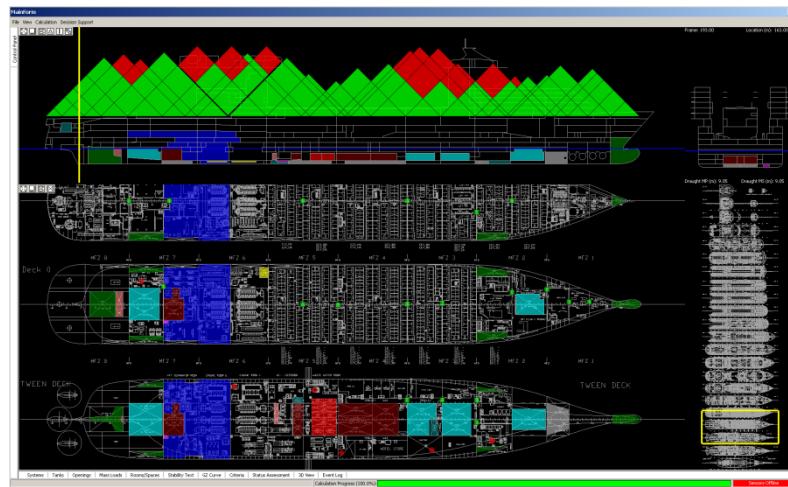


Fig 14 Screenshot of iStand (Onboard Decision Support System)

Emergency response: preparedness / crisis management

In support of a life-cycle risk management thrust, the first two elements of the DSS provide for monitoring of ship operation and feedback functions whilst 3 to 5 provide internal capability for handling emergencies. Moreover, the on-board experience gained to date provides invaluable information to guide improvements in the design for the next generation of cruise ships. Emergency response is the last line of defence in life-cycle risk management and given the potential time constraints in an emergency, emphasis in developing and familiarizing crew with emergency re-

sponse procedures is paramount. This brings to the fore the need for continuous monitoring, a key element to preparedness. Equally as important is the ability to provide the master with clear cut advisory related to managing a crisis. All these are elements currently under development by leading cruise ship operators, Fig 15.

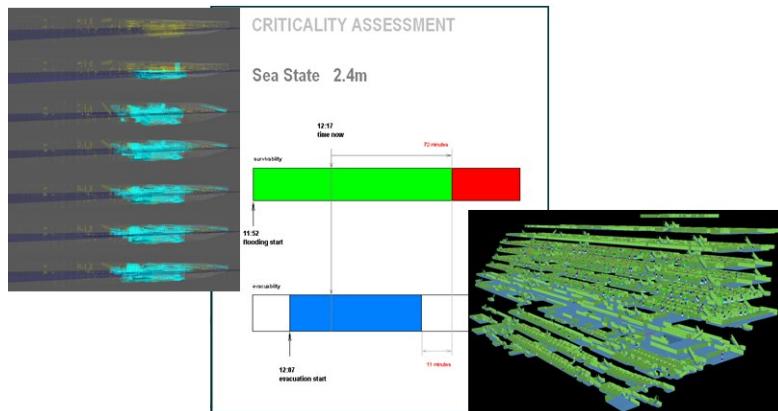


Fig 15 Screenshot of iStand (Emergency Response - Crisis Management)

TRANSFER OF TECHNOLOGY FROM COMMERCIAL TO NAVAL VESSELS

With the obvious exception of weapons, what differentiates a naval from a commercial vessel is:

- The ability to maintain its fighting and aviation support activities in design defined sea states
- The ability to retain a high level of operational effectiveness under hostile action – i.e. its survivability.

Part of the Float-Fight-Move ethos of the navy renders the ability to recover from an incident a priority requirement. The scenarios that need to be considered in design are:

- Above water attack;
- Internal & external blast;
- Underwater explosions;
- Shock;
- Whipping;
- Fragmentation;
- Residual strength.

These were (and remains in part) a fundamental difference between naval and commercial vessels. However, the SOLAS requirement for “Safe Return to Port (SRtP)” may be perceived (at least in part) as the application of naval philosophy on commercial ships, notwithstanding the “probabilistic version” of SRtP as it is being now implemented for verification purposes in passenger ships. Whilst classification has been a requirement for commercial vessels (over a certain size – i.e. L>24m. or D>500gt), classification of naval vessels is an optional process. According to Lloyds Register (2014), the role of Class in commercial shipping is to demonstrate that materiel safety is in compliance with international legislation; whereas its role in naval vessels is “to demonstrate that materiel safety has been benchmarked against international legislation while recognising the operational role of the vessel and also recognising that the navy may have a higher tolerance of risk in specific situations”.

The Naval Ship Code (2014) has been at the centre of naval ship design in recent years. The NSC is a goal-based standard that determines a minimum level of safety for naval vessels. It is published by NATO (ANEP-77; currently at issue E, 2014). It covers areas such as:

- Structure
- Buoyancy, Stability & Controllability;
- Engineering Systems;
- Fire Safety;
- Escape, Evacuation & Rescue;
- etc.

In Chapter 1 Part A Para.4 it states:

The regulatory function implied in this Code requires as a minimum that the ship offers:

- 4.1 An equivalent level of safety to that were it regulated under international conventions or regulations applicable to merchant shipping;
- 4.2 An additional level of safety for normally occurring hazards that reflect the foreseeable operations on which a naval ship is or may be engaged;

4.3 An appropriate level of safety under extreme threat conditions as determined by the Naval Administration.

By being a goal-based approach it does lend itself to non-prescriptive methods, but on the whole Class Rules and Naval Authority Notices are used in its application. There are references to SOLAS, noting that some SOLAS concepts are not applicable to naval vessels (e.g. bulkhead deck). Also, naval vessels carry ammunition (& troops), replenish at sea, and fight damage (rather than abandon ship; however damage control and emergency response are becoming common language and practice in passenger ships, as indicated in the foregoing). It should be noted that the safety of a naval vessel and its embarked personnel may (in war) be secondary to the safety of those under her protection (c.f. in merchant terms, safety of life at sea and environmental protection are paramount).

Notwithstanding the differences, the key development that could provide the right conduit to designing and building optimal naval vessel, reflecting the triple-A philosophy, relates to risk-based approaches and goal-based standards as they are currently implemented to passenger vessels at large. More important, considering the current climate of declining defence budgets and increasing ship costs, the number of ships in most western navies has experienced a significant decline. The only way to counter a potential decrease in capability is through innovation in the ship design process.

In this respect, could Risk-Based Design lead to the following? (These are some examples to whet the appetite!)

- 1) **Optimised subdivision – how?** The MoD Naval Authority (DESNAG-Stab) has issued a NAN with updated templates for the various damage scenarios that need to be considered (200+). How can a risk based approach optimise subdivision?

The application of the probabilistic rules for damage stability require consideration of thousands of damage scenarios in order to ensure appropriate subdivision but, more importantly, in order to identify design vulnerabilities to flooding and address these in the concept design phase. More importantly, as subdivision is a key element in the design process, the Subdivision Index, is chosen as one of the KPIs and defined in a knowledge-intensive form (response surface) to allow for fast and accurate calculations and trade-offs between subdivision and other design objectives (weight, strength, powering, systems availability post-casualty, etc.) through overlaps at parameter level. In this respect, the latter are also addressed through the use of parametric models and access to fast, accurate and Knowledge-Intensive Models (KIMs) as well as access to databases (past designs, incident /accident data, etc.). As indicated earlier, there is need for integration of all the tools and data under one umbrella (Integrated Design Environment) to facilitate data and process management.

Optimised structure – how? Structural weight accounts for ~40-50% of the total lightship for a naval vessel. Yet, structural arrangements are rarely optimised for weight at the concept design stage, as the emphasis is placed on defining the hull, general arrangement and powering solution to meet the client's operational requirements. In commercial ship design, due to the sheer numbers, there is a good database of experience to draw from. This is not the case for naval vessels where the turnover of designs is less frequent, and these days the design solutions represent significant extrapolations from historical data, which renders historical (and published) data almost unusable. Can RBD assist in achieving optimised solutions in the early design phases?

Even though structural strength in passenger ships is ensured by focussing on the strength deck (subdivision deck), carrying deadweight is an undesirable expense and as such focus on light materials and optimal structural arrangements is paramount. Moreover, comfort and aesthetics in passenger ships requires the use of extensive continuous spaces, some positioned on top of the pods/propellers and demanding feathery smoothness and quietness. Thus, structural optimisation is a key. Indeed, structural reliability in commercial shipping (initially offshore) has been one of the proponents of risk-based design. The process is similar to what has been explained above, i.e., using structural reliability index in parametric form as one of the KPIs to be considered in the concept design phase.

- 2) **Optimised passive and active firefighting measures – how?**

Even though probabilistic rules for damage stability have not found their way to SOLAS, approval of Alternatives and Equivalents (Chapter II-2, Regulation 17, MSC/ Circ. 1002) provides the motivation and the framework for risk-based design. Similarly, EC projects like SAFEGUARD and FIREPROOF have elaborated the development of a probabilistic framework for fire safety in a similar fashion to the probabilistic framework for damage stability, leading to a Fire Safety Index (similar to the Subdivision Index) that allows the risk from fire to be considered alongside the risk from flooding in the design process, as outlined earlier in the paper. This way, a Fire Safety Index is used as a measure of passive and active fire protection (again in a parametric form), alongside the Subdivision Index, for optimisation studies during the concept design phase.

CONCLUDING REMARKS

Based on the review of development and implementation of RBD in commercial shipping, the following concluding remarks can be drawn concerning the naval sector:

- Life-cycle Risk Management is a formal process providing a holistic framework, to embrace all phases of the life-cycle of the vessel from design (risk reduction/mitigation) to operation (management of residual risk) and emergency response (preparedness/crisis management), leading to safety assurance in the most cost-effective way possible.
- With experience gained in application to commercial shipping, the advantage of being able to address complexity at the concept design stage, leads to drastic evolutionary developments that nurtures innovation whilst facilitating notable safety improvements cost-effectively.
- There is enough knowledge accumulated in commercial shipping in the form of tools, data and processes and maturity gained though application to knowledge-intensive and safety-critical ships to advocate that Risk-Based Design is the only way to realise truly optimal designs, in this particular forum the Triple-A Navy.

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REFERENCES

1. D Vassalos, ‘Shaping Ship Safety: The Face of the Future’, *Journal of Marine Technology*, Vol. 36, No. 4, pp. 1-20 (1999).
2. D Vassalos, ‘(Chapter 2: Risk-Based Ship Design) in Papanikolaou, A., (Editor): Risk-Based Ship Design – Methods, Tools and Applications’, Springer, ISBN 978-3-540-89042-6, pp. 17-98 (2008).
3. IMO FSA, ‘Guidelines for Formal Safety Assessment for Use in the Rule-Making Process’. MSC.1-Circ.1023 - MEPC.1-Circ.392 (2002).
4. HSE Safety Case, ‘The Offshore Installation (Safety Case) Regulations, UKSI 3117’ (2005).
5. IMO ADA, ‘Guideline on Alternative Designs and Arrangements for SOLAS chapter II-1 and III’, MSC/Circ.1212 (2006).
6. IMO MSC 85, ‘FSA Cruise Ships’, submitted by Denmark (2009).
7. A Jasionowski, D Vassalos, ‘Conceptualising Risk’, *9th International Conference on Stability of Ships and Ocean Vehicles*, Rio de Janeiro (2006).
8. D Vassalos, L Guarin, G Vassalos, M Bole, H S Kim, L Majumder, ‘Advanced Evacuation Analysis – Testing the Ground on Ships’, *2nd International Conference on Pedestrian and Evacuation Dynamics*, PED 2003, Greenwich, London (2003).
9. A Jasionowski, ‘An integrated approach to damage ship survivability assessment’, PhD, University of Strathclyde (2005).
10. IMO, MSC77/INF.12 - SAFEDOR . Risk-Based Design, Operation and Regulation of Ships, (2003).
11. Lloyd’s Register Marine, Naval ship safety assurance, (2014).
12. NATO Standard ANEP-77, Naval Ship Code; Edition E Version 1; (January 2014).