DESIGN FOR DAMAGE SURVIVABILITY OF PASSENGER SHIPS

D. Vassalos and **A. Jasionowski**, Universities of Glasgow and Strathclyde, UK
L. Guarin, Safety at Sea Ltd, UK

SUMMARY

The age of mega-ships is clearly upon us and it is here to stay, fuelling innovation and technological breakthroughs and challenging societal perception on safety in an unprecedented manner. Experience finds no fertile ground to breed and the regulatory system is stretched to breaking point. Conjecture will not do, for the risk is too high. Difficult questions demand (and deserve) answers that can be measured, verified and defended. This paper argues that for the first time in the history of Naval Architecture, the path to matching this "demand" is well paved. The real issues at hand are presented and explained and the roadmap to achieving the much sought out answers highlighted and demonstrated with focus on damage survivability. Emphasis is placed on demonstrating the considerable potential offered to the marine industry by embracing innovation, in terms of routine utilisation in the ship design process of scientific and technological breakthroughs, to contain risk.

1. INTRODUCTION

Phenomenal changes in scientific and technological developments at an ever increasing pace and an overall better technical capability at a much larger scale are fuelling innovation in the shipping sector to meet the demand for larger, faster, more complex and specialised ships. This is taking place in an environment that is still fragmented, undermanned and intensely competitive and with society more vigilant and more demanding on issues pertaining to human life safety and the environment. Safety could easily be undermined and the consequences could be disastrous. This cannot be truer than in the case of mega-ships in the cruise industry with blue prints on ships carrying 10,000 people on the design table.

The need to change the way safety is being dealt with is driving all concerned to a new realisation that the marine industry is a "risk industry", necessitating the adoption of holistic risk-based approaches to maritime safety capable of striking a balance between all the many facets affecting safety cost-effectively and throughout the life cycle of the vessel. As a result, a clear tendency to move from prescriptive to performance-based approaches to safety is emerging internationally and this, in turn, is paving the way to drastic evolutionary changes in design, where safety is dealt with as a central issue with serious economic implications rather than a simplistic compliance. Notable efforts to respond to these developments in the marine industry led to the establishment of the first significant EU Thematic Network (TN) SAFER EURORO (1997, 2001), aiming to promote a new design philosophy under the theme "Design for Safety" with the view to integrating safety cost-effectively within the design process in a way that safety "drives" ship design and operation. This in turn entails the development of a formal state-of-the-art design methodology (Risk-Based Design) to support and nurture a safety culture paradigm in the ship design process by treating safety as a design objective rather than a constraint. It also provided the inspiration and the foundation for SAFEDOR (2004 – Design / Operation / Regulation for Safety), a 20-million Euro EU FP6 Integrated Project, aimed at integrating safety research in Europe and beyond and to fully implement Risk-Based Design from concept development to approval.

Considering the above, adopting a risk-based design methodology that embraces innovation and promotes routine utilisation of first-principles tools will lead to cost-effective ways of dealing with safety and to building and sustaining competitive advantage, particularly so for knowledge-intensive and safety-critical ships; knowledge-intensive, as such ship concepts are fuelled by innovation and safety-critical as with such ship designs safety is indeed a design "driver". In this respect, the continuously increasing regard for human life and the rapid escalation of passenger ship size, has exacerbated what is perceived to be an inherent risk in passenger ships to the extent that risk containment, in a way that public confidence is reassured, has become a top agenda item at IMO.

Setting goals that encourage zero tolerance with regard to human life loss demands close scrutiny of all the issues that could upset such expectation, first and foremost, designing to a higher standard of survivability. Striving to understand what is to be done and how to achieve it led to the introduction of new "buzz" words such as "casualty threshold", "time to flood", "safe return to port", safety level" with issues ranging from causality analysis (leading to identification of principal hazards and design scenarios), consequence analysis (e.g., damage survivability and fire safety analysis) and mitigation analysis (e.g., evacuation and rescue) as well as systems redundancy to ensure availability of key functionalities in an emergency.

But whilst the intention was good, the pace of development was too fast for comfort, leading to a rather unclear situation that engulfs the whole profession. The need for clarity is immediate and it is paramount. It also forms the main aim of this paper which is addressed by presenting and explaining a holistic framework that includes all the aforementioned elements and by focusing on one of the main issues affecting passenger ship safety, that of design for damage survivability.

2. SAFETY LEVEL (TOTAL RISK)

An F-N diagram clearly implies that the risk to human life of a ship carrying more people is greater than that carrying a lesser number (when both comply with the same safety standards), see Figure 1.

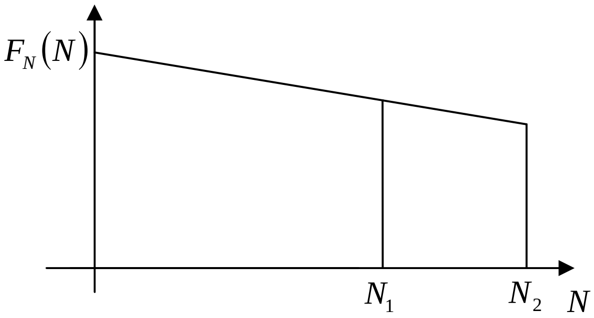


Figure 1: The law of risk, $Risk_{N_2} > Risk_{N_1}$

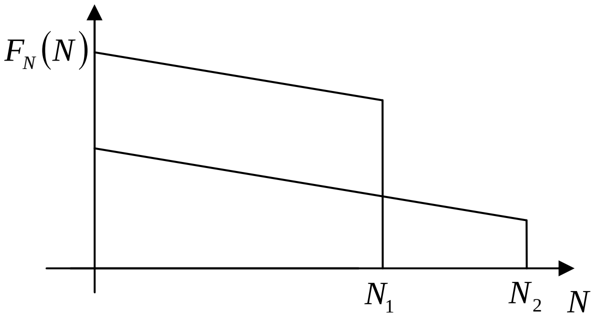


Figure 2: The law of risk, $Risk_{N_2} < Risk_{N_1}$

Figure 2 illustrates that this simple truth can be reversed if the bigger ship is designed to a higher safety standard/level. Arguably and with support from intuition, the bigger ship offers a better platform for achieving a higher safety level but intuition, conjecture or engineering judgement will not suffice when the argument concerns 10,000 lives. All forms of knowledge must be called to play a role, provided that a comprehensive risk model and framework are availed to calculate the total risk for a ship type (risk to human life for passenger ships). Such a model was proposed in [10], and is outlined briefly in the following:

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

Where, the FN curve is given as:

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

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

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

Where n_{hz} is the number of loss scenarios considered, and hz_j represents an event of the occurrence of a chain of events, (a loss scenario), identifiable by any of the principal hazards shown in Table 1.

j	Principal hazards, hz_j	Average historical frequency of its occurrence, $fr_{hz}(hz_j)$
1	Collision and flooding	2.58e-3, ref [1]
2	Fire	
3	Intact Stability Loss	
4	Systems Failure	
	… etc	

Table 1: Principal hazards

Furthermore, $fr_{hz}(hz_j)$ is the frequency of occurrence of a scenario hz_j per ship per year, and $pr_N(N|hz_j)$ is the probability of occurrence of exactly N fatalities, given loss scenario hz_j occurred. In principle, there is nothing new here, except, perhaps, for the emphasis of the need to estimate the probability of exactly N fatalities, $pr_N(N|hz_j)$, conditional on the occurrence of any of the principal scenarios j.

However, considering the fact that flooding- and fire-related scenarios comprise over 90% of the risk space and almost 100% of all the events leading to decision to abandon ship, the idea of addressing these two principal hazards in a consistent manner and framework that their contribution to risk can be formally combined to allow for calculation of what would be the total risk (safety level) will have been realised. In this respect, it is important to appreciate that the emphasis on the aggregate number deriving from such process will only serve to measuring safety at ship level, a goal that has been pursued by SSRC for over 15 years; risk components contributing to the total risk will still have to satisfy hazard-specific risk acceptance criteria to avoid undermining safety through what is known as *compensation effect* (e.g. achieving a safety level by reducing flooding-related risk at the expense of increased fire-related risk). Similar safeguards ought to be in place for all the component parts contributing to the calculation of this single number, right down to loss scenario level (i.e., achieving a high index of subdivision by focusing on average safety standard must not be allowed in the knowledge that highly probable damage scenarios are non-survivable).

Following on from the foregoing, for flooding-related events, the harmonised probabilistic rules for damage stability provide such a framework, which could be used as a basis for similar developments to address fire. With regard to collision and flooding hazards, $j = 1$, substantive elements of the risk model (3) have already been developed, [10], as indicated next:

$$pr_N\left(N \middle| hz_1\right) = \sum_{i}^{3} \sum_{j}^{n_{flood}} w_i \cdot p_j \cdot \sum_{k}^{n_{Hs}} e_k \cdot c_{i,j,k}(N) \qquad (4)$$

$$c_{i,j,k}(N) = \left(-\ln\left(\varepsilon_{i,j,k}\right) \cdot \left(\varepsilon_{i,j,k}\right)^{\frac{t_{fail}(N)}{30}} \right) \cdot \frac{\left|\partial t_{fail}(N)\right|}{30} \qquad (5)$$

Where, $fr_{hz}(hz_1)$ of (3) represents the probability of collision ($2.58 \cdot 10^{-3}$ derived from statistics, [1]); the terms w_i and p_j are the probability mass functions of the 3 specific loading conditions and n_{flood} the number of flooding extents, respectively, calculated according to the harmonised probabilistic rules for ship subdivision, [2], [3]. The term e_k is the probability mass function derived from the statistics of sea states recorded at the instant of collision and n_{Hs} is the number of sea states considered. The term $c_{i,j,k}(N)$ is the probability mass function of the event of capsizing in a time within which exactly N number of passengers fail to evacuate, conditional on events i, j and k occurring, and can be tentatively estimated from (5).

The term $\varepsilon_{i,j,k}$ (with σ_r) represents the capsize band, that is the spread of sea states where the vessel might capsize and is evaluated as a function of the survival probability "s", calculated according to the harmonised probabilistic rules, hence accounting for ship geometry, loading, seas state in any given flooding event. The other terms in equation (5) lead to evaluation of the passenger who fail to evacuate with the time it takes the vessel to capsize/sink. In this respect, estimates of the time required for orderly evacuation of passengers and crew in any given event (N_{evac}) derived from numerical simulations of advanced evacuation simulation software [4] as well as the *time to capsize/sink* (t_c) are of paramount importance to meaningfully calculate risk. Hence, knowledge of the time evolution of any event that is likely to lead to abandoning the ship is paramount.

3. SAFE RETURN TO PORT

In May 2000, the IMO Secretary-General called for a general review of the safety of these ships noting that "what merits due consideration is whether SOLAS and, to the extent applicable, the Load Line Convention requirements, several of which were drafted before some of these large ships were built, duly address all the safety aspects of their operation – in particular, in emergency situations". This visionary prompt led IMO MSC to adopt a new "philosophy" and a working approach for developing safety standards for [large] passenger ships. In this approach, illustrated in Figure 2 (SLF 47/48), modern safety expectations are expressed as a set of specific safety goals and objectives, addressing design (prevention), operation (mitigation) and decision making in emergency situations: More specifically:

- The ship should be designed for improved survivability so that, in the event of a casualty, persons can stay safely on board as the ship proceeds to port. In this respect and for design purposes (only), a *casualty threshold* is defined whereby a ship suffering a casualty below the defined threshold is expected to stay upright and afloat and be habitable for as long as necessary [5 days recommended] in order to return to port under its own power or wait for assistance.
- Should this threshold be exceeded the ship must remain stable and afloat for sufficiently long time to allow safe [3 hours recommended] and orderly evacuation (assembly, disembarkation and abandoning) of passengers and crew.

Achievement of these goals in the proposed goal-based and proactive approach would ensure safety of human life commensurate with the safety expectations of today, by implicitly addressing total risk, and by focusing on the timeline development of different events (flooding / fire / evacuation scenarios) in a remarkably consistent manner to the ideas portrayed in the previous section. The implementation of such an approach targets, in addition, some specific requirements related to the hazard in question (in this case flooding or fire) and ship functions that are verifiable during design –referred to as "functional requirements". All these requirements can be addressed during early design stages if the right knowledge is available to the designer and incorporated in the design concept.

Prerequisite knowledge for design or for rule-making normally derives either experientially or through numerical modelling and systematic investigation using verified/calibrated models. In this sense, and in the absence of experience particularly with new vessel types, advanced simulation tools should be used for gaining such knowledge and ultimately for verification purposes, in the same way as model testing is used today to gain better understanding" and to verify specific performance achievements. Such a verification process, in turn, requires clear and quantifiable [performance] criteria that can be evaluated with available tools and methods. However, the ultimate *goal* is to verify that the functional requirements are met and hence, the safety goals will be achieved. The verification process can also provide the means to categorise the outcome of different design scenarios, information useful if one (designer, legislator, and decision-maker) wishes to know the safety boundaries of specific ship designs, hence specify *casualty threshold* for pertinent hazards.

In the knowledge that consideration of flooding as a result of collision/grounding and fire/smoke adequately covers the risk space for passenger ships, the ideas described in this and the previous sections can be presented in a workable framework, shown in Figure 4), adopted by SSRC/Safety at Sea in collaboration with Deltamarin Ltd to systematically deal with passenger ship safety in the design stage. Elements of this framework, in particular related to fire, are presently undergoing development as part of the SAFEDOR project as well as an industry-funded project, consistent with damage survivability and this would aloe for estimation of total risk (safety level) of passenger ships. Results of this work will be presented in the near future.

However, designing for damage survivability of passenger ships as a result of collision / grounding / stranding is largely complete and will be the focus of the following sections.

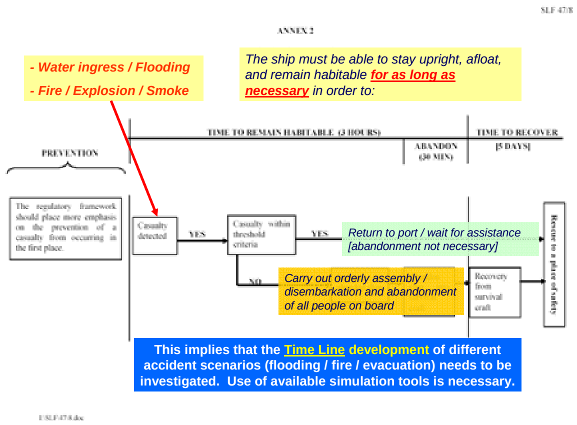


Figure 3: Safe Return to Port – The IMO Framework

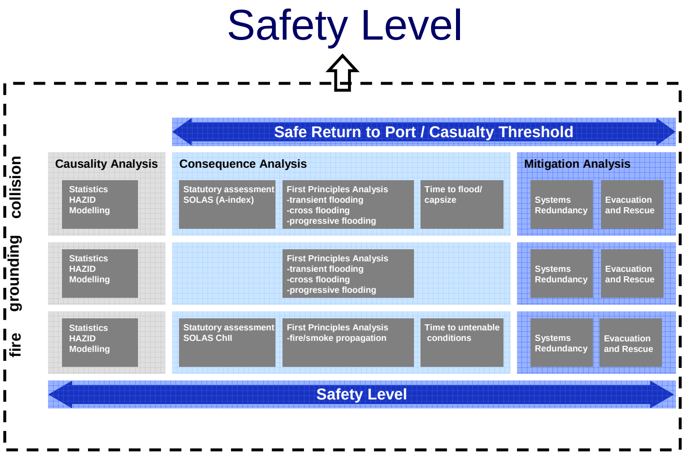


Figure 4: Passenger Ship Safety Implementation

4. DESIGN FOR DAMAGE DURVIVABILITY

Related to Figure 3, the following items are being considered in early design stages.

4.1 STATUTORY ASSESSMENT (SOLAS 2009)

In the simplest of levels, the dilemma of prescriptive SOLAS-minded designers can be demonstrated in the Figure 5.

It is obvious that internal subdivision arrangement is a key issue affecting ship performance, functionality and safety, all of which have to date been catered through the provision of rules and regulations, reflecting in essence codification of best practice. Throwing this away and leaving on the table a blank sheet, makes ship subdivision a very difficult problem indeed. This was essentially the problem addressed in the EU project ROROPROB.

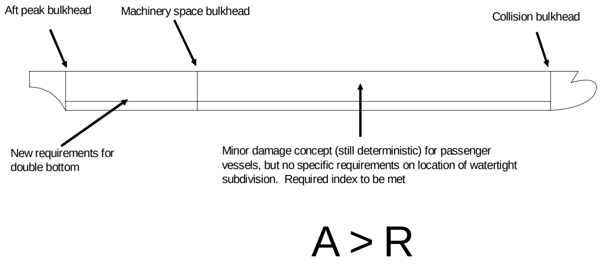


Figure 5: Largely "unguided" subdivision (Probabilistic rules)

In line with the probabilistic rules for damage stability, an internal watertight subdivision arrangement of a ship can be designed to meet the exact statutory requirements. This will lead to a ship design with an acceptable level of flooding-related risk contribution that can be optimised for along with cost-effectiveness, functionality and performance objectives. In order to achieve the above, a parametric model of the watertight subdivision should be prepared. This is easily achieved with commercially available software packages. The developed probabilistic methodology can then be implemented using established optimisation algorithms, such as Genetic Algorithms tailored to this application. The fully automated optimisation process typically produces several hundred design alternatives depending on the complexity of the ship's layout and the number of variables.

Typical variables of the optimisation problem include: type of subdivision, number, location and height of watertight bulkheads, deck heights, tank arrangement, casings, double hull, and position of staircases, lifts and escapes. Using the Attained Subdivision Index, payload capacity, steel weight and other regulatory requirements as typical objectives/constraints, the optimisation problem outcome typically includes: reduced number of bulkheads, reduced deck heights and reduced void volume, reduced number of escape ways and required staircases, reduced steel weight, reduced complexity in tank arrangements, increased crew and service areas, improved functionality and, if required, improved Attained Subdivision Index.

In order to make the process effective, participation by all decision-makers (designer, owner and yard) is essential to properly define the optimisation variables, objectives and constraints. Using this approach, known as *platform optimisation*, high survivability internal ship layouts have been developed, without deviating much from the current SOLAS practice, this making it easier for ship designers to relate to the proposed practice. Typical level of progress achieved can be demonstrated by Figure 6 below.

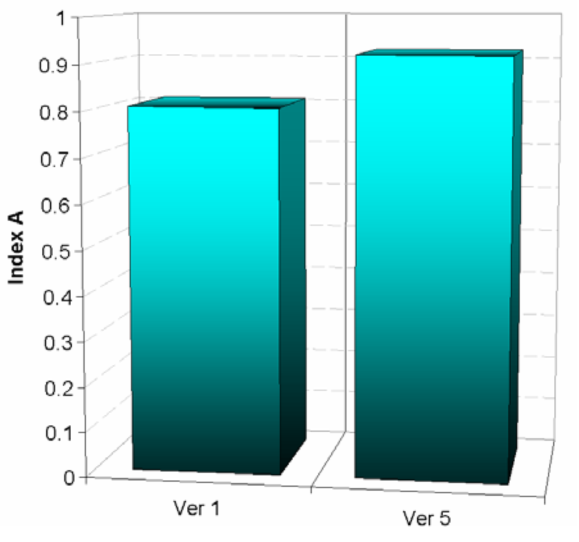


Figure 6: Probabilistic Damage Stability Calculations for ships shown in Figure 7 and Figure 8, respectively.

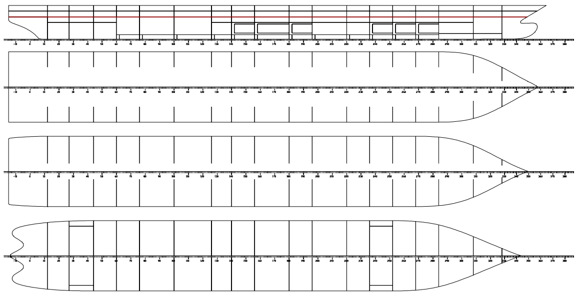


Figure 7: Hypothetical cruise vessel subdivision, Ver 1

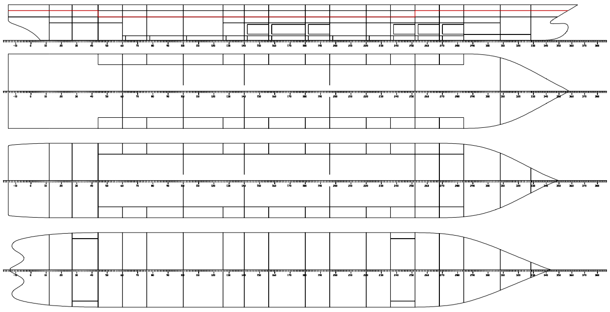


Figure 8: Hypothetical cruise vessel subdivision, Ver 5

4.2 FIRST-PRINCIPLES ANALYSIS (TIME-DOMAIN SIMULATIONS)

Building on the elements composing into the index A, affords a way of identifying relative contribution of each collision damage case to the risk at an early design stage and hence devise an effective means of risk reduction by focusing primarily on the high risk-contributing loss scenarios. This concept is illustrated in Figure 9 for a typical cruise ship.

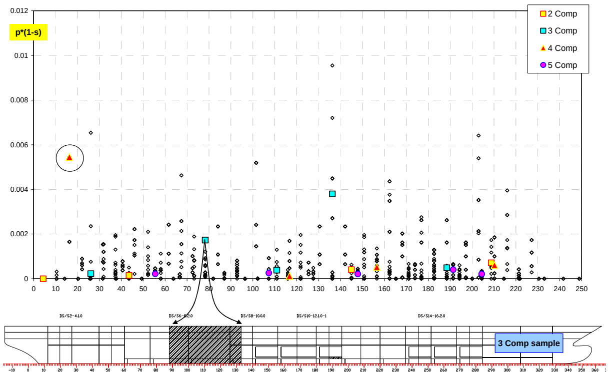


Figure 9: Distribution of relative contribution to risk per damage case, Ver 1, see Figure 7.

In Figure 9, the longitudinal location (horizontal axis) corresponds to the mid coordinate of the flooded compartments. The relative "risk" of non-survival, assumed here as simple dot product of probability of damage and probability of non-survival, $p_i \cdot (1 - s_i)$, is plotted on the vertical axis. For a specific damage location, there may be several damage case scenarios depending on the extent of flooding (longitudinally, vertically and transversely). The non-survival probability ("risk") can be used to identify high-risk areas of the watertight subdivision; changes made in those areas will be the most effective in reducing risk, and of course in improving the subdivision index. These scenarios could be supplemented by using judiciously relevant statistics and through HAZID/brainstorming sessions with designer /yard/owner aiming to identify any design vulnerability.

Numerical simulations are then being used in calm water and in waves (as required) to establish the exact flooding mechanism and identify cost-effective changes for the local watertight arrangement using PROTEUS-3 software suite [5]. The results are analysed in terms of occurrence of potentially dangerous attitudes as well as the process of flooding itself relating to the following three flooding stages, namely:

(a) Transient flooding: This analysis aims to assess ship response during the transient stage of flooding and in particular the formation of multiple free surfaces, see Figure 10. This is a mechanism of capsize, recently identified, [6], that is relevant to ships with complex watertight subdivision such as cruise ships. As the hull is breached, water may rush through various compartments at different levels, substantially reducing stability even when the floodwater amount is relatively small. As a result the ship could heel to large angles, even for small damage openings, letting water into the upper decks that spreads rapidly through these spaces and may lead to rapid capsize.

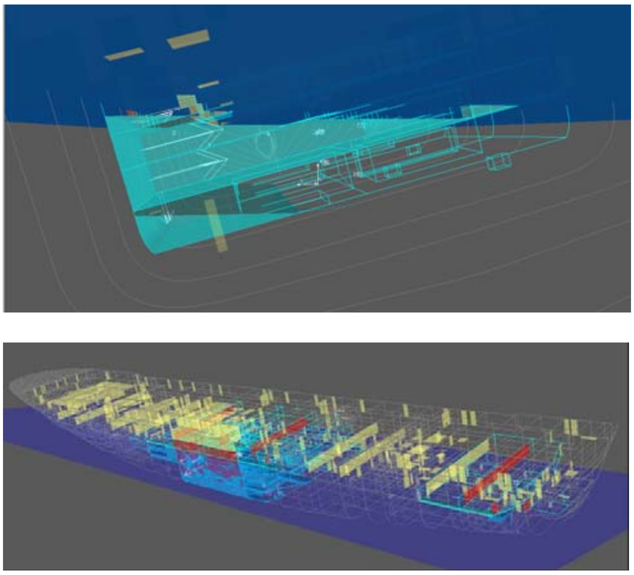


Figure 10: The phenomenon of multiple free surfaces.

(b) Cross flooding: This analysis focuses on dimensioning connection arrangements to ensure cross-flooding time in less than 60 seconds in accordance with SOLAS requirements. Verification of cross-flow using Computational Fluid Dynamics (CFD) might be undertaken if obstructions impede the flow and the simple Bernoulli model (in PROTEUS3) cannot be used

(c) Progressive flooding: This investigation focuses on potential design vulnerability concerning loss of freeboard and subsequent flooding through system penetrations, piping and ducting, doors, windows etc.

The results of the foregoing investigation will also be analysed in terms of the distribution of the time to capsize and will be supplemented with results using an analytical method, as explained next.

4.3 TIME TO CAPSIZE

Considerable progress has been achieved over the last ten years in development of the relevant engineering tools, such as the model underlying equation (5), and thus understanding of the character of the stochastic process of ship capsize when subject to a collision damage in waves, as discussed in [8], [9], [7] and most recently [10].

It can be shown on the basis of such model, for instance how likely is it that a vessel is expected to capsize within any period of time after any arbitrary collision, as can be seen in Figure 11 and Figure 12 below, where comparison of the probability of capsize within given time is made for the two ship arrangements shown in Figure 7 and Figure 8.

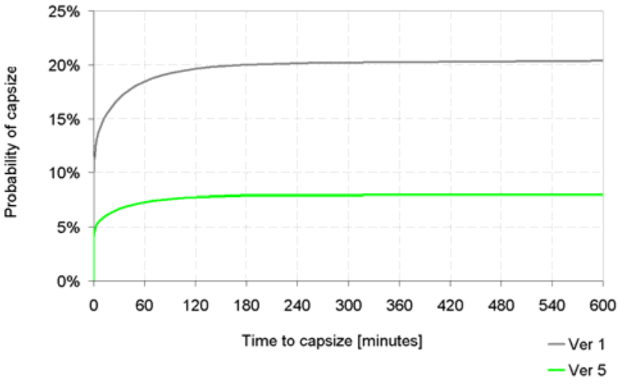


Figure 11: Distribution of probability (cdf) to capsize within given time for two ship arrangements shown in Figure 7 and Figure 8.

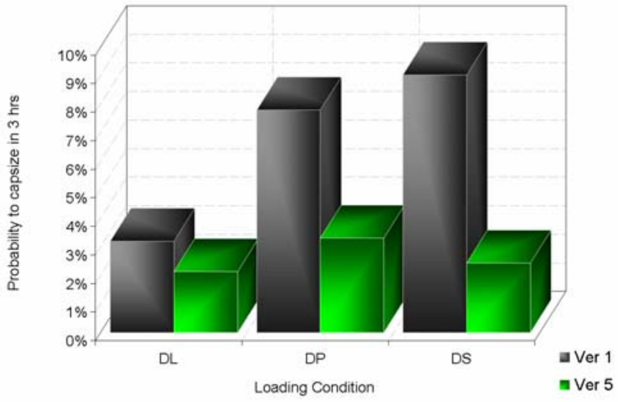


Figure 12: Joint probability mass function (loading and time to capsize of up to 3 hours) for two ship arrangements shown in Figure 7 and Figure 8.

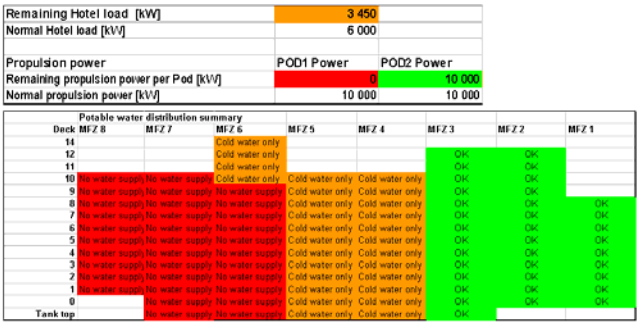
Despite what might appear from Figure 6 as not significant increase of A index, the reduction of the probability to capsize within 3 hours time, recommended by the IMO, see §3, of some *60%* can be attained.

4.4 EMERGENCY SYSTEMS REDUNDANCY

A novel and highly important element in the IMO framework of "safe return to port" relates to evaluation of systems availability, in a casualty situation in accordance with the requisite functional requirements to meet the set safety objectives. Such an analysis ought to address emergency services availability in all the scenarios considered for the hazard in question. This problem needs to be subdivided into two sub-problems: Firstly, to identify the requisite emergency functions and services and, secondly, to develop pertinent criteria (functionality- and safety-related) to ensure that functional requirements and safety objectives, respectively, are met (e.g., range, speed, supplies, etc.) for e.g., safe return to port. This entails that subject to a collision and flooding event a number of issues need to be ascertained:

- Vessel survival in all design scenarios
- Time to capsize exceeding requisite time to return (or be towed) to a safe refuge or to abandon ship
- Systems availability rendering the ship functional and habitable for the requisite time if abandoning ship is considered unnecessary.
- Emergency systems availability for the evacuation process.

A recently developed emergency services availability tool by Deltamarin is used to examine availability in all one- and two-compartment damage scenarios as specified in the probabilistic rules as well as the critical scenarios identified in the foregoing. In addition, efforts are being expended to couple this tool to PROTEUS with the view to examining the possibility of progressive flooding through for example damaged pipes as well to attempt to fully automate this process to cope with the very large number of scenarios. A typical output of this analysis is shown in Table 2.



Remaining Hotel load [kW]	3 450	
Normal Hotel load [kW]	6 000	
Propulsion power	POD1 Power	POD2 Power
Remaining propulsion power per Pod [kW]	0	10 000
Normal propulsion power [kW]	10 000	10 000

	Potable water distribution summary							
Deck	MFZ 8	MFZ 7	MFZ 6	MFZ 5	MFZ 4	MFZ 3	MFZ 2	MFZ 1
14			Cold water only					
12			Cold water only			OK	OK	
11			Cold water only			OK	OK	
10	No water suppl	No water supply	Cold water only	Cold water only	Cold water only	OK	OK	
9	No water suppl	No water supply	No water supply	Cold water only	Cold water only	OK	OK	
8	No water suppl	No water supply	No water supply	Cold water only	Cold water only	OK	OK	OK
7	No water suppl	No water supply	No water supply	Cold water only	Cold water only	OK	OK	OK
6	No water suppl	No water supply	No water supply	Cold water only	Cold water only	OK	OK	OK
5	No water suppl	No water supply	No water supply	Cold water only	Cold water only	OK	OK	OK
4	No water suppl	No water supply	No water supply	Cold water only	Cold water only	OK	OK	OK
3	No water suppl	No water supply	No water supply	Cold water only	Cold water only	OK	OK	OK
2	No water suppl	No water supply	No water supply	Cold water only	Cold water only	OK	OK	OK
1	No water suppl	No water supply	No water supply	Cold water only	Cold water only	OK	OK	OK
0		No water supply	No water supply	Cold water only	Cold water only	OK	OK	OK
Tank top		No water supply	No water supply	Cold water only	Cold water only	OK		

Table 2: Available Services (Deltamarin)

4.5 EVACUATION ANALYSIS

The last element in addressing the issue of safe return to port and indeed to estimate the risk related to occurrence of flooding pertains to the evacuation process, Figure 13

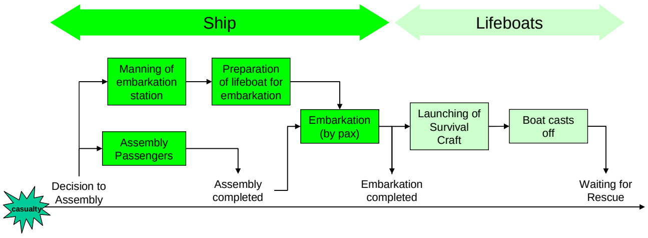


Figure 13: The Evacuation Process

In IMO evacuation analysis, undertaken for new cruise ships and existing passenger ships on a voluntary basis, allows for assessment at the design stage of passive safety (in-built) of the ship evacuation system only, while operational safety (active), pertaining to any measures to enhance emergency preparedness and to better manage crisis in case of an emergency, is only dealt with by means of a safety factor. In this respect, the IMO evacuation scenarios address issues relating to layout and availability of primary evacuation routes as well as passenger distribution and response times but does not address any real emergencies and hence the need to prepare for these trough better planning, training and decision support, all related to the functionality of the crew onboard, which is as crucial to passenger mustering as a good layout of the escape routes. Breaking away from the traditional approach of the marine industry to design aspects, RINa has recently developed and launched the first ever notation dedicated to operational aspects with help from SSRC and implemented it on the *Spirit Class* of Carnival, [11].

This Class Notation aims at assessing the effectiveness of crew functionality by comparing the evacuation performance of a ship in several specific scenarios (in addition to 4 IMO scenarios, scenarios pertaining to social events, ship at berth and owner specified scenarios to reflect real emergencies are considered) with and without crew assistance. This new concept makes evacuation analysis much more relevant offering real "means" for enhancing passenger evacuation performance as well as incentivising passenger ship owners to improve emergency procedures.

Stemming from these developments, evacuation analysis through numerical simulations can now be undertaken meaningfully. The term *Evacuability* reflects ability to evacuate a *ship environment* within *a given time* and for *given initial conditions* and is defined as follows:

$$E = f\{env, d, r(t), s(n_i); t\}$$

Thus, *Evacuability* is a function of a set of initial conditions, *env*, *d* and *r(t)*, and evacuation dynamics, *s(n_i)* and provides a direct risk measure of passenger evacuation in a ship-sea environment as explained in [11].

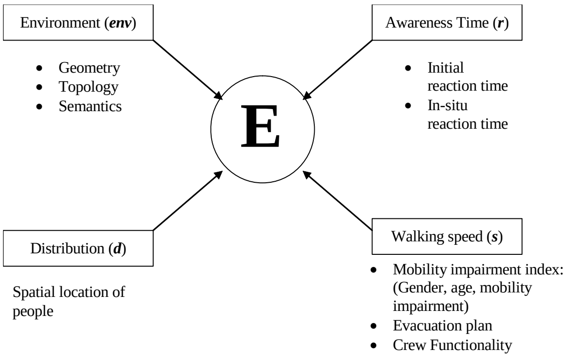


Figure 14: The concept of *Evacuability* (E)

On the basis of the above, it may be stated that *Evacuability* is a well-defined problem that can be formulated and solved (simulated) for given initial conditions and passenger flow parameters. In fact, there exist several advanced passenger evacuation simulation tools, some of which are able to deal with design and operational issues as well as be coupled with advanced simulation tools for flooding (PROTEUS3) or fire (LESSFIRE, [12]) and be utilised to prevent /reduce human life loss, as postulated in the foregoing. EVI, for example, uniquely incorporates capabilities to estimate the effects of both fire and flooding in the evacuation process. In the cases considered, data from external tools that address flooding and fire hazards independently (outside the evacuation environment) is required. This data is then imported into the EVI evacuation simulation environment as additional semantic information for the agents (evacuees). The agent model considers human behaviour in an evacuation to a small set of crucial characteristics such as speed and awareness. A hazard within the evacuation environment will affect these characteristics changing the performance of the agents.

Finally, comparing the evacuation completion curve (cumulative distribution of the time taken by passengers and crew to evacuate) with the corresponding distribution of time to capsize at scenario level for all the scenarios considered, the number of fatalities could be estimated and hence risk calculated or more importantly appropriate measures taken to reduce/negate at the design stage.

5. CONCLUDING REMARKS

On the basis of the foregoing discussion and results presented, the following concluding remarks can be made:

- The new probabilistic framework for damage stability offers the potential to achieving much better standards than those set out by deterministic regulations and without doubt constitutes a significant and long awaited step towards improved safety, particularly if state-of-the-art knowledge and tools are utilised to address damage survivability in a meaningful manner.

- Moreover, frameworks proposed by IMO and others soon to be embarked upon provide the right platform to accommodate and promote scientific approaches to dealing with ship safety.

- In support of the above the paper highlights the use of first-principles tools and presents a workable model for quantifying risk in passenger ships with regard to loss of human life. The integration of such tools allows for an explicit and direct evaluation of human life loss in any given flooding scenario. This type of capability is essential if a "holistic approach" for ship design is to be adopted, particularly in relation to passenger ships (SLF 47/8). This approach entails that passenger ships must be able to withstand a stipulated damage (extent of damage) threshold and still safely return to port. Even if the casualty threshold is exceeded, a ship is to remain habitable for a minimum time (3 hours) to allow for safe and orderly abandonment.

- Such approaches reflect the trend toward goal-based standards and highlight the merits of a risk-based design methodology. This is particularly useful when dealing with innovative ship design concepts and alternative design and arrangements. In such cases, quantitative risk analysis is the only reliable route to ensure that an appropriate level of safety (equivalent to an acceptably low level of risk) and the set safety goals (e.g. safe return to port) are achieved.

6. ACKNOWLEDGEMENTS

The authors are indebted to the Maritime and Coastguard Agency UK, the European Commission, Color Line, Royal Caribbean Cruise Lines and especially Deltamarin who have contributed in the development of the tools and concepts presented in this paper through funding, data and valuable discussions.

7. REFERENCES

[1] Vanem, E, Skjong, R, *"Collision and Grounding of Passenger Ships – Risk Assessment and Emergency Evacuations"*, Proc. the 3rd International Conference on Collision and Grounding of Ships, ICCGS 2004, Izu, Japan, Oct 25. – 27. 2004.

[2] SLF 47/17, Sub-Committee On Stability And load Lines And On Fishing Vessels Safety, 27th Sept 2004.

[3] Pawlowski, M, *"Subdivision and damage stability of ships"*, Euro-MTEC series, Technical University of Gdansk, 2004.

[4] Vassalos D, Kim H, Christiansen G and Majumder J, *"A Mesoscopic Model for Passenger Evacuation in a Virtual Ship-Sea Environment and Performance Based Evaluation"*, Pedestrian and Evacuation Dynamics, April 4-6, 2001 – Duisburg, www.safety-at-sea.co.uk/evi/publications.htm.

[5] Jasionowski, Andrzej, *"An integrated approach to damage ship survivability assessment"*, PhD, University of Strathclyde, 1997-2005

[6] Vassalos, D, Jasionowski, A, Guarin, L, *"Passenger Ship Safety – Science Paving the Way"*, Proceedings of the 8th International Ship Stability Workshop, Istanbul, October 2005.

[7] Jasionowski A, Bulian G, Vassalos D, Francescutto A, Pawlowski, M, Maccari A, *"Modelling survivability"*, SAFEDOR, D2.1.3, www.safedor.org.

[8] Vassalos, D, Jasionowski, A, Dodworth, K, Allan, T, Matthewson, B, Paloyannidis, P: *"Time-Based Survival Criteria For Ro-Ro Vessels"*, RINA Spring Meetings 1998, London.

[9] Jasionowski A, Vassalos D, Guarin L, *"Theoretical Developments On Survival Time Post-Damage"*, Proc. The 7th Int Ship Stability Works., Shanghai, Nov 2004.

[10] Jasionowski, A, Vassalos, D, *"Conceptualising Risk"*, 9th International Conference on Stability of Ships and Ocean Vehicles, Rio de Janeiro, September 2006.

[11] Dogliani, M, Vassalos, D, Strang, T, *"Evacuation Notation – A new concept to boost passenger evacuation effectiveness in the cruise industry"*, COMPIT 2004, 3rd international Euro-conference on computer applications and information technology in the marine industries, May 2004, Parador Siguenza, Spain.

[12] Guarin, L, Majumder, J, Shigunov, V, Vassalos, G, Vassalos, D, *"Fire and Flooding Risk Assessment in Ship Design for ease of evacuation"*, 2nd International conference on design for safety, Osaka, Japan, October 2004.

8. AUTHORS BIOGRAPHIES

Professor **Dracos Vassalos** BSc, MBA, PhD, CEng, FRINA, FIMarEST. Professor Dracos Vassalos is the Head of Department of Naval Architecture and Marine Engineering of the Universities of Glasgow and Strathclyde and the Director of the Ship Stability Research Centre (SSRC), a world-leading centre of excellence on ship stability and safety. He has been involved in research, development and application for 29 years and has published and lectured widely in these areas, compiling various prizes and awards including some 100+ major research contracts totalling £14M and some 350 technical publications. Professor Vassalos is Chairman of the International Standing Committee of the "Design for Safety" Conference, a theme instigated and promulgated by SSRC through the EU Thematic Network SAFER EURORO and a member of the UK delegation to IMO for ship stability. He is also the Managing Director of Safety at Sea Ltd., an engineering consulting company offering specialist services to the maritime industry on ship stability and safety and on the design of knowledge-intensive, safety-critical ships.

Andrzej Jasionowski, MEng, PhD, CEng, MRINA. Graduated from the Technical University of Gdansk (1997), and University of Strathclyde (2002). Currently engaged as Technical Manager of the Ship Stability Research Centre, Universities of Glasgow and Strathclyde, and as a Director of Safety At Sea Ltd. His main interests comprise ship hydrodynamics, damaged ship dynamics, stability, modern risk assessment, inductive inference, plausible reasoning, modelling uncertainty, numerical algorithms development, philosophy of safety. Author of 30 journal and conference papers.

Dr **Luis Guarin,** MEng, PhD. Luis Guarin currently works as Project Manager for the Glasgow-based consulting company Safety at Sea Ltd. He holds a PhD in Naval Architecture (University of Strathclyde, Glasgow, UK) and a MEng in Ship Design and

Construction (Technical University of Gdansk, Poland). His areas of expertise, gained over the past 10 years working at the Ship Stability Research Centre of the Universities of Glasgow and Strathclyde and Safety At Sea Ltd, include risk analysis, fire safety, ship evacuation, seakeeping and damage stability. He has been responsible for carrying out Formal Safety Assessments addressing structural integrity of bulk carriers and navigation safety. In relation to ship design, he has been actively involved in the application of alternative design and arrangements for passenger vessels.