Influence of life-cycle damage stability requirements on the ship internal arrangement

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ABSTRACT

Historically speaking, the primary driving force behind internal ship layout (mainly subdivision) has come in the form of rules and regulations. In such instances, change has occurred slowly, often in a reactive manner in the wake of accidents. However, the nature of internal layout that is favourable for operation, is often in conflict with that for safety and hence objectives pertaining to each generally lie in antithesis. This is particularly true for passenger ships, for which the extent of the hotel/accommodation arrangements is substantial, considering onboard habitability. For this reason, the rate of safety progression by introducing more stringent watertight subdivision requirements has often been slowed due to industry resistance on the grounds that their ability to operate a viable business would be impaired. This, in turn, is indicative of a greater problem relating to the efficiency and variety of existing design changes for flooding risk reduction and control. It would appear that there is an urgent need to start seeking alternative and more effective solutions, rather than continued sole reliance on conventional measures such as watertight subdivision. In order to achieve this aim, one must consider the vessel throughout its entire life cycle (design, operation, emergency response) and understand the essence of the trade-off between the regulatory and owner's requirements within each stage. This would involve consideration of the constraints and conflicting requirements that each stage brings to the decision-making process in relation to the optimal configuration of the internal ship space. Only then, can one hope to provide solutions capable of achieving this aim. The paper presents a framework to address this imbalance with specific applications on design, operation, and emergency response on a large passenger ship.

Keywords: *Damage stability, evacuation, flooding risk, passenger ships, multi-level approach.*

1. INTRODUCTION

The idea of configuring the internal volume of a ship into compartments in order to mitigate the effects of hull breach and flooding is by no means a recent one. In fact, the importance of doing so, intuitive as it is, was established some 38 centuries ago by the Babylonians and sanctioned within the Code of Hammurabi (Francescutto & Papanikolaou, 2010). However, despite this early development, the question of flooding protection slept for many years until awoken once again in the 19th century, during which vessel designs were undergoing transformative changes. Firstly, moving from wood to iron construction and secondly, growing much larger in size and capacity. Concerning the latter, more people are now at risk than ever before and unfortunately, the development of flooding protection did not come fast enough. Instead, a number of major accidents and great loss of life drove development. Having said this, there have always been people of practice with great vision and intuition, who have paved the way to reconfigure the ship's internal space for safety in ways that we still struggle to master today. The design of the 'Great Eastern' is one such example of this and was a vessel that stretched the limits of Victorian technology. She was built at an unprecedented scale for her time, with a length of 207 m, displacement of 22,000 tons and a speed of 14 knots. During regular service, the vessel could accommodate 4,000 passengers, which could be further increased to 10,000 soldiers when acting as a troop ship. Incorporated into the design were the very latest technological achievements in Naval Architecture and Marine Engineering including riveted iron construction, steam power, and propulsion in the form of paddle wheels and a stern screw propeller. Perhaps most remarkably, the Great Eastern had not only watertight subdivisions but also a ‘double hull’, which acted to improve crashworthiness and prevent minor damage penetrations leading to large-scale flooding. These are concepts only recently being adopted in modern passenger vessel design under the provisions of Safe Return to Port.

However, what may appear obvious or ingenious, needs to be contrasted against other design requirements pertaining to performance, functionality, and cost. In fact, despite the many great advances described, the Great Eastern was never a commercial success and there is a lesson in that. Internal layout impedes functionality (reduces ergonomy and space), performance (flow of people and goods) and comes at a cost (construction and maintenance). Further still, structural strength and reliability as well as the basic need for structures to be crashworthy, add more constraints on top of those pertaining purely to safety, leading to a complex design optimisation problem. Vectorisation (turning constraints into objectives – Design for X) has been a vehicle to facilitate design optimisation and, as such, design for safety and risk-based design. This, in turn, has facilitated rational decision-making in the design process, particularly concerning configuration of the internal ship space.

In this respect, this paper will address the various requisite ingredients for life-cycle consideration of the internal ship layout, leading to a cost-effective configuration for damage stability protection/enhancement. This is achieved by considering ship design and operation (including emergencies) as well as pertinent design constraints/objectives in the form of rules, regulations, performance, functionality and cost. Too often, safety-minded practitioners in the maritime industry feel that compliance and evasion cover the whole safety spectrum. However, this paper will demonstrate that safety has been the largest single factor affecting the evolution of ship design and operation, with the configuration of the internal ship environment representing the most treaded avenue to enhancing maritime safety with respect to damage stability.

2. RULES & REGULATIONS AS THE PRIME MOVER

This section discusses how rules and regulations for damage stability protection (as Risk Control Options) have been developed and how these rules, as the key determining factors, have influenced internal ship configuration, namely subdivision at the design stage. It should be noted that the term configuration is meant to imply the evolutionary process involved as well as the concept of active intervention in reconfiguring the internal space of a ship. This, in turn, is linked inextricably with ship stability quantification and provision, particularly when the ship hull is damaged as a result of collision or grounding incidents. In 1939, Jaakko Rahola made propositions to use a function of GZ curve to express the ability of a ship to stay in functional equilibrium after flooding (Rahola, 1939). This is a development of particular significance, as it is one of the earliest examples of informed reconfiguration of the ship environment for flooding protection. The emphasis, however, was on global ship parameters rather than the details of the internal ship environment, which is highly influential in the case of large passenger ships. Regardless, his approach influenced subsequent regulatory developments for all ship types, an issue, which Rahola could not possibly have conceived of at the time. As advances in identifying “stability” parameters progressed, the legislation process for implementation of any such “technicalities” has surprisingly been slow, even though the need for some “legal” safety instrument was realised for many centuries. First attempts to introduce governmental intervention have been in place since ancient times, such as a ban on sailing in winter (15th September to 26th May) in Rome during the Roman Empire (27 BC – AD 476 / 1453), which remained in force in some places until as late as the 18th century. Other examples include the first recorded regulations on load line during the Middle Ages in Venice in 1255 (cross marked on each ship), or the first system of survey inspections imposed by The Recesses of the Diet of the Hanseatic League of 1412.

However, it was not until the Industrial Revolution of the 19th century that the true face of risk encountered by shipping started to show, with the introduction of steam-powered engines, steel hulls and the rapid escalation of sea trade to the dimensions of an “industry”. During the winter of 1820 alone, more than two thousand ships were wrecked in the North Sea, causing the death of twenty thousand people in just a single year, with some 700-800 ships being lost annually in the UK on average. Such loss toll has prompted the main maritime nations of the time, France and the UK, to exercise their policy-making powers to introduce accident-preventive regulations, to great opposition from the industry. Of note are Colbert’s Naval Ordinance, instituted by a Royal Declaration of 17th August 1779 in France, which introduced again the office of huissier-visiteur, a surveyor. In addition, the Merchant Shipping Act of 1850 (reinforced by the Government in 1854 and amended by the Act of 21 December 1906) in the United Kingdom, obliged the Board of Trade to monitor, regulate and control all aspects of safety and working conditions of seamen. The latter also saw the implementation of load line requirements, which were applied to all vessels, including foreign ships, which had to comply with Plimsoll’s freeboard requirements when visiting UK ports.

However, the catalyst for significant change did not come until the sinking of the Titanic in 1912, after having struck an iceberg on her maiden transatlantic voyage to New York. In this single incident, 1,500 people lost their lives, leading to the adoption of the first International Convention for the Safety of Life at Sea (SOLAS) on January 21st, 1914, gaining international recognition[1]. The SOLAS Convention has been subsequently revised and adopted four times since then, specifically in 1929, 1948, 1960 and 1974, with the latter still in force today. This is supported by the provision of a flexible process of revisions through amendment procedures included in Article VIII. It is worth noting that, although the provisions of SOLAS 1914 prescribed requirements on margin line and the factor of subdivision in addressing the state of a damaged ship, the Convention did not even mention the concept of stability at all. Instead, all focus was on intuitive/empirical internal volume configuration (i.e., subdivision) as opposed to informed configuration by stability calculations. It was the third Convention of 1948, which finally referred to stability explicitly in Chapter II-B, Regulation 7, and subsequently, SOLAS 1960, which actually prescribed specific stability requirements. Unfortunately, only one parameter of stability after flooding was considered, with the regulations calling for a residual GM of 1 cm. Finally, SOLAS 1974, adopted Rahola’s proposals of using properties of the GZ curve as a measure of stability. In principle, Rahola’s approach has formed the basis for amendments of technical requirements on stability ever since (Womack, 2002), applied in various frameworks for adherence to the SOLAS ’74 goal “The subdivision of passenger ships into watertight compartments must be such that after an assumed damage to the ship's hull, the vessel will remain afloat and stable”. Further still, Rahola’s use of GZ curve properties to guide subdivision and to quantify stability are at the core of even the most modern amendments to SOLAS 1974 criteria of ship stability in the damaged condition, (IMO, 2006), (Tuzcu, 2003). This can easily escape attention, since the overall damage stability assessment framework, based on Kurt Wendel’s concepts of the probabilistic index of subdivision A, (Wendel, 1960), (Wendel, 1968), is rather a complex mathematical construct, with the basic details not easily discernible. This framework is also a major step-change in the philosophy of stability standardisation or indeed internal ship space configuration. It was further elaborated in a series of EU-funded research projects (SAFER-EURORO, SAFEDOR, HARDER, ROROPROB) in the late 1990s/early 2000 and eventually led to the introduction of the harmonised damage stability regulations for dry cargo and

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[1] Remarkably, the sinking of RMS Titanic in 1912 happened 50 years after a serious grounding of Great Eastern on the same voyage to New York. However, in view of Great Eastern’s double hull concept, , the outer hull damage of Titanic did not lead at that time to ship sinking (Papanikolaou, 2014). As pointed out by Roy Brander, “the Great Eastern, like the Titanic, had fifteen transverse bulkheads. In Great Eastern, however, these went a full 30 inches above the water line and right up to the top deck in the fore and aft. In the engine rooms, they were lower, but the engines were further protected by longitudinal bulkheads on either side. The middle deck was also watertight, further subdividing the compartments into some 50 in all.This was defence in depth against flooding” (source: lecture by Roy Brander, “The RMS Titanic and its Times: When Accountants Ruled the Waves”, 69th Shock & Vibration Symposium, Minneapolis, 1998)

passenger ships on the basis of the probabilistic concept of SOLAS 2009 (Papanikolaou, 2007).

As indicated above, it seems that such implicit reliance on Rahola's measures is a major obstacle to practical disclosure of the meaning of stability standards, as no common-sense interpretations are possible, regardless of the acclaimed rationality of the overall framework. Rahola himself has stressed: "When beginning to study the stability arm curve material … in detail, one immediately observes that the quality of the curves varies very much. One can, therefore, not apply any systematic method of comparison but must be content with the endeavour to determine for certain stability factors such values as have been judged to be sufficient or not in investigations of accidents that have occurred". This then leads one to ask, "what is sufficient?" and unfortunately today's standards do not offer an explicit answer. The profession seems to be content with an implicit comparative criterion, whereby a Required Index R is put forward as an acceptance instrument (ultimately as "a" stability measure). However, this is offered without a clear explanation as to what is implied if the criterion is met or in what sense the goal of keeping the vessel upright and afloat is catered for. In essence, the question "what does A=R mean?", had not been explicitly disclosed until the early 2000s. Here, the adoption of Design for Safety and the ensuing design methodology "Risk-Based Design" provided the means to design ships with a known safety level and, in the case of damage stability, known flooding risk, (Vassalos, 2008), (Vassalos, 2012), thereby guiding the impact of internal ship layout from a life-cycle perspective. Notwithstanding this, the vast majority of damage stability regulatory developments have failed to deal with internal space layout in a direct manner. Instead, regulations tend to implicitly, but not explicitly, deal within internal configuration despite this being such an obvious, predominantly influencing feature, particularly for large passenger ships. A key reason for this stems from the fact that the original damage stability criteria, derived from model tests by Bird and Browne (Bird and Browne, 1973), used global parameters to assess damage stability, as shown in Equation 1, and everybody subsequently followed their lead. Of course, damaged GM and freeboard, as Bird used, are influenced by internal configuration, but the nature of the formulation is such that it does not clearly provide much feedback to the designer in this direction.

$$s = 4.9\sqrt{\frac{F_E \cdot GM}{B}} \tag{1}$$

Where, F_E = effective freeboard (m), GM = metacentric height (m) and B = beam (m).

In a similar manner, Tuzcu and Tagg (Tuzcu and Tagg, 2002), in project HARDER, derived a survivability factor that formed the basis for the SOLAS 2009 damage stability probabilistic rules, linking sea state (Hs_{crit}) to parameters of the residual stability curve, namely GZmax and Range, as given in Equation 2.

$$\begin{gathered} Hs_{crit} = 4\frac{GZmax}{0.12} \cdot \frac{Range}{16} = 4s^4 \\ \leftrightarrow s = \left(\frac{Hs_{crit}}{4}\right)^{0.25} \end{gathered} \tag{2}$$

Again, despite damaged GZmax and Range being heavily influenced by internal layout and truncated as regards unprotected openings, there is no direct feedback granted to the designer as regards internal layout and this is an important missing link. The first attempt to escape from this regulatory "trap" is evident in the work of (Vassalos, Turan, and Pawlowski, 1997) in their proposal of the Static Equivalent Method targeting the reconfiguration of the vehicle deck in RoPax ships, as shown in Equation 3.

$$Hs_{Crit} = \left(\frac{h}{0.085}\right)^{\frac{1}{1.3}} \tag{3}$$

Here, both the Hs_{crit} and h are taken as median values of the respective random quantities. The critical significant wave height can be then used in the s-factor formulation adopting the cumulative distribution of waves from IMO. In project HARDER (HARDER, 2003), the formulation was updated following a statistical relationship between dynamic water head (h), the freeboard (f), the critical heel angle and the mean significant survival wave height, see Figure 1.

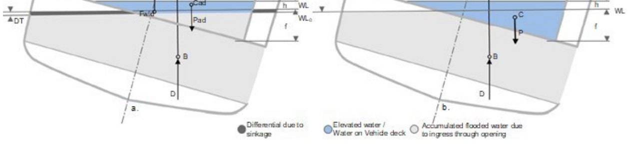

Figure 1: Depiction of SEM parameters with water elevation in the vehicle deck at the Point of No Return (PNR) - case of RoPax (left), conventional method considering the floodwater volume as a total water on the vehicle deck inside an undamaged tank (right). (HARDER, 2003)

This has signalled that there are alternative routes to considering s-factor formulations accounting for the layout of the internal ship space, even above the strength deck, a real novelty, which was taken further in Project GOALDS, see Equation 4 (Cichowicz et al., 2016).

$$Hs_{crit} = \frac{\frac{1}{2} GZ_{max} \cdot Range}{\frac{1}{2} GM_f \cdot Range} V_R^{\frac{1}{3}} \tag{4}$$

Where, V_R is a measure of the residual volume (scaled appropriately)

The scene was set properly for this concept to be further considered in the project eSAFE where Atzampos has developed a new formulation for Hs_{crit} with emphasis on scaling between different vessel sizes, (Atzampos, 2019).

$$Hs_{crit} = 7 \cdot \left[\frac{MIN(\lambda \cdot Range, TRange)}{TRange} \cdot \frac{MIN(\lambda \cdot GZ_{max}, TGZ_{max})}{TGZ_{max}}\right]^{1.05} \tag{5}$$

Where,

TRange = target value for Range, 30 degrees

TGZmax = target value for GZmax, 0.3m

λ = scaling factor, based on intact to damage volume ratio.

However, despite achieving a better estimate of ship stability by considering in more detail the internal ship layout, the general formulation failed to account for the complex internal layout of cruise ships, which undoubtedly determines the evolution of flooding and the eventual outcome. This has ultimately led to a compromise being reached at IMO concerning damage stability standards. Key reasons for this relate to the industry having reached a conclusion that further measures to improve damage stability standards, primarily through further reconfiguration of the internal environment has reached saturation.

3. LIFE-CYCLE CONSIDERATIONS OF INTERNAL SHIP LAYOUT - DESIGN PHASE

Traditionally, regulations focus on built-in solutions, identified normally during the design phase. However, whilst active/interventional measures considered during operation or emergency response phases fuel debates on their risk reduction potential from the point of view of damage stability, these have never actually been measured or verified. In this respect, a framework that facilitates assignment of risk merit to every risk control measure is key to life-cycle risk management. A life-cycle perspective facilitates a holistic approach to damage stability, encompassing risk control options for all three phases and accounting for each by using, for example, IMO cost-effectiveness criteria. This, however, assumes that the risk reduction potential of all such measures is known and, because this is lacking, this is where there is a big gap in this approach that needs to be overcome before such a process can be formalised and adopted.

The Design Optimisation Problem (Subdivision)

Ship design is inherently multi-disciplinary, and consequently any design modification is accepted or rejected based on its impact across a wide array of performance criteria, rather than dealing with any single performance quality in isolation, i.e., life-cycle cost. The debate over sequential or parallel processes and design vectorisation no longer resides solely in the academic sphere and is instead very much a problem being faced and addressed by the industry (Vassalos-Papanikolaou, 2018). The SOLAS ‘90 approach for bulkhead spacing imposed limitations based on ship floodable length criteria under Regulation 6, which restricted the degree of flexibility afforded to the designer in optimising the vessel subdivision arrangement. Even after the adoption of probabilistic rules in which the decision on the number of bulkheads is part of the overall goal-based approach, the internal layout still has the tendency to become overly cluttered and expensive, with diminishing returns being realised as the number of bulkheads increases. The EU-funded project (ROROPROB, 1999-2002) focussed exactly on this problem and provided valuable input to the industry in this respect. Typically, cruise ships being were initially designed with some 25-30 bulkheads, which following optimisation of the subdivision arrangement was subsequently reduced to nearly half this number. This resulted from the fact that it was demonstrated that the difference in the A-Index was negligible, whilst the cost of adding additional bulkheads and the subsequent requirement for additional systems (heeling tanks, pumps, etc.), was completely unjustified. However, the push for continuously increasing damage stability standards for new buildings, and with attention spreading above the bulkhead deck (two additional decks), brought the need for additional subdivision above the bulkhead deck, this time with A60 bulkheads. More importantly, however, it brought competition through interference with ship functionality (for example with evacuation routes), so the problem became not only one of multi-disciplinary optimisation, but also multi-objective (Vassalos and Papanikolaou, 2018), (R. Puisa, 2012).

In (Vassalos & Papanikolaou, 2018), the suggestion is made that such a problem is covered by a Risk-Based Ship Design framework, where optimisation is inherent to the concept and safety is one of the quantifiable objectives. In this respect, Life-Cycle Assessment of ship safety, performance and return on investment are inherently integrated. In (R. Pusia, 2012 and the elaboration of Papanikolaou et al., 2013 in project GOALDS, 2009-2012), this approach, as a design and decision support tool, is proposed to be used both in the conceptual and preliminary design stage to quickly arrive at design alternatives that both satisfy requirements (owner and regulatory), thus affecting positively commercial performance. As ship design is inherently multi-disciplinary, a proposed design modification is accepted or rejected based on its multi-disciplinary performance rather than on a single performance metric such as life-cycle cost. To assess the performance of each such function (discipline) and thus the feasibility of the entire design, dedicated instruments and measures must be applied. Conventionally, these have been applied sequentially (Gale, 2013), as during the past neither computers nor software tools were powerful enough and there was an absence of relevant numerical techniques to facilitate parallel assessment. The need for a parallel assessment or design evaluation is essential for multi-disciplinary design, for it seeks to identify trade-offs between different performance measures. As such, parallel design evaluation dramatically reduces the number of iterations towards a ship design, whilst satisfying all constraints and providing the best performance achievable.

Furthermore, as virtually any new build ship is a variation of some past design, any such design may serve as a prototype for future designs. This practice is common amongst all shipyards and design offices, where new designs are often an evolution from older designs. However, regardless of the amount of deviation from the baseline design, we still face the design customisation problem. The baseline design must be customised to new owner requirements and further modifications can be required within a limited timeframe, especially if such design changes occur later within the process or even after construction has commenced. Additionally, regulatory requirements (e.g., stability, fire safety) have to be fulfilled and these might already be different to those used for the baseline design, particularly as damage stability regulations constantly evolve, thus featuring so-called SOLAS'90, SOLAS 2009, SOLAS2020 and in the future SOLAS 20XX ships. It is also the case that satisfaction of various regulatory requirements, though essential, is not always a sufficient condition to maintain competitiveness. For example, there exist other marketing objectives such as low life-cycle cost (i.e., capital, operational, maintenance, etc.) and high earning capacity that must also be addressed. To this end, the design customisation problem becomes a rather complex one and designers are faced with the challenge of producing a design solution that is not only feasible and safe, but also competitive.

Structural Design Influences

The internal space in a ship could vary from a single space like the launches of the river Meghna in Bangladesh (zero configuration of internal ship layout) to modern megaships with some 8,236 spaces, 717 compartments, 1,160 openings (Oasis of the Seas, RCL). Hydrodynamic performance dictates the ship shape whilst structural strength and reliability requirements dictate the ship frame (decks, girders, plating, bulkheads – longitudinal and transverse, outer shell); a good summary is provided in Table 1 (Misra, 2016). Table 2, (Klanac, 2011), adds to this by providing a direct connection between various accidents and the measures taken to affect internal ship layout.

Table 1: Strength and operational utility of various structural parts and components, (Misra, 2016)

Item	Function
Strength deck, side shell and bottom plating	Form a box girder resisting bending and other loads.
Freeboard deck, side shell and bottom plating	Function as a watertight envelop providing buoyancy.
Bottom plating	Withstands hydrostatic pressure.
Forward bottom plating	Withstands slamming; plating thickness is increased; intermediate frames are provided. Breast hooks and stringers are fitted. Minimum forward draught is recommended.
Inner bottom, bottom plating DB floors and girders	Act as a double-plated panel to distribute the secondary bending effects due to hydrostatics loads and cargo loads to main supporting boundaries such as bulkheads and side shell. Resist docking loads.
Inner bottom	Acts as tank boundary for bottom tanks and withstands local loading due to cargo. Contributes to longitudinal strength.
Strength deck, upper deck	Withstands cargo handling equipment loading and cargo loading in some case as that of the container ship. Withstands loading due to shipping of green seas.
Remaining decks	Mainly withstand cargo loading, depending on extent and distance from neutral axis; contribute to longitudinal bending strength.
Side shell	Withstands hydrostatic pressure, dynamic effects due to pitching heaving rolling and wave loads.
Transverse bulkheads	Act as internal stiffening diaphragms for the hull girder and resist in plane torsion. Do not contribute to longitudinal strength. Generate watertight longitudinal subdivisions.
Longitudinal bulkheads, Bulkheads in General	Contribute to longitudinal strength. From tank boundaries support decks and loads generating equipment such as king posts and add rigidity. Serve as watertight partitions.
Stiffening of Plates	
Corrugations on bulkheads	Stiffen the bulkheads in place of vertical horizontal stiffeners.
Deck beams	Stiffen the deck.
Deck girders	Support the beams, deck transverses and transfer the load to pillars and bulkheads.
Transverse framing	Stiffens the side shell; supports the longitudinal stiffening. Supported in turn, by the decks, stringers and the longitudinal girders.
Longitudinal framing	Stiffens the shell, decks, tank top etc. Is supported by the deep transverses.
Side shell framing (general)	The web size is an important factor as regards a. Cargo stowage b. Panelling and insulation c. Running of wiring, vents, piping etc.
Vertical plates in double bottom (side and centre girders)	Stiffen the bottom panel as tank boundaries.

Table 2: Historical perspective on the improvements in the minimum requirements of safety, (Klanac, 2011)

Incident	Type of Accident	Convention instated/updated	Measures instigated
Titanic (1912)	Collision with iceberg and loss of 1517 lives as a result of poor organisation of disembarkation and lack of lifeboats.	SOLAS (1914)	Watertight subdivision.
Torrey Canyon (1967)	Grounding and spillage of 120,000t of crude.	CLC (1969) MARPOL (1973)	Compulsory liability for damage imposed on the owner/Segregated ballast tanks for all new tankers w/t 70,000+ DWT.
Amoco Cadiz (1978)	Grounding and spillage of 250,000t with claims of $2bn. presented by the French government.	MARPOL (1978)	Segregated ballast tanks for all new tankers w/t 20,000+ DWT with protective arrangement.
Herald of Free Enterprise (1987)	Flooding and capsizing with the loss of 193 lives.	ISM / SOLAS Ch. II-1 (1990)	Operational safety management, Watertight subdivision of garage decks.
Exxon Valdez (1989)	Grounding and spillage of 40,000t with damage of $3bn.	OPA (1990)/ MARPOL (1992)	All ships entering US waters to have double hulls/Double hull or risk-equivalent alternative arrangement for all newly-built ships.
Scandinavian Star (1990)	Fire with the loss of 158 lives.	SOLAS Ch.II-2	Requirements for fire zone subdivision.
Bulk carrier lost in the early ’90s.	Flooding and breaking.	SOLAS Ch. XII (1997)	Bulk carriers to have sufficient strength to undergo partial flooding of compartments.
Estonia (1994)	Flooding and capsizing with the loss of 852 lives.	SOLAS Ch. II-1 (1995)	Requirements for flooding tolerance, instigated in SOLAS (1990), to be applied to existing ships and also newly-built ships.
Erika (1999)	Breaking of hull and spillage of 20,000t with some €840 mil. worth of damage.	EU EMSA (2002)	Accelerated phase-out of single-hull tankers
Prestige (2002)	Breaking of hull and spillage of approximately 60,000t of crude with total damage claimed of more than $2.5bn	Resolution on places of refuge (2003)	Ship in distress should be accepted to a harbor providing a controlled environment

4. IMPACT OF OPERATION ON SHIP LAYOUT

Ship operation is not only the longest phase in the ship life cycle but is the only phase that justifies (more often than not) return on investment. As such, configuring the internal ship layout for any reason that may impact upon this will meet strong opposition. This is, of course, why safety comes into rules and regulations, which if not met the ship could not operate. Therefore, trying to raise the safety level beyond rules takes a great deal of time, effort and inculcation. This interaction between operation and safety objectives internal environment configuration and this, in turn, affects damage stability and safety. However, even if operation were restricted to the design envelop, it is during this phase where design assumptions and other limitations, leading to the residual risk, need to be managed. This means that the flooding risk needs to be monitored and controlled to ensure that risk remains tolerable throughout the life of the ship. Such control may be achieved by passive and active means, and this will be explored in this section.

Large passenger vessels, like most ships, are operated with the primary intention of making money, whilst at the same time aiming to do so in a safe manner. Unfortunately, when it comes to ship internal layout and architecture, what is good for safety is often bad for business. Hence, satisfying both objectives, becomes somewhat of a delicate balancing act and inevitably, conflicts manifest themselves in various forms within the internal arrangement. Passenger ships and particularly cruise vessels, generate money through two primary channels, namely ticket sales and on-board purchases. The former is linked closely, though not exclusively, to passenger capacity and the latter to the provision of on-board services and entertainment. In both instances, transformational changes have been taking place in internal ship layout and, over the recent past, economies of scale have driven developments towards increasingly large vessels at unprecedented rates, see Figure 2.

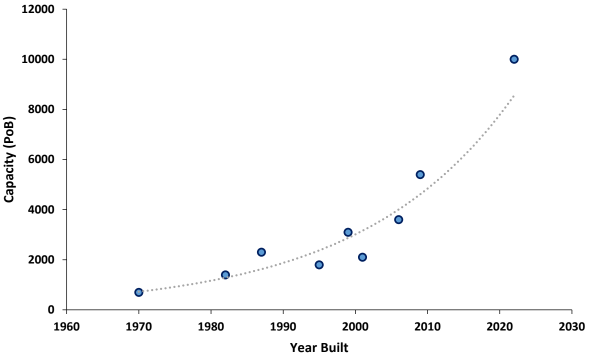

Figure 2: Cruise Vessel Growth Trend

A secondary effect of this growth has been the provision of a far greater platform from which the operator can offer increasingly diverse and elaborate forms of on-board entertainment, with it now being possible to "open up" the vessel more than ever before (Kulovaara, 2015). Modern cruise ships must cater for many cultures, demographics, and interests, all of which must be achieved on a mass scale. In so doing, they tend to offer a multifarious array of features including, but by no means limited to, restaurants, bars, casinos, spas, theatres and even ice rinks. Consequently, ship internal layout is primarily aimed at accommodating all these features within limited real estate. Furthermore, flowing, and uninterrupted spaces are often favoured in order to create an unconfined atmosphere, whilst also ensuring a continuous passenger flux along the ship (S McCartan, 2015). This is where the first notable conflict arises between internal layout for operation and that for safety. Most of these spaces are normally situated across the two decks located above the vessel bulkhead deck, which is favoured given that the boat deck would otherwise obstruct cabin views and balconies should accommodation be situated here. However, having these spaces located relatively low within the vessel superstructure also leaves them vulnerable to flooding and this is where problems arise. Large flowing spaces, while favourable from an operational and aesthetic perspective, can give rise to rapid floodwater accumulation and propagation. Firstly, when damaged, such spaces offer no reserve buoyancy, which is crucial during initial flooding. For this reason, damages with large vertical extents are particularly vulnerable to transient capsize, in fact, almost invariably transient losses involve at least one of these decks. Further still, should the vessel survive the transient flooding stage, in certain damage scenarios, these open spaces have the tendency to act much like a ro-ro space and fall prey to the effects of water on deck. This phenomenon occurs predominantly in high sea states, where wave-induced pumping effects may cause progressive flooding on the upper decks. Floodwater then rapidly spreads, giving rise to large free-surfaces and often leading to vessel capsize. As such, the prevalence of open spaces within large passenger vessels presents somewhat of a design paradox, whereby the safer a vessel is, the more open spaces it can have. However, the more open spaces it has, the less safe it becomes.

Such spaces also pose a risk regarding the propagation of fire but, in contrast to flooding, a great deal of progress has been made in this area through the alternative design and arrangements process. In 1986, the cruise vessel "Sovereign of the Seas" was designed with an atrium extending over three decks within one fire zone, which was approved under equivalent arrangements according to SOLAS I/5. Later, in 1999, "Voyager of the Seas" pushed the boundaries further still, with an atrium spanning three fire zones, again approved using equivalency design. Such developments then ushered in SOLAS II.2/17 on "Alternative Design and Arrangements for Fire Safety" and the second-generation Voyager-class vessels have atria spanning over four fire zones (Sames, 2009). In each instance, novel means were adopted in order to mitigate fire risk, either in the form of advanced analysis techniques, technology or both. Perhaps there is a lesson to be learned here as regards flooding, where unfortunately no such regulatory system exists yet in order to facilitate the implementation of alternative designs concerning flooding specifically. Perhaps SOLAS Ch. II-1, Regulation 4 (Damage Stability /Equivalence) offers such a possibility but this, as far as it is known, has not yet been taken up. Consequently, there has been little innovation in this respect, despite great potential, and recognition of this has fuelled many developments to address this problem. In addition to the prevalence of open spaces, there is another key example in which internal layout for operation and safety lies in opposition. This relates not to spaces, but instead, the channels of communication between them. Effective vessel operation relies on the ability to transport people and goods throughout the vessel in an efficient manner. An example of this is provided in Figure 3, showing catering spaces and flows for a typical cruise ship. This is just one of many processes that require such movements throughout the vessel, but even in this isolated case, one can observe the widespread pathways that exist. Such pathways, though essential, impair safety by providing conduits through which progressive flooding may occur. These exists as corridors in the case of longitudinal flooding progression and in the form of service elevators and stairwells, where up/down flooding may occur. Unfortunately, to date, there is little that can be implemented in the protection of such openings without greatly impairing operability.

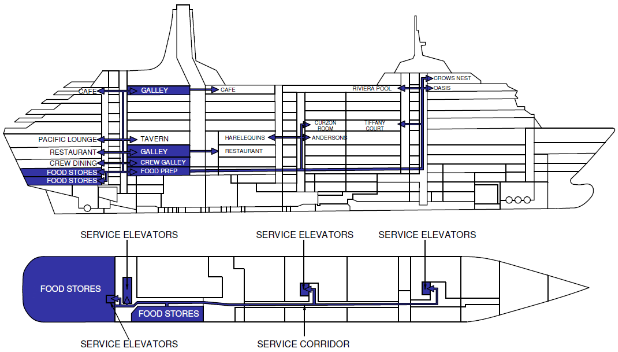

Figure 3: Catering spaces and flows for a typical cruise ship, based on the diagram shown in (Vie, 2014)

5. IMPACT OF EMERGENCY RESPONSE ON SHIP LAYOUT

The internal environment of a vessel and its configuration are heavily influenced by emergency response considerations. Perhaps most notably, provisions relating to means of escape and evacuation have a significant bearing on the internal layout. SOLAS Ch. II-2, Reg.3, pertains to means of escape and governs the design and designation of doors, corridors, and stairwells. This is further supported by evacuation principles, which are concerned with emergency routing and the safe and timely transport of passengers and crew in an emergency (Champion, Ahola, & Kujala, 2015). In order to inform the internal configuration in this respect, evacuation analysis is often conducted in line with MSC.1/Circ.1033 (IMO, 2007). Through doing so, optimal evacuation routes can be identified, along with their appropriate dimensions. This is a highly important characteristic of the internal layout, as evacuation routes, though undoubtedly an essential safety feature, can themselves exacerbate flooding by providing conduits for floodwater progression. These come predominantly in the form of corridors, escape trunks and stairwells that penetrate both horizontally and vertically through watertight structure. Furthermore, evacuation considerations can also impose on the operational functionality of the vessel, especially where there are multiple corridors within accommodation spaces, which remove the footprint available for cabin space.

Emergency response considerations also affect the vessel internal configuration in accordance with SOLAS Chapter III, relating to lifesaving appliances and arrangements. Here, stipulations are made regarding the design and location of muster stations which, in accordance with Regulation 11, should be located as close as possible to embarkation spaces, whilst being readily accessible from accommodation and workspaces. Furthermore, each person assigned to a given muster station should have at least 0.35 m^2 area available to them and this is where large open spaces within cruise vessel designs have their advantage and are, as such, often used for this purpose. SOLAS Chapter III also mandates, in accordance with Reg.13, that lifeboats and survival craft should be located on both port and starboard sides of the vessel, positioned as close to the waterline and as far forward from the propellers as practical. For this reason, most cruise vessels are configured with lifeboats situated two decks above the bulkhead deck, where the vertical travel required for deployment is minimal, whilst ensuring the lifeboats are clear from green water effects or indeed immersion in the damaged floating position. Another highly influential factor over the vessel internal arrangement is the requirements of Safe Return to Port (SRtP), as outlined within MSC. 216(82). The aim here is to provide a safe and habitable environment for both crew and passengers, while the damaged vessel returns to a safe harbour. This entails that certain vital systems remain functional post damage such as propulsion, portable water system, HVAC system, galley systems, lighting etc. Unfortunately, to date the degree of damage considered for flooding under SRtP is rather limited, with just one-compartment flooding scenarios considered, meaning that residual functionality is not assessed for a large percentage of probable damage scenarios. In any case, the effect of these requirements on internal layout comes in the form of compartment segregation in order to protect vital systems, or otherwise, systems are replicated in order to ensure availability. This can add a great deal of complexity to the vessel internal arrangement and in some cases can introduce asymmetries within the flooding process, where the longitudinal subdivision is employed. Further to the above, and much like the designation of muster stations, vessels are also allocated safe zones. These provide safe locations where passengers can gather in order to have access to the benefits of retaining such systems, including heating, food, sanitation, lighting, ventilation and so on. Again, for this purpose, larger public spaces are often utilised, such as restaurants and bars.

Emergency response considerations also affect the vessel internal arrangement in the form of damage control. In accordance with SOLAS II-1, Reg.19, each vessel must have a damage control plan and manual onboard, containing the information specified within MSC/Circ. 919 and MSC.1/Circ. 1245. This generally comprises a series of actions to be taken in the immediate wake of an accident in order to identify damage extents and subsequently minimise and localise the spread of floodwater. An example of the general damage control process is provided in Figure 4, with items relating specifically to space layout shown in green colour. Here, the first of these items concerns the preservation of the vessel watertight envelope by closing all watertight doors and hatches, along with weathertight appliances. In addition, all valves on pipe runs passing through watertight structures are also to be closed. All such features exist within the vessel arrangement specifically to prevent the propagation of floodwater and essentially work to reduce the permeable volume available to a given damage breach. Following this stage, a more informed process of layout takes place in the form of actively redistributing mass within the vessel. This generally occurs in two ways, firstly by activating the bilge pumps within the damaged space to lessen floodwater accumulation and secondly through the process of counter ballasting, using ballast and heel/trimming tanks. The aim here is to improve the vessel floating position to either facilitate a more timely and orderly evacuation or indeed to enable the vessel to safely return to port. This comes, however, without due consideration of the dynamic behaviour of the ship and the effect that this might have on counter-ballasting and any other actions being considered by the simplistic approach that currently prevails. In this respect, Project FLARE (2019-2022) is paving the way to address this issue more effectively, using direct approaches and first-principles tools.

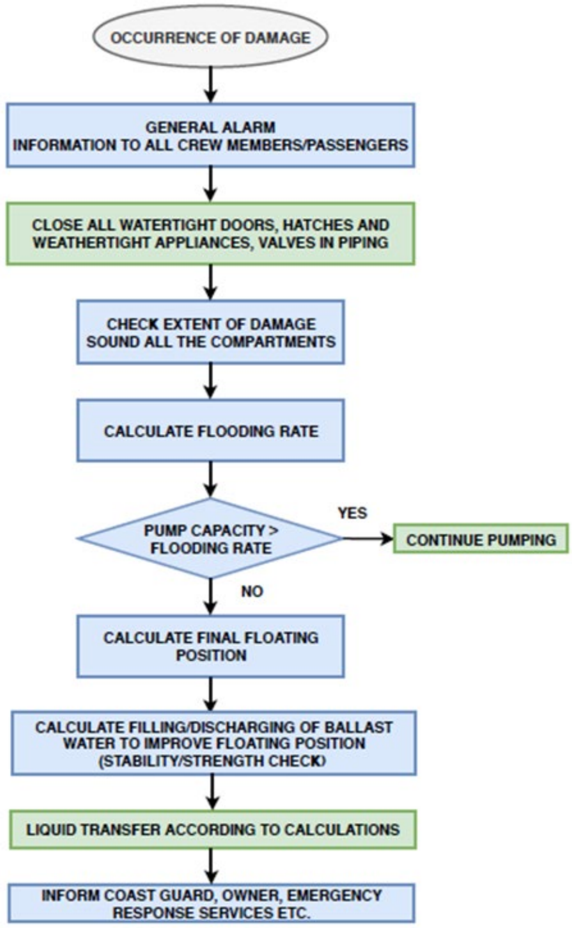

Figure 4: Damage Control Actions List

6. CONCLUSIONS

Based on the work presented in this paper, the following conclusions can be drawn:

- Historically speaking, the primary driving force behind internal vessel layout has come in the form of rules and regulations pertaining to damage stability and to a lesser extent fire. In such instances, change has occurred slowly, often in a reactive manner in the wake of accidents.
- Gradually, however, an increasingly proactive approach to the problem of damage stability is emerging with, for example, IMO instruments such as Safe Return to Port making significant strides in this direction.
- The nature of internal layout that is favourable for operation is often in conflict with that for safety and hence objectives pertaining to each generally lie in antithesis. For this reason, the rate of safety progression has often been slowed due to industry resistance on the grounds that their ability to operate a viable business would be impaired. This, in turn, is indicative of a greater problem relating to the efficiency and variety of existing options for flooding risk prevention and control. It would appear that there is an urgent need to start seeking alternative and more effective solutions, rather than continued sole reliance on conventional measures such as watertight subdivision.
- Further exacerbating this problem is the tendency towards building progressively larger passenger ships, which places an ever-growing number of people at risk.
- In order to achieve this aim, one must consider the vessel throughout its entire life cycle (design, operation, emergency response) and understand the requirements within each stage. This would involve consideration of the constraints and conflicting requirements that each stage brings to the decision-making process in relation to the optimal configuration of the internal ship space. Only then, can one hope to provide solutions capable of achieving this aim.

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REFERENCES

Atzampos, G., 2019, “A Holistic Approach to Damage Survivability Assessment of Large Passenger Ships”, PhD Thesis. University of Strathclyde, Department of Naval Architecture, Ocean, and Marine Engineering.

Bird, H., & Browne, R., 1973, “Damage Stability Model Experiments. Transactions of the Royal Institute of Naval Architects”, Vol. 116, 69-91.

Champion, J., Ahola, M., & Kujala, P., 2015, “Outlining a Provident Initial Design Approach with regard to Cruise Ship Conversions”, 12th International Marine Design Conference, (pp. 235-246). Tokyo, Japan.

Cichowicz, J., Tsakalakis, N., Vassalos, D., & Jasionowski, A., 2016, “Damage survivability of passenger ships - Re-engineering the safety factor”, MDPI.

FLARE, (2019-2022), “Flooding Accident Response”, EU H2020 RTD project, Contract No.: 814753.

Francescutto, A., & Papanikolaou, A., 2010, “Ship Buoyancy, Stability and Subdivision: From Archimedes to SOLAS 90 and the Way Ahead”, Proceedings of the Institution of Mechanical Engineers, Vol.255, Part M, 17-32.

GOALDS (2009-2012), “GOALDS – Goal Based Damage Stability”, EU FP7 RTD project, Grant Agreement 233876

HARDER, 2003, "Harmonisation of Rules and Design Rationale": Final Technical Report. EC Contract No. GDRB-CT-1998-00028.

IMO, 2006, “Guidelines on Alternative Designs and Arrangements for SOLAS, Chapter II-1 & III”, MSC/Circ.1212. London: IMO.

IMO, 2006, “MSC 82/24/Add.1, Adoption of amendments to the International Convention for the safety of life at sea”, 1974, Res MSC.216(82).

IMO, 2007, “MSC.1/Circ.1238, Guidelines for Evacuation Analysis for New and Existing Passenger Ships”, London: IMO.

Klanac, A., 2011, “Design Methods for Safe Ship Structures”, Aalto, Finland: Aalto University.

Kulovaara, H., 2015, “Safety & Stability through Innovation in Cruise Ship Design”, Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles, (pp. 3-14). Glasgow, UK.

Misra, S., 2016, “Design Principles of Ship and Marine Structures”, Taylor and Francis Group.

Papanikolaou, A., "Review of Damage Stability of Ships - Recent Developments and Trends", Proc. PRADS 2007, Houston, October 2007

Papanikolaou, A., 2014, “Ship Design- Methodologies of Preliminary Design”, 628p, 575 illus., SPRINGER Publishers, e-book ISBN 978-94-017-8751-2, Hardcover ISBN 978-94-017-8750-5.

Papanikolaou, A., Hamann, R., Lee, B. S., Mains, C., Olufsen, O., Tvedt, E., Vassalos, D., Zaraphonitis, G., 2013, “GOALDS – Goal Based Damage Stability of Passenger Ships”, Trans. SNAME, Vol. 121, pp 251-293 (SNAME Archival Paper; Captain Joseph H. Linnard Prize for the best paper contributed to the Annual Meeting of the Society of Naval Architects and Marine Engineers (SNAME) in 2013).

R. Puisa, A. M., 2012, “Design Customisation and Optimisation through Effective Design Space Exploration”, International Marine Design Conference IMDC, Glasgow, UK.

Rahola, J., 1939, “The Judging of the Stability of Ships and the Determination of the Minimum Amount of Stability”, Doctoral Thesis, The University of Finland.

ROROPROB, (1999-2002), “Probabilistic Rules-Based Optimal Design for Ro-Ro Passenger Ships”. EU FP5 RTD Project G3RD-CT-2000-00030.

S McCartan, T. T., 2015, “Design-Driven Innovation: A New Design Meaning for Superyachts as a Less Egocentric User Experience”, Marine Design Conference, London, UK: The Royal Institution of Naval Architects.

Sames, P. C., 2009, “Introduction to Risk-Based Approaches in the Maritime Industry”, In A. D. Papanikolaou, Risk-Based Ship Design (pp. 1-15), Berlin: Springer.

Tuzcu, C., & Tagg, R., 2002, “A Performance-based Assessment of the Survival of Damaged Ships -Final Outcome of the EU Research Project HARDER”, Proceedings of the 6th International Ship Stability Workshop. New York, USA.

Tuzcu, C., 2003, “A Performance-Based Assessment of the Survival of Damaged Ships”, Final Outcome of the EU Research Project HARDER, Marine Technology, 40(4), 288-295.

Vassalos, D., & Papanikolaou, A., 2018, “A holistic view of Design for Safety”, Proceedings of the 7th International Maritime Safety Conference on Design for Safety. Kobe, Japan.

Vassalos, D., 2008, “Chapter 2: Risk-Based Ship Design - Methods, Tools and Applications”, In A. Papanikolaou, Risk-Based Ship Design (pp. 17-98). Springer.

Vassalos, D., 2012, “Design for Safety, Risk-Based Design, Life-Cycle Risk Management”, The 11th International Marine Design Conference (p. Keynote Address). Glasgow, UK: IMDC.

Vassalos, D., Turan, O., & Pawlowski, M., 1997, “Dynamic Stability Assessment of Damaged Passenger/Ro-Ro Ships and Proposal of Rational Survival Criteria. Marine Technology”, Vol. 34, 241-266.

Wendel, K., 1960, „Die Wahrscheinlichkeit des Uberstehens von Verletzungen“, Schiffstechnik, Vol.7, No.36, 47-61.

Wendel, K., 1968, “Subdivision of Ships”, Proceedings, 1968 Diamond Jubilee International Meeting – 75th Anniversary (p. Paper 12). New York, USA: SNAME.

Womack, J., 2002, “Small Commercial Fishing Vessel Stability Analysis Where Are We Now? Where Are We Going?”, Proceedings of the 6th International Ship Stability Workshop. New York, USA.