Acronym:	FLARE
Project full title:	Flooding Accident REsponse
Grant agreement No.	814753
Coordinator:	BALance Technology Consulting GmbH

FLOODING RISK MODEL

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.: 814753)

Deliverable data

Deliverable No	5.14		
Deliverable Title	Flooding Risk Model		
Work Package no: title	WP5		

Dissemination level	Public	**Deliverable type**	Report
Lead beneficiary	MSRC		
Responsible author	Dracos Vassalos		
Co-authors	Mujeeb Ahmed MP		
Date of delivery	22-01-2021		
Approved	**Name (partner)**		**Date [DD-MM-YYYY]**
Peer reviewer 1	Luis Guarin (BB)		
Peer reviewer 2	Odd Karsten Olufsen (DNV)		
Peer reviewer 3	Apostolos Papanikolaou (NTUA)		30-11-2021
Peer reviewer 4	Alessandro Maccari (RINA)		30-11-2021

Document history

Version	**Date**	**Description**
1	**28-04-2021**	First draft
2	**04-05-2021**	Comments from Luis and Odd addressed
3	**01-07-2021**	Updated risk model based on D2.5 report
4	**18-11-2021**	Comments from Henning and Mike addressed
5	**03-12-2021**	Comments from Apostolos and Alessandro addressed

The research leading to these results has received funding from the European Union Horizon 2020 Program under grant agreement n° 814753.

CONTENTS

List of figures

List of tables

1 EXECUTIVE SUMMARY

Concepts of ship stability and safety and their quantitative assessment go back to antiquity. Evolution is not always smooth and discontinuities do not always serve for an effective transition and wider understanding of the underlying concepts. This has had two negative impacts in our strive to quantify safety: (a) most of the earlier attempts to measure safety were generalisations and abstractions, not serving the intended purpose and (b) specific attempts lacked pertinence to ship types, data and failure modes. However, having learned from dismay accidents and gained knowledge from scientific developments and the practice of ship design/building and operation, a new concerted effort aiming to provide both the ingredients and the glue for a new pragmatic approach to ship damage stability and safety, based on first principles, was launched by the FLARE project. The project has brought together a consortium with stakeholders from the whole spectrum of the European maritime industry and research community, working on the damage stability and safety of the passenger ships for the past 3 decades. This report provides both the historical background on the quantification of stability and safety as well as the recent developments leading to and adopted by FLARE. More specifically, the following has been addressed:

- General concepts of stability/safety measurement (Archimedes, Hoste, Bouguer, Euler, Atwood, Moseley)
- Residual damage stability measurement (Rahola, Wendel, SOLAS 60, A.265, SOLAS '90, Stockholm Agreement, SOLAS 2009, SOLAS 2020)
- Statistical (Probabilistic) Damage Stability Assessment: A-Index, capsize band, s-factor, Hs_{crit}, s-factor development
- s-factor development, capsize band and critical Hs
- Numerical Time-Domain Simulations and Survivability Assessment: Survivability Index, Capsize Rate, Time To Capsize (TTC), Time to Evacuate (TTE), risk quantification (Potential Loss of Life – PLL or Estimated Loss of Life – ELL).
- Quantitative Risk Assessment

  HARDER (1999-2003), [27]**:** analysis of accident data for collision → high level risk model for collision; damage breach distributions for SOLAS 2009.

  SAFEDOR (2005-2009), [28]**:** update and analysis of accident data for collision and grounding and of high level risk models; detailed risk model for collision and grounding.

  GOALDS (2009-2012), [33]**:** analysis of accident data for collision and grounding for passenger ships → high level risk model for flooding.

  EMSA III (2013-2016), [92]**:** review of the risk model (including the update of casualty data; cost-benefit assessment for several sample ships; new required index R for passenger ships (SOLAS2020) for collision, results from grounding used to support political decisions.

  eSAFE (2018-2019), [35]**:** combination of collision, bottom and side grounding hazards based on EMSAIII high risk models; safety metric for combined collision and grounding (side and bottom) events.

  FLARE (2019-2022), [93]**:** revision of high level risk models, leading to a new structure; development of a new open accident database; revision of frequencies for collision and groundings; revision of eSAFE safety metric; direct assessment of flooding risk; crashworthiness.

2 General Concepts of Stability/Safety Measurement

Early developments in ship stability and safety are discussed in Appendix A. The intricate nature of ship stability has resulted in a slow and discontinuous evolution of the subject and its measurement in Naval Architecture despite two millennia having lapsed since its initial conception and measurement. This has been influenced by two major factors; Naval Architects of the past were primarily "men of practice" and hence not able to understand scientific concepts bounding and defining Naval Architecture whilst the scientists occasionally being involved with ship stability and safety may not necessarily understood how ships are designed and operated. This modus operandi has had profound effects on how damage stability measurement and flooding risk assessment have evolved, as described in the following.

3 Damage Stability Measurement Evolution

3.1 Regulations

In response to the Titanic catastrophe in April 1912, when 1,503 people lost their lives, the British Government devised the first international regulations for the safety of ships namely, [17], which has not entered into force due to World War I. The first requirements were addressing safe navigation, watertight and fire-resistance bulkheads, and life-saving appliances. In line with this, two subsequent treaties followed in 1929 and 1948, [18], [19]. In the latter, a series of improvements were reported with regards to stability standards, introducing requirements to watertight arrangement and alternative subdivision methods. According to the standards of 1912 and 1929, the maximum damage longitudinal and transverse extents, for statutory compliance, were 0.02L+3.05 along with B/5, respectively. The factorial approach aiding decision-making with regards to subdivision was broadly employed with terms such as floodable or permissible length to be of great importance. However, IMO was becoming aware of the shortcomings in place, which gradually weakened the utilisation within the design process and, as a result, the approach has been withdrawn today. The change in the design trends brought about an increase in the beam of the vessels and, therefore, the introduction of the first residual stability criteria was inevitable. This was accounted for through the first "Safety of Life At Sea" (SOLAS) convention of 1960, [20], stipulating a minimum residual GM of 0.05 metres. The conventions leading to SOLAS 1960 consolidated the series of requirements for the number and arrangements of watertight bulkheads along with the ship stability following collision damage. The first probabilistic damage stability rules for passenger ships were derived from the work of Professor Kurt Wendel [13], [14] and they were introduced in the late 60's as an alternative to the prevailing, at the time, deterministic requirements of SOLAS 1960. This, in turn, inspired a series of developments towards probabilistic regulations for subdivision and stability, initially for the case of passenger ships as a proposed alternative to the deterministic regulation of SOLAS (A.265), [21]. The IMO resolution A.265, so called Equivalent Passenger ship Regulations, was the first resolution that referred to equivalent safety and safety level as part of a set of explanatory notes. Subsequently, in the same line, the 1974 SOLAS convention accounted for Rahola's proposals, [9]. The proposals comprised requirements for the residual stability curve and intermediate stages of flooding based on a deterministic approach. In December of 1987, the RoRo vessel Herald of Free Enterprise capsized in Belgium with 193 passengers perishing. This accentuated the need to address the dynamic phenomena capturing water on deck (WoD). IMO adopted stringent standards for new ships within the convention of SOLAS 1990. These entailed a range of 15 degrees beyond the equilibrium angle, an area of 0.015m.rad, residual GM of 0.05m and a maximum GZ ≥ 0.1 metres. The amendments took into consideration passenger crowding on to one side of the ship, survival craft launching on one side of the ship and wind pressure, all utilising full deterministic elements. It also stipulated that the maximum angle of heel after flooding should not exceed 15 degrees. A series of studies followed [23], [24], [25], assessing the impact of dynamics on RoRo and passenger ships; however, utilising only a small sample of ships.

Another major step change in stability standards followed again in 1992 with the introduction of SOLAS part B-1 (Chapter II-1), integrating a probabilistic standard for cargo ships, using the same characteristics as embodied in the earlier 1974 regulations based on the data collated by IMO regarding collisions. For the case of RoRo vessels, further enhancements took place following the Estonia accident in 1994, when 850 passengers lost their life. This led to the so called "Stockholm Agreement", which was reached by the North West European Nations as part of the North West European R&D project (JNWEP) in December of 1997, aimed at rationalising the probabilistic approach. Extensive research in the field indicated that the main cause of the capsize of Estonia was due to excessive water accumulation on the main deck, [26].

In 1995, SOLAS 1990 was adopted as a global safety standard of damage stability with provision for water on deck standards. The stability committee adopted a series of amendments to SOLAS 1974 related to the stability of Ro-Ro passenger ships in Chapter II-1, containing special requirements for Ro-Ro passenger ships carrying 400 passengers or more. This was intended to filter out ships built to a "one-compartment standard".

The future direction of rule development set course through the European research project HARDER (HARmonisation of DEsign Rationale), [27]. The main objective entailed the generation of fundamental knowledge in the underlying relationships and physics of damage stability by systematic research with a view to clarifying implications of the harmonisation task conducted by the IMO-SLF subcommittee. During project HARDER, the new harmonised probabilistic damage stability concept, known as the SLF42 proposal was systematically assessed and an improved proposal was introduced for discussion at IMO, known as the HARDER-SLF46 proposal. Several concerns were raised after the completion of the project in 2003, related to the severe impact of the harmonisation on the design and economic impact of large passenger ships. With this in mind, the proposal was revisited in IMO-SLF47 with respect to large ships assessment method on the way from the MSC79 to the MSC80, where it was finally adopted. The project set the foundation of SOLAS 2009 through the MSC80 Committee.

Safety in the life cycle of cargo and predominantly passenger ships was addressed through the subsequent EU-funded R&D project SAFEDOR [28], representing an effort to foster a radical transition from the current maritime safety regime, via the actions of the thematic network SAFER EURORO ("Design for Safety"). The project demonstrated the potential of a risk-based frameworks undertaking a series of high-level formal safety assessments.

The adaption of probabilistic assessment methods in the maritime industry had a profound effect, which was achieved via projects HARDER and SAFEDOR, the latter leading to the adoption of Risk-Based and Performance-Based approaches in the safety of passenger ships. New regulations came into force in 2010 (first draft in 2006) applicable to passenger ships having length of 120 metres or more, or having three or more main vertical zones. The so-called Safe Return to Port (SRtP) regulations ,[29],[30], as per SOLAS 2009, incorporated two new design concepts; that of "casualty threshold" and "safe areas", which formed a steppingstone in naval architecture. One of the top-agenda items within IMO was the Goal-Based Standards by targeting, in the longer term, a broader range of ship types approaching safety from a completely new perspective – one that is the goal and performance-oriented, in lieu of the traditional prescriptive-based approach - introducing safety goals and relevant functional requirements. Another regulatory cornerstone in the same period was the introduction of the Alternative Design and Arrangements for SOLAS chapters II-1 and III, [31], providing a methodology based on engineering analysis for the safety assessment of a design deviating from SOLAS prescriptive requirements. Passenger ships and especially RoPax vessels were the primary focus while it was becoming implicitly apparent the need of addressing in more detail the damage stability standards of such vessels, [32]. The EU funded, FP7 project GOALDS [33], (GOAL based Damaged Stability), was aimed at addressing the shortcomings of the standards in place by providing state of the art scientific methods and instruments along with formulation of a rational regulatory framework accurately accounting for the damage stability properties of passenger ships.

In January of 2012, the cruise ship Costa Concordia[1] capsized attempting "A sail by salute" across the Italian coast. This was perceived as a defining moment for the modern cruise ships and, in the wake of this, CLIA and EMSA arranged a series of committees to address critical safety elements, [34]. Even though the industry had already formed a basic understanding of damage stability of passenger vessels, the missing piece of the puzzle was the understanding of the real safety level after flooding in the case of cruise ships.

One predominant step in this direction was taken by the Joint Industry project eSAFE (enhanced Stability After Flooding Event), [35], funded by the Cruise Ship Safety Forum in 2016. The project aimed at enhancing damage stability of cruise ships using modern first-principles tools within early design process. Another attempt DGMOVE [36], [37], [38], [39] focused in assessing the impact of European stability and survivability standards for RoRo ships and, in turn, it indicated that the risk thresholds need special attention as they do not cater for newly designed ships. Generally, the fundamental requisite is that pertinent risks need quantification most of the time, almost in real time, and in an appropriate way throughout the life cycle of a vessel, from design and daily operation to crisis situations. This is precisely what is being promulgated within project FLARE.

Finally, SOLAS 2020, [36] as adopted by resolution MSC 421(98), entered into force in early January of 2020. This addresses a new Required Index R, which depends only on the number of passengers on board, new practices in treating local Attained Indices when calculating multiple trims, along with increased Range and GZmax requirements in the final stage of the flooding. The latter applies only in the case of RoPax ship damages involving RoRo spaces and, as a result, it is not applicable to cruise vessels. Building on this, the shortcomings one could observe in the early SOLAS 2009 with regards to the survivability formulation and the Attained Index are still present in SOLAS 2020. A summary of these developments is provided in Figure 1 and Table 1 next.

[1] A less disastrous, but similar accident happened 5 years earlier (April 2007) with the cruise ship Sea Diamond that sank after grounding in the Caldera Bay of the Greek island of Santorin.

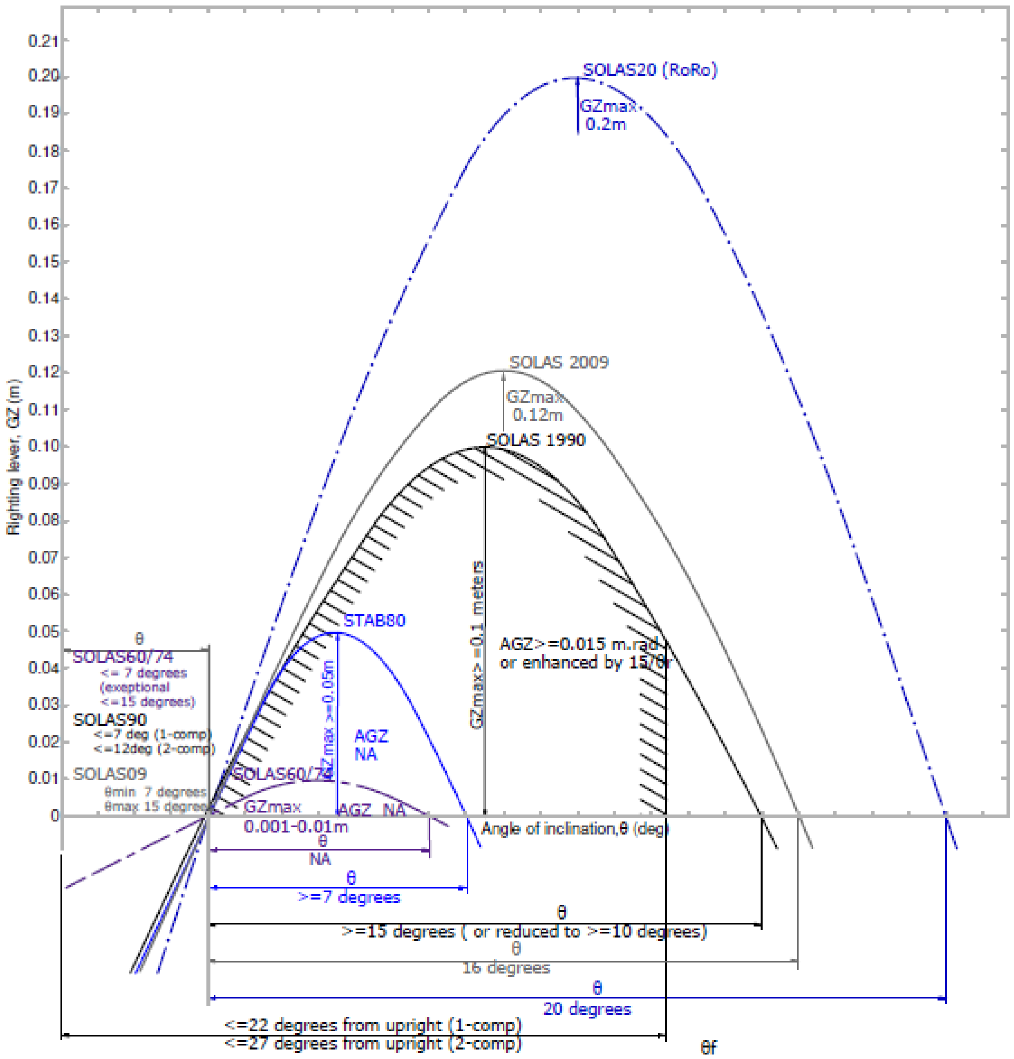


Figure 1. Residual stability GZ-based standards from 1960 to 2020

Table 1. Damage stability criteria, 1960 to 2020

	Deterministic				Probabilistic	
Criterion	IMO SOLAS60/74	UK STAB80	IMO SOLAS90		IMO SOLAS2009	IMO SOLAS20
Positive residual righting level (GZ) curve range, θ_{RoS}	NA	≥7	≥15	$15 \geq \theta_{RoS} \geq 10$ (if A_{GZ} is increased by $15/\theta_{RoS}$)	16	20
Area under GZ curve, A_{GZ}	NA	NA	≥0.015	≥0.015 x $15/\theta_{RoS}$	-	

Maximum residual righting lever, GZ_{max}	0.001 to 0.01 (UK)	≥0.05	≥0.100	0.120	0.200
Angle of heel due to unsymmetrical flooding after equalisation, θ_B	≤7 degrees	≤7 degrees	≤7(1 compartment damage) ≤12 (2 compartment damage)	Minimum 7 Maximum 15	
Positive residual metacentric height, GM_T	≥0.05	≥0.05	≥0.05	-	

3.2 Numerical Approaches

3.2.1 Statistical (Probabilistic Method)

The main ideas for probabilistic damage stability assessment are embedded in SOLAS 2009 based on the fundamental assumption that the ship under investigation is damaged with ensuing large-scale flooding stemming from hull breach (collision is the only hazard presently being considered). This can be regarded as the conditional probability of losing ship stability in the wake of a collision event, ignoring among others the area of operation and hence operating environment, type of ship, type of breach, technology, and crew onboard. More importantly, the time element, hence evacuation and abandon ship arrangements and associated Risk Control Options (RCOs) are being overlooked, [40]. This said, many risk-related factors such as the size of the ship, number of persons on board, lifesaving appliances, subdivision and other arrangements are accounted for by the Required Index of Subdivision, R. This plays a vital role within the probabilistic framework, as provided by the inequality (1), where A is the probability of ship surviving collision damage, namely the Attained Subdivision Index.

$$A \geq R \tag{1}$$

This Attained subdivision index, as outlined within SOLAS 2009, [41], is shown in eq. (2) below.

$$A = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j \cdot p_i \cdot s_i \tag{2}$$

Where,

j Represents the loading condition under consideration.

J Represents the total number of loading conditions considered in the calculation of A, usually three draughts covering the operational draught range of the vessel.

w_j Represents a weighting factor applied to each initial draught.

i Represents each compartment or group of compartments under consideration for loading condition, j.

I The total number of all feasible damage scenarios involving flooding of individual compartments or groups of adjacent compartments.

p_i The probability that, for loading condition, j, only the compartment or group of compartments under consideration are flooded, disregarding any horizontal subdivision.

s_i Accounts for the conditional probability of survival following flooding of the compartment or group of compartments under consideration for loading condition j weighted by the probability that the space above a horizontal subdivision may not be flooded.

The Attained Subdivision Index represents the conditional "averaged" probability of survival or else the "weighted average s-factor", as depicted in eq. (3).

$$A = E(I) \tag{3}$$

Using different wording, Index A is the marginal probability for time to capsize within certain time, assuming that the time being considered is sufficiently long for capsize to have occurred in most cases. Finally, the Required Index of Subdivision, R represents the level of safety associated with collision and flooding events that is deemed to be acceptable by society, in the sense that it is derived using ships, which society considers fit for purpose, since they are in daily operation. In line with the standards in place, the Attained Index must be greater than the required R (A>R) and specifically for passenger ships (A≥0.9R) to form the limiting GM (metacentric height) curves.

In line with the probabilistic framework of assessing damage stability, the fundamental element, which describes the probability of surviving collision damages in waves is described by the s-factor as depicted by eq. (4). The relationship between the survivability factor and the critical wave height stems from the consideration of the s-factor as an average probability of survival with the averaging function being the probability density function of the encountered sea states during collision incidents as provided by eq. (4), [41], [42], [43]

$$s = Prob\{Hs \leq Hs_{crit}\} = \int_{0}^{\infty} f_c(Hs)P(Hs)dHs \tag{4}$$

Where,

$f_c(Hs)$ Probability density function of a sea states recorded at the instance of collision

$P(Hs)$ Probability of surviving flooding casualty in sea states for a specific time, given the specific loading condition and flooding extent.

Furthermore, it can be assumed that $P(Hs)$ is a unit step function centred at the critical or limiting Hs (i.e., $P(Hs) = 1$ for all $Hs \leq Hs_{crit}$ and 0 otherwise), hence the s-factor can be expressed as follows:

$$s = Prob\{Hs \leq Hs_{crit}\} = \int_{0}^{Hs_{crit}} f_c(Hs)dHs \tag{5}$$

The above suggests that to evaluate the factor s it is necessary to establish the critical (or limiting) sea state Hs_{crit}. It should be noted that, with all the tests performed during the s-factor development being limited to 30 minutes, the probability of survival is in fact a conditional probability, yielding:

$$\begin{aligned} &s(t = 30\,min) = \\ &= \int_{0}^{\infty} dH_S \cdot f_c(H_S) \cdot P_{surv}(t = 30min|_S|) \end{aligned} \tag{6}$$

It should be noted that even though replacing the probability distribution by a step function, is supported by little evidence, it does the "trick" and allows avoiding integration with little impact on the accuracy of the prediction, as long as the bandwidth of the capsize band is narrow. Eventually, the final formulation becomes:

$$\begin{aligned} s &= \int_{0}^{H_{Scrit}} dH_S \cdot P_{H_S|coll}(H_S) = \\ &= exp(-exp(0.16 - 1.2 \cdot H_{Scrit})) \end{aligned} \tag{7}$$

Where $H_{S\,crit}$ is given as:

$$H_{S\,crit}\Big|_{t=30\min} = 4\left(\frac{\min\left(GZ_{\max},\ 0.12\right)}{0.12}\frac{\min\left(Range,\ 16\right)}{16}\right) = 4\cdot s\left(t = 30\min\right)^4 \tag{8}$$

This approach, adopted within the GOALDS Project, [33], is similar to that of the HARDER project, [27], with the main difference stemming from the assumption of Hs_{crit} corresponding to the lower limit of the capsize band, thus allowing for a justified assumption of very long ("infinite") time of survival. In this respect, the main problem deriving from the need of accurately predicting the critical significant wave height is a major flaw of the SOLAS 2009 s-factor formulation (although not readily obvious in the regulation).

Notwithstanding this, the critical sea state for a specific damage extent and loading condition can be established either with the aid of model test experiments or employing time-domain numerical simulations. Both approaches have been utilised in the past in the course of the development and verification of survivability criteria. Generally, the experiments either of physical or numerical nature are subjected to repeated time trials (usually 30 minutes full-scale) in a random realisation of a specific sea state with the view to deriving the capsize rate at that specific wave height. A distribution $P(Hs)$ can be derived, following multiple repetition of tests, [44]. Depending on the definition, the critical sea state can be regarded as a wave height at which $P(Hs)$=0.5 or alternatively as the highest sea state with low probability of capsize (e.g., $P(Hs) < 0.05$, as proposed in GOALDS [33] and more in-line with the notion of limiting wave height, as explained in [37].

Normally, the critical wave height is related to the geometrical characteristics of the vessel and its residual stability. These of course vary depending on the derivation process and design of experiments implemented. Customarily, this step is implicitly considered with the s-factor calculations. In this sense, the s-factor eclipses the presence of the critical sea state and instead survivability is expressed directly as a function of ship stability residual parameters. The history of the related development is presented next.

<u>IMO Resolution A.265</u>

The survivability factor adopted in resolution A.265, [45] is based on an extensive experimental research on survivability, [46]. Historically, this was the second time model experiments were conducted on a flooded ship model, the first being by Middleton and Numata in 1970, [47], aimed at identifying relationships that characterises the survival sea state of a ship damage case as a function of residual stability parameters, as shown in Figure 2. The formulation for the survivability factor as later adopted by IMCO (Inter-Governmental Maritime Consultative Organization), [48] in a slightly modified approximate format as shown in eq. (9).

$$s = 4.9\sqrt{\frac{F_E \cdot GM}{B}} \tag{9}$$

Where,

F_E Equivalent residual freeboard (m)

GM Initial stability (flooded metacentric height) (m)

B Breadth of the ship (m)

The process of deriving the s-factor for the given damage condition underlying damage stability calculations in A.265 is illustrated in Figure 2. Simply, using different residual GMs (one GM is presented below), can provide an approximation on the survival state obtained through the cumulative probability of survival. Unfortunately, like in the case for Rahola, using global ship parameters to establish a relationship between residual stability and sea state has influenced almost every subsequent attempt to refine this, which for the case of passenger ships with complex internal environments provides the wrong focus, as explained later.

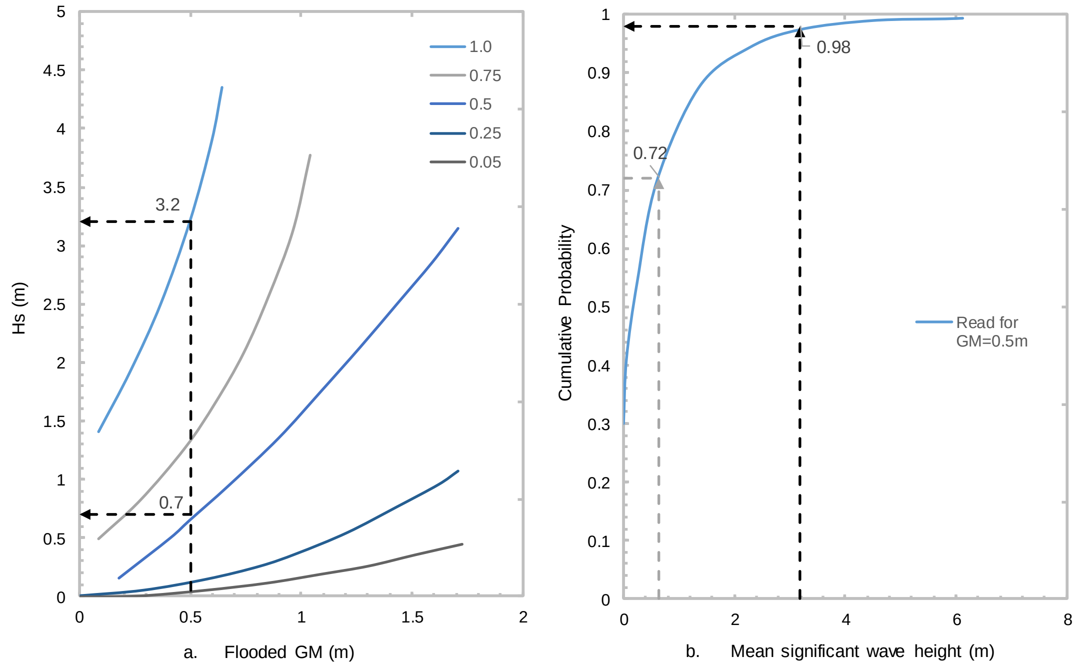


Figure 2. Method of deriving limiting sea-state and survival index s: (a) H_s vs. flooded GM for different freeboards (for example at flooded GM = 0.5 and freeboard = 1.0 m), limiting H_s = 3.2 m. For the same flooded GM and freeboard = 0.5 m, limiting H_s = 0.7 m; (b) cumulative probability distribution (CPD) of Hs at occurrence of capsize (from accident statistics). At H_s = 3.2 m, the probability is 0.98 (hence exceedance probability 0.02) and at H_s = 0.7 m, the probability is 0.72 (hence exceedance probability 0.28)

Static Equivalent Method (SEM)

Historically, SEM is an approach originally recommended following many model test observations, [49], [50], [51]. Based on the findings from HARDER, it was suggested that SEM should be used for the estimation of survivability in waves of RoRo ships while the conventional s-factor should be used for the estimation of survivability of cargo ships.

Notably, as mentioned in [12], the SEM methodology was developed on the basis that the traditional survivability methods (residual GZ parameters) do not adequately estimate survivability of RoRo ships. At the time, a distinction was made between low freeboard Ro-Ro vessels and non-RoRo vessels, because of the observed differences in the mechanisms of capsize, pertinent to these ships. The original SEM method linked the critical sea state to ship performance in waves (dynamic elevation of floodwater resulting from action of waves on the vehicle deck, h, (applicable only to RoRo vessels with large undivided spaces like vehicle decks), as shown in eq. (10), Figure 3.

$$Hs_{crit} = \left(\frac{h}{0.085}\right)^{\frac{1}{1.3}} \tag{10}$$

Where 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, 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.

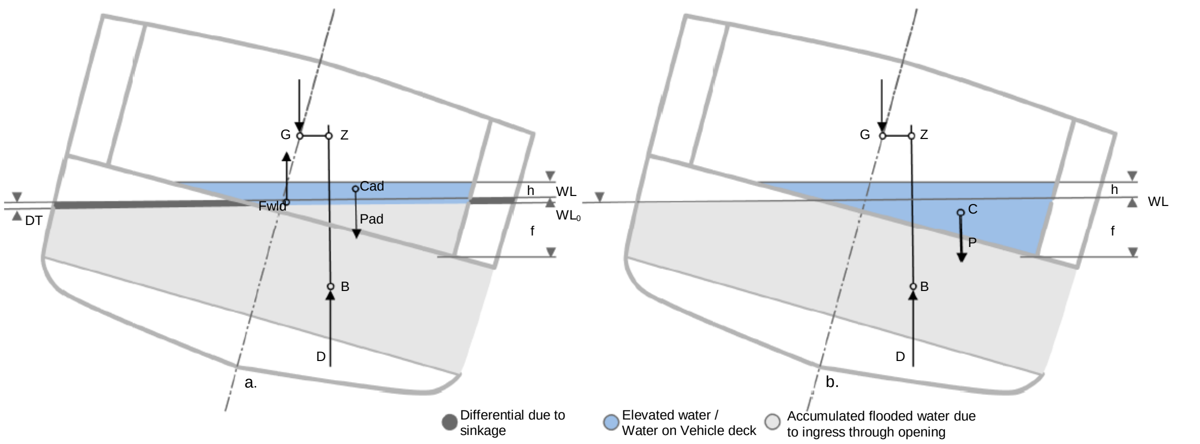


Figure 3. (a) Depiction of SEM parameters with water elevation in the vehicle deck at the Point of No Return (PNR) - case of RoRo ship. (b) Normal method employed by damage stability software considering the floodwater volume as a total water on the vehicle deck inside an undamaged tank [22].

<u>SOLAS 2009</u>

Survivability in SOLAS 2009 is calculated from the findings of project HARDER by means of the s-factor as a metric of the safety level for statutory compliance, based on cargo ships. Figure 4 below shows all the related parameters, which are involved in the calculation of the s-factor and Index-A according to SOLAS II-1 §7-2.

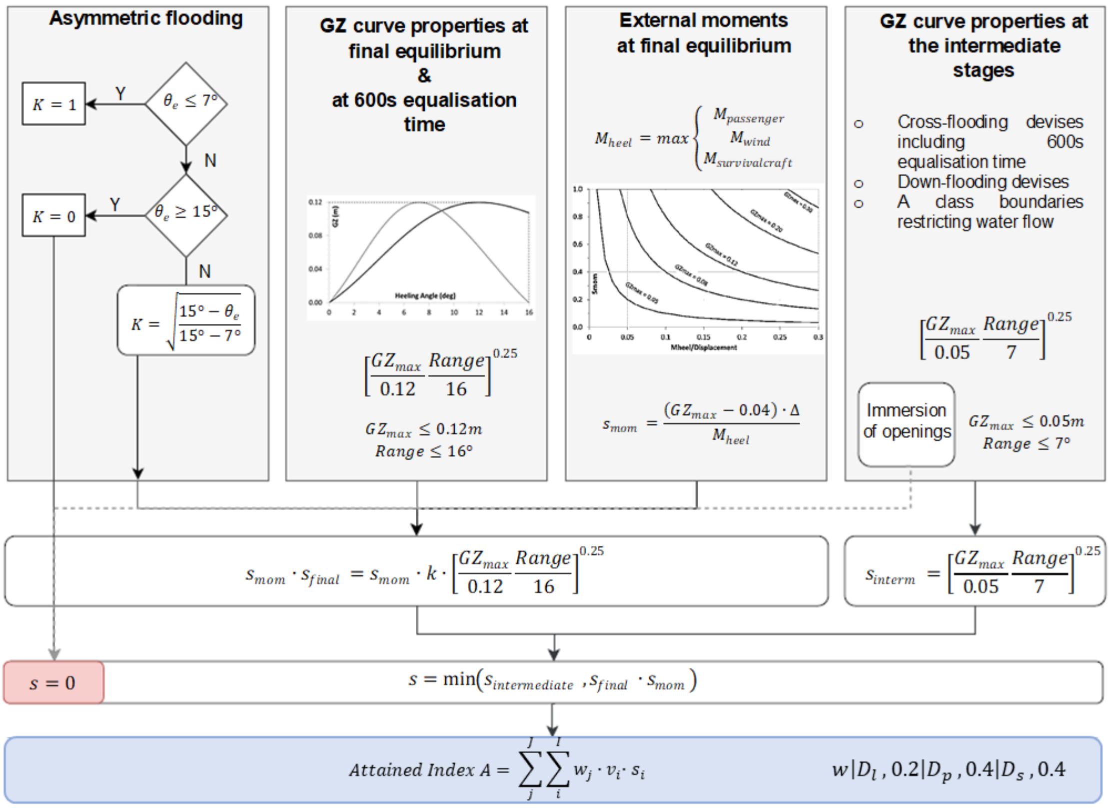


Figure 4. Calculation process of s-factor as per SOLAS 2009, accounting for external moments at final and intermediate stages of flooding.

The coefficients of 0.12 meters and 16 degrees are regression parameters, usually referred to as targeting values TGZ_{max} and TRange, respectively. As in the case of resolution A.265, the probability of survival of a flooding event after a collision damage involving one or more compartments is currently defined in SOLAS Ch. II-1 Regulation 7-2 through the s-factor. The formulation of the s-factor is also based on the concept of critical significant wave height Hs_{crit}, as derived in HARDER project, [52].

$$Hs_{crit} = 4\frac{GZmax}{0.12}\cdot\frac{Range}{16} = 4s^4 \leftrightarrow s = \left(\frac{Hs_{crit}}{4}\right)^{0.25} \tag{11}$$

It is noteworthy that the survival factor established through harmonisation produced a survival probability relating to the dynamic effects of encountering waves only when the vessel had reached final equilibrium after damage. In addition to using some old cargo ships for the derivation of an Index for universal application, there are many pitfalls in its derivation, especially with reference to passenger ships, for example [53], [54], [55], [56], [57], [58], [59]. These have been ironed out in attempts to produce harmonised regulations between cargo and passenger ships, until project eSAFE brought attention to some of these problems, [32], which are being attended to in project FLARE.

EMSA 2009

The study led by EMSA in 2009 on the investigation of survivability of different ships, [60], [61] focused on the impact of the different probabilities within the framework. In this sense, a new formulation is not proposed but instead a recommendation is brought forward to change the SOLAS targeting values for GZ_{max} and Range to 0.25m and 25 degrees, respectively, which by all accounts seem to be capturing the RoPax survivability with sufficient accuracy. However, despite the attempts of the EMSA study to address an accurate survivability factor for passenger ships, the drawbacks of the formulation are not diminished with application to cruise ships and a call for further improvements led to project GOALDS, [33], aiming to cater for passenger ships whilst accounting for the main differences between RoPax and cruise ships.

GOALDS Project (2009-2012)

The project conducted a re-analysis of the damage statistics for collision and grounding damages of passenger ships, updating and complementing earlier knowledge base; it also dealt with the development of improved risk models (as part of Formal Safety Assessments) for collision and grounding damages of passenger ships (RoPax and cruise ships), updating earlier related studies of project SAFEDOR; this was followed by the conduct of a series of cost effectiveness analyses of various risk control options (RCOs) implemented in the conceptual design of a series of sample passenger ships (RoPax and cruise ships) and the development of a *new risk-based damage stability requirement*; this was complemented by the development of a series of innovative ship design concepts, meeting the proposed new risk-based requirements, through multi-objective formal optimization, ensuring enhanced safety cost effectively; the main results are outlined in details in IMO-SLF 55/INF.7, IMO-SLF 55/INF.8, IMO-SLF 55/INF.9, submitted by the delegations of Denmark and United Kingdom in December 2012, [62].

As part of this project, 20 RoPax and 2 cruise ships were subjected to parametric investigation numerically, [37] for the establishment of survivability whereas, tank experiments were conducted on two RoPax and two cruise ships, respectively, for verification purposes in collision damages. For this, worst SOLAS 2-compartment damages were used ±35%L amidships, whilst, for the case of cruise ships, which exhibited high resistance to capsize, 3-comparment damages were used for the derivation of the survivability boundary, [37]. The study presented in [37] concluded that the two stability parameters in the current survivability formulation, namely GZ_{max} and Range are insufficient in capturing the relationship between critical wave height and residual stability and, as a result, an additional element was identified reflecting ship size. In this respect, the centroid of the residual volume as a function of the vertical centres of intact and damaged compartments divided by the draft of the intact condition was used to compensate for the size parameter. This is the second attempt (the first one being formulation (10)), to account for ship geometry above the bulkhead deck and, as such, it constitutes a major innovation, see equation (12).

$$Hs_{crit} = \frac{A_{GZ}}{0.5 \cdot GM \cdot Range} \cdot V_R^{\frac{1}{3}} \qquad (12)$$

Where,

A_{GZ}	Is the area under the GZ curve (untruncated)
GM	Represents the flooded GM
Range	Represents the range of positive stability
V_R	Reflects the residual volume of the watertight envelope (i.e., excluding compartments within the damage extent)

However, severe limitations concerning the choice of parameters, lack of cruise ship data in the formulation, the type of formulation (GM being a denominator), interdependence of parameters and lack of demonstrable applicability to grounding damages have limited further application or indeed discussion.

Project eSAFE

This is the first project where focus on cruise ships has been maintained throughout the research effort. Moreover, this is the first research project in damage stability where all results are based on numerical time-domain simulations for the assessment of the critical wave height in relation to residual stability parameters. Put differently, numerical simulations were used to generate the requisite statistical information. The simulations have been conducted according to the worst case three-compartment damage lying within 1/3 of the subdivision length about midships and across a range of loading conditions with varying GM values. The dynamic behaviour of each vessel in the damaged condition has been assessed under a range of environmental conditions characterised by varying magnitudes of significant wave height, using a JONSWAP spectral shape. For each damage scenario assessed through simulation, the critical significant wave height has been identified, enabling the relationship between the residual stability properties and the critical significant wave height ($H_{s,crit}$) to be derived. Based on this information, a new cruise ship-specific formula for predicting the $H_{s,crit}$ has been derived on the basis of GZ properties through regression of the simulation results. Following this, a new s-factor formulation that accounts more accurately for cruise vessels has been proposed using a regression formulation of the significant wave height distribution at the time of the accident. The results of two ships of different size indicated that a scaling methodology should be applied. The most suitable scaling parameter was found to be the "Effective Volume Ratio"; a parameter which accounts for both the scale of the damage and of the vessel. This is an innovation, inspired by project GOALDS. Applying this methodology and populating further the area below 4 metres significant wave height, consistency could be observed.

To ensure that the method is robust and suitable for cruise ships, several additional damages for a whole range of cruise ship size have been analysed. On this basis, the obtained $H_{s,crit}$ formula is provided as follows:

$$H_{s,crit} = 7 \times \left[\frac{MIN(\lambda \times Range, TRange)}{TRange} \times \frac{MIN(\lambda \times GZmax, TGZmax)}{TGZmax}\right]^{1.05} \tag{13}$$

Where,

TGZ_{max}= 0.30 m

$TRange$ = 30 deg

A formulation for calculating the s-factor was also derived by the regressed CDF of significant wave heights at the time of collision (in line with HARDER, i.e., up to 4 meters), eq. (14):

$$s(H_{s,crit}) = 1 - \exp(-1.215 \cdot \mathrm{H_{s,crit}}) \tag{14}$$

Based on the wave distribution of global wave statistics, where a 7 m significant wave height represents the 99th percentile, the formula becomes:

$$s(H_{s,crit}) = e^{-e^{(1.1717 - 0.9042 \cdot H_{s,crit})}} \tag{15}$$

One of the key findings of Project eSAFE is that numerical simulations are consistent with the static calculations, in terms of comparative assessment between ships. However, the numerical simulation results indicate higher survivability than the static calculations, such discrepancies being particularly large in grounding scenarios. In general, it is suggested that time-domain simulations of flooding within complex geometries require significantly longer simulation runs than the 30 minutes embedded in SOLAS and that attempting to capture the complexity of the internal environments in cruise ships, using generalised formulae, has its limitations. It may also be the case that using too many approximations in the attempt to represent reality and, in all of these, trying to err on the side of safety might lead to conservatism in the results, as shown in Figure 5 and Figure 6.

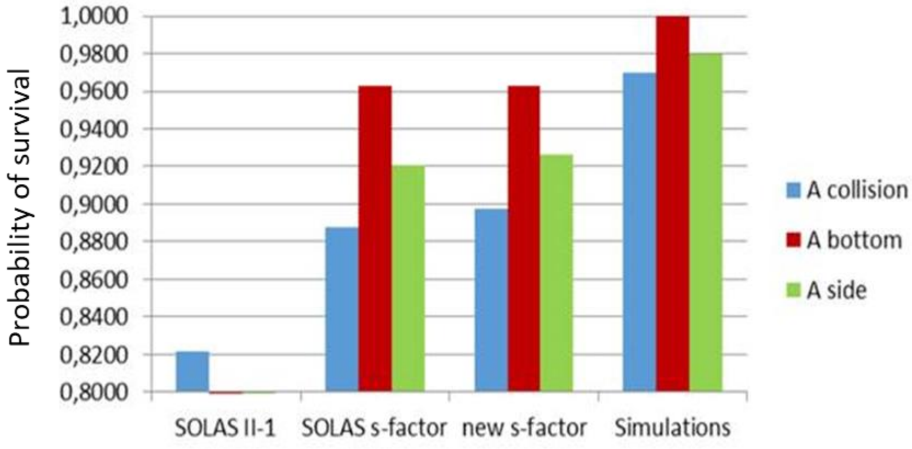


Figure 5. Comparison between static calculations and time-domain simulation results – Ship A

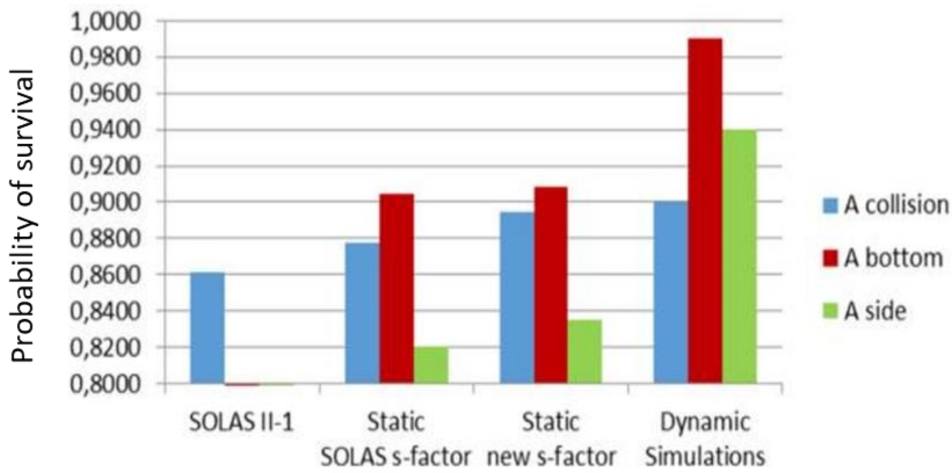


Figure 6. Comparison between static calculations and time-domain simulation results – Ship C

3.2.1.1 Concluding Remarks

Generally speaking, there is a consistent methodology underlying the development of the s-factor in all the formulations proposed over the past half a century. However, when it comes to cruise ships, there is not enough risk information in the s-factor formulations based on statistical approaches with focus on global parameters. The main conclusion from the eSAFE project is that the statistical approach does not provide enough granularity to assess survivability of cruise ships by a statistical approach. This formed the basis and the inspiration for embarking on Project FLARE and for exploring in some detail a direct approach for estimating damage survivability of passenger ships, using numerical time-domain simulations, as described next.

3.2.2 Direct Method (Numerical Time-Domain Simulations)

Development of Numerical Time-Domain Simulation Tools for Damaged Ships in a Seaway

Pitfalls in using generalised formulae for damage stability assessment, can be overcome through understanding of the underlying mechanisms leading to vessel loss and to identification of governing design and operational parameters to target flooding risk reduction cost-effectively. This, in turn, necessitates the development of appropriate methods, tools and techniques capable of meaningfully addressing the physical phenomena involved. Having said this, it was not until the 1990s when damage survivability, pertaining to ship dynamics in a damaged condition in seaway, was addressed by simplified numerical models, [23], [63], [64], [65], [66]. The subject of damage survivability in waves (with the ship hull breached), received considerable attention following the tragic accident of Estonia, namely by assessing the performance of a vessel in given environment and loading condition based on first principles. In parallel, motivated by the compelling need to understand the impact of the then imminent introduction of probabilistic damage stability regulations on the design of cargo and passenger ships and the growing appreciation of problems embedded in both the regulations and the harmonisation process itself, an in-depth evaluation and re-engineering of the probabilistic framework was launched through the EC-funded project HARDER, [27]. In this respect, the HARDER project became an IMO vehicle carrying a major load of the regulation development process, fostering international collaboration at its best. This was a major factor, contributing to the eventual success in achieving harmonisation and in proposing a workable framework for damage stability calculations in IMO SLF 47. Deriving from developments at fundamental and applied levels in this project as well as other EC-funded projects, such as NEREUS [67], ROROPROB [68], SAFENVSHIP [53] and other international collaborative efforts (work by the Stability in Waves Committee at the International Towing Tank Conference from 1996 onwards, e.g., [69]), a clearer understanding of damage stability and survivability started to emerge. Application and verification of the developing numerical tools helped raise confidence in the available knowledge to address the subject matter effectively and with sufficient engineering accuracy. All this effort provided the inspiration and the foundation for Project SAFEDOR [28], which offered the opportunity to consolidate contemporary developments on damage survivability, thus rendering implementation possible even as at concept design stage. The knowledge gained has been used to address critically contemporary regulatory instruments and to foster new and better methodologies to safeguard against known design deficiencies.

Surprisingly, the biggest influence has been seen at the birthplace of prescription, namely IMO, with goal-setting-performance-based approaches becoming the new face of safety. What is known as Safe Return to Port (SRtP) of SOLAS 2009, enforceable on every passenger newbuilding vessel and on special purpose ships over 120m in length or having three or more main vertical zones (MVZs), has paved the way for holistic approaches to risk, specifically fire and flooding risks. These regulations represent a step change from the deterministic methods of assessing subdivision and damage stability. The old concepts of floodable length, criterion numeral, margin line, 1 and 2 compartment standards and the B/5 line have disappeared from newbuilding projects, which now adopt a more holistic approach to addressing damage stability and survivability. Moreover, such considerations cover the life cycle of the vessel, targeting cost-effective safety as a key design objective, alongside other conventional design objectives, [16].

Assessment of ship performance in terms of damage survivability, however, is not a straightforward undertaking, as in addition to the complexity of predicting ship behaviour in waves utilising techniques pertinent to intact ships, further intricate phenomena arise with water ingress-egress through the ship hull and the ensuing ship-floodwater interaction and water sloshing, [70]. This, in turn, depending on compartment geometry, dimensions and position with respect to the axis of rotation, amount of floodwater, and amplitude and frequency of motion, [71], displays a behaviour ranging from small-amplitude short waves formation and non-linear standing waves to highly non-linear hydraulic jumps or combinations of all these, [72]. The dynamic pressures exerted on the compartment walls are also of non-linear nature as they comprise both non-impulsive loads related to fluid transfer as well as impulsive localised loading. Such dynamic effects of fluid motion on the ship response, and vice-versa, have been extensively studied since the late 1960s, mostly from the viewpoint of roll stabilising tanks, water trapped on deck, tanks in LNG carriers and related problems, where the amount of fluid mass in the tank is constant. However, the problem of a ship undergoing progressive flooding entails further degrees of freedom and complexity arising from fluid mass variation, which also renders all related processes non-stationary.

Published research on the subject exhibit tremendous variety in levels of sophistication and type of approaches used to solving these problems. Two approaches can be broadly distinguished: simplified numerical methods based on rigid-body theory and using a Bernoulli-based mechanism for modelling water ingress-egress and techniques employing the latest advances in Computational Fluid Dynamics (CFD). Studies on coupled ship motion and water sloshing based on the latter approach have been reported by [73], [74], [75] and [76]. In these studies, the excited internal fluid behaviour due to tank/ship motion is dealt with by coupling the solution of RANS equations with the simultaneous time-domain solution of equations of intact ship motions, treating the fluid forces as external input. Further, [77], presented an attempt to predict, in a similar manner, effects of water ingress with the rate of flooding itself estimated from Bernoulli's equation. In addition, water sloshing coupled to a 6-DOF ship motion prediction model, [78], led the way to representing water ingress/egress and damaged ship dynamics in a more sophisticated (albeit still simplified) manner, allowing for direct coupling between external and internal fluid domains.

Even though addressing the problem of intact and damaged ship dynamics with water sloshing at the most fundamental of levels, these techniques are plagued with practical solution setbacks, deriving from two reasons: the very large fluid domains required and the presence of free surfaces. The applied numerical solution schemes proposed, such as the VOF method, suffer from notorious inability to conserve the fluid mass with time marching, due to fluid diffusion near the free surface, which is severe especially in the presence of wave fields. Highly refined space discretisation must be used, which increases grid density, thus rendering computation excessive and unaffordable. Additionally, for the case of bodies undergoing motions, the grids must be instantaneously adapted to the new fluid geometry, which is a non-trivial numerical problem, adding to the complexity of using even the most advanced general-purpose CFD tools available today. This prevents methodological application for routine studies on damage survivability in waves. It is envisaged that, presently, the use of these tools will be applied to address many basic problems, such as higher order effects of waves diffraction upon encountering a ship with a breached hull, highly turbulent (rotational) and locally 3-dimensional flows at the damage opening or non-linear floodwater behaviour inside the ship compartments coupled with effects of instantaneous water ingress/egress on ship hydrodynamics. More methodological treatment of such tools, leading to knowledge intensive models (for example response surfaces) paved the way as far back as the early 2000s, for example in the EC-funded IP project VIRTUE [79]. Other than some gains attributable to higher computing power, no significant advance is noted in this direction as concluded in Project eSAFE [35]. However, such numerical treatment of damage stability is deemed to evolve into a viable alternative to physical model testing. This also forms part of FLARE, where in addition to validating numerical tools for routine evaluation of damage stability and survivability in waves, high fidelity numerical tools will be utilised for verification and validation of the numerical tools that will be used routinely in the design process.

Damage Stability Measurement Concepts Deriving from First Principles

Capsize Band

In assessing the ability of a ship to survive a damaged state in a random wave environment, answers to two questions are sought: (a) probability to survive or capsize in each sea state and, (b) given the latter, the time that it takes for this to happen. The second is such a basic question but it was not until the mid-1990s (North West European Project), where the capsize band concept, [80], [81], [82], offered the basis for a credible answer. I simple terms, the capsize band describes the transition of sea-states from those at which no capsize is observed (lower boundary) to those at which the probability of capsize equals unity (upper boundary). This is a region outside which capsize is either unlikely to happen or certain. The capsize band can be depicted in two ways: through the variation of the KG or the GM for different sea states. One example of the latter is provided in Figure 7.

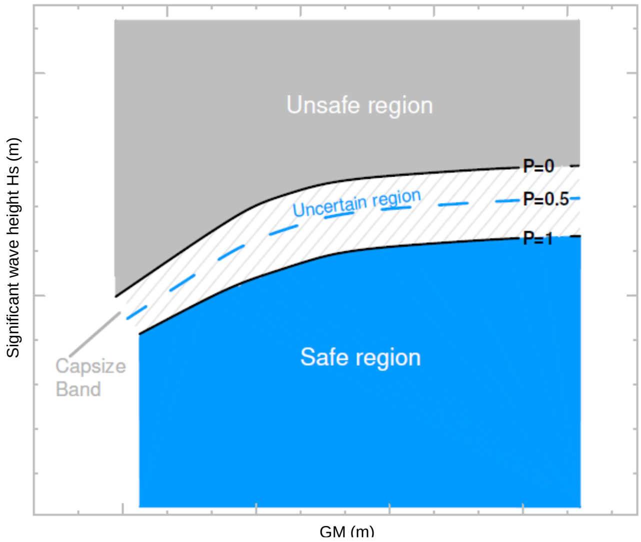


Figure 7. Capsize band with indication of safe, uncertain, and unsafe regions (one damage scenario in different loadings conditions and sea states)

The capsize band indicates the range of sea states within which a transition from unlikely (Ps=1/ Pc=0) to certain capsize (Pc=1/Ps=0) can be observed. The width of the capsize band reflects the variation of the damage characteristics and ship loading conditions. Even though the capsize band is depicted in the form of confidence intervals, in fact it measures the dispersion of capsizes, which in turn relates to separate sea states for which the capsize rate (i.e., the conditional probability of capsize) is very low from those in which the rate is very high. Allied to this, the capsize band signifies that there is no distinct boundary that separates safe from unsafe sea states, but instead a transition zone within which capsize is possible. Although there are sea states that the vessel always survives and sea states that the vessel will inevitably always capsize, the lower and upper capsize/survival boundaries can be represented by means of limits. In this case, this asymptotic nature requires the use of threshold values of the conditional probability outside of which the occurrence of capsize will either be impossible or practically certain.

Figure 8 represents a sample of capsize rates for various simulation times, forming a sigmoid shape distribution. The rate of observed capsizes is depended upon the time of observation and, in case of the limiting case of infinite exposure, the capsize rate distribution will turn into a unit step function, as indicated in Figure 8 for increased simulation times. In this vein, for a small number of capsize probability, the corresponding significant wave height will remain the same (with only minor difference) with time of observation. In other words, a sea state corresponding to a small capsize rate can be established on a basis of relatively short simulations and would remain valid for longer observations.

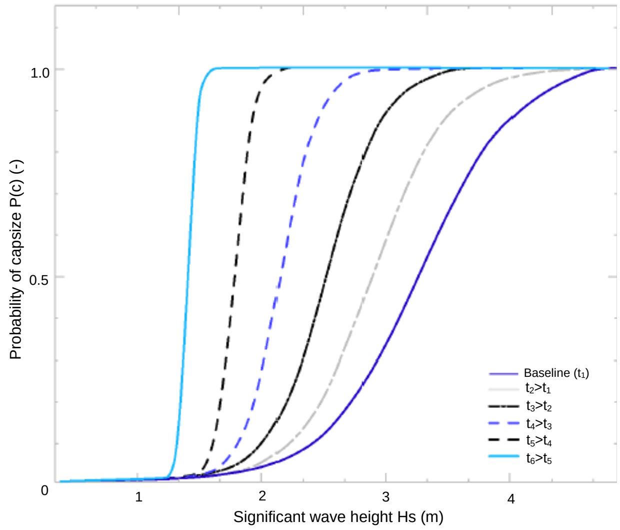


Figure 8. Change in shape of the capsize band with increasing exposure time t_1 for the baseline scenario (dark blue line). The capsize rate is derived for one damage, one loading condition and varying significant wave heights.

3.2.2.1 Concluding Remarks

This section presents the development of a few concepts and tools, essential for flooding risk assessment, particularly by direct approaches. Pertinent rules are also now in place to fuel further development and application in ship design and operation and to encourage further development and validation, with real life applications, as in the EC-funded Project SAFEPASS, [91]. Moreover, such concepts are essential for use in direct estimation of flooding risk, as in FLARE, which will further facilitate their use in practice. Notwithstanding this, the level of readiness and implicit capability in such developments could help transform maritime safety with a huge impact on the whole industry.

4 Emergence of Quantitative Risk Assessment

For a good introduction to risk and risk metrics in the maritime industry and other relevant risk industries, the EMSA III research report, [92], provides a comprehensive review. Related developments in FLARE will be expanded hereunder.

FLARE High Level (Statistical) Flooding Risk Models, [94], [95]

This section provides details of high-level flooding risk models in the form of event trees developed in Project FLARE, [93], based on a new flooding accident database of large passenger ships developed in the project. Related risk models from previous EC research projects are utilised as basis, in particular GOALDS, EMSA III and eSAFE, updated as required. This section also provides the basis for quantification of the new high level flooding risk model based on the new accident database within FLARE where the dataset of 3 hazards, namely collision, side grounding and bottom grounding is utilised.

<u>Prevailing Risk Models</u>

One of the objectives in developing an accident database is to provide input to different nodes/branches in related event trees, which have customarily been used by the maritime industry for flooding risk assessment. Figure 9 and Figure 10 show the different nodes (or high-level event sequences) followed in the GOALDS, EMSA III and eSAFE projects. The same model has been used for Cruise and RoPax ships. These models use largely accident statistics and assumptions based on expert judgment to inform/quantify different nodes in the risk models (such as sinking/capsizing and ensuing consequences).

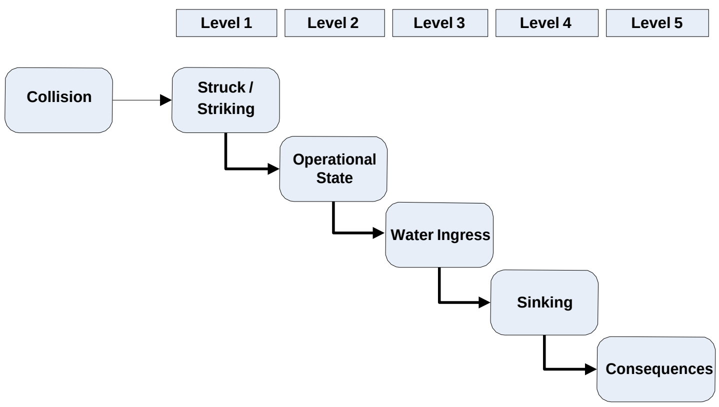


Figure 9. High-level event sequence for collision risk model based on GOALDS/EMSA III/eSAFE

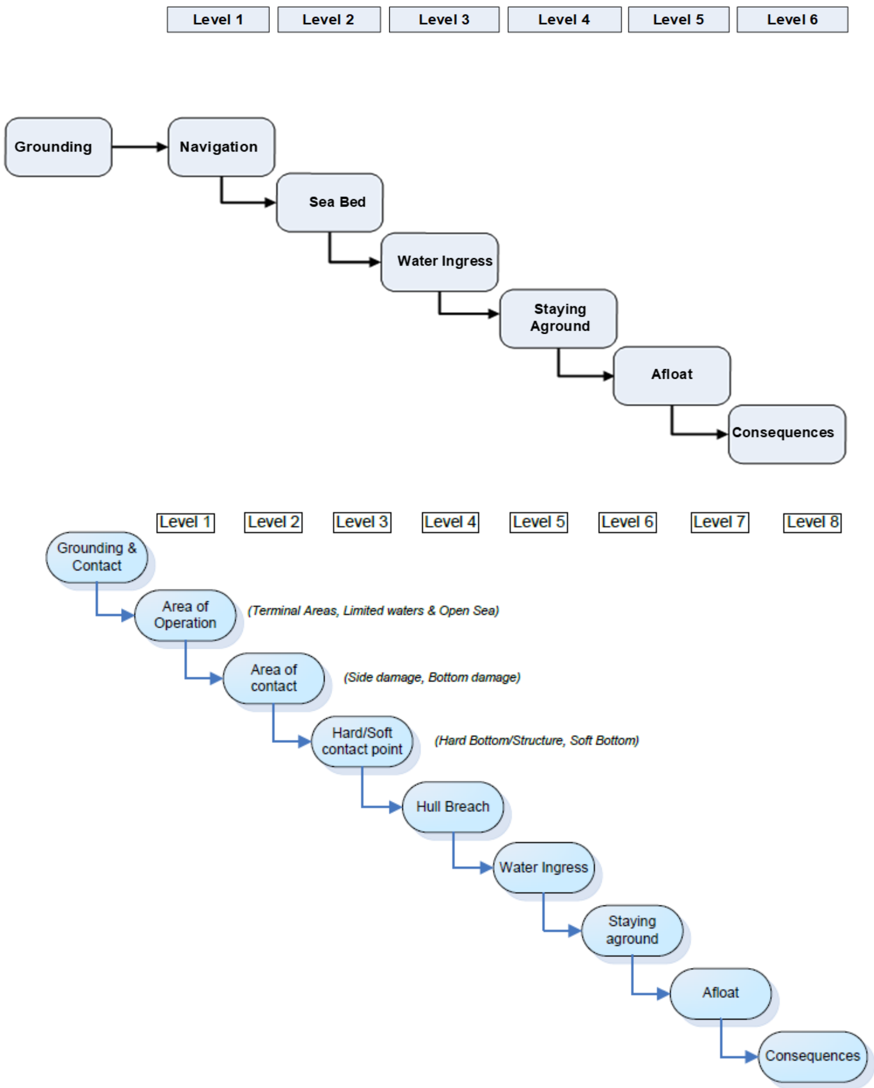


Figure 10. High-level event sequence for grounding risk model based on GOALDS (top) and EMSA III/eSAFE (below)

Finally, Figure 11 shows the generic risk model developed in FLARE. A noticeable difference is that, unlike previous high level risk models, where the risk model starts with accident type followed by operational state/area for a given ship type, the node 'operational area' is preceding the accident type (i.e., collision, side grounding and bottom grounding). In addition, emphasis is placed on the quantification of different nodes using numerical simulation tools. For instance, the node probabilities for 'damage extent' (which is remarkably influenced by the crashworthiness of the ship) and their corresponding 'survival', the model suggests using the formulation for the "p-factors", the "s-factors" and the A-Index in SOLAS 2009/2020, the non-zonal approach for collision developed in eSAFE and numerical flooding simulations tools for collision and grounding accidents, following suitable verification. For grounding accidents, the probabilities are evaluated based on the damage breach probabilistic models and the "non-zonal" approach for the calculation of the corresponding

A-Indices, developed in the framework of the EMSA III study as well as numerical flooding simulations, the latter again constituting one of the FLARE targets. In addition, the node 'consequences' relating to fatalities is evaluated based on the GOALDS/EMSA III assumptions for fast/slow sinking and the corresponding fatality rates based on experiential knowledge. These are so substituted in FLARE by using direct assessment, as described hereinunder.

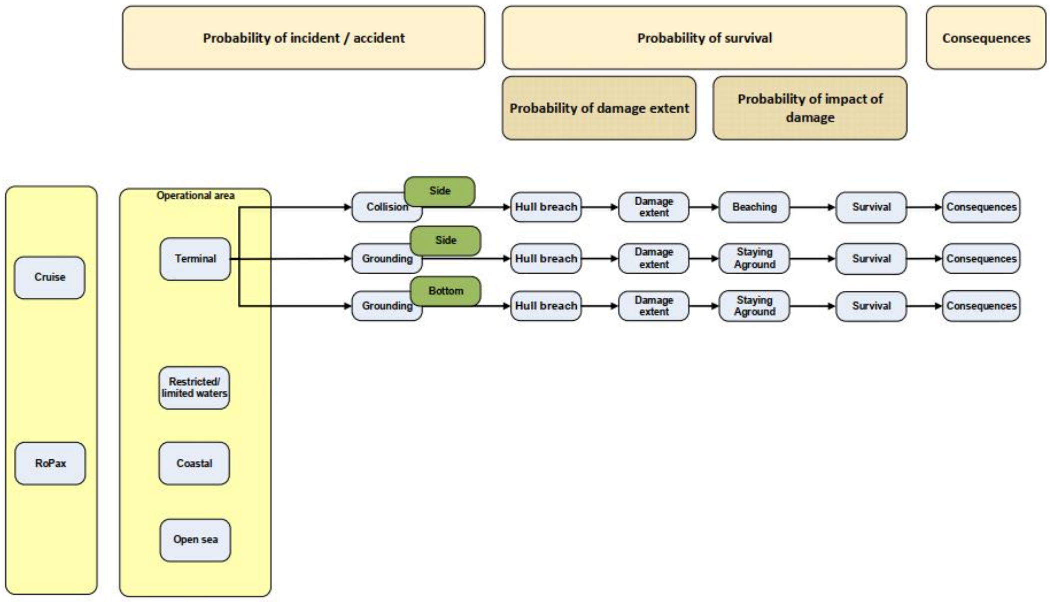


Figure 11. High-level structure of an influence model guiding the development of the flooding risk model

<u>New Developments in Project FLARE</u>

Figure 13 and Figure 14 show the different levels or filters used for the collision and grounding high level risk models used in project FLARE. For collision, nine distinguished levels have been considered, while for grounding 11 levels have been used. The basic structure of the risk model has followed that from GOALDS/EMSA III models, with various updates guided by the new dataset in the FLARE accident database and on direct flooding risk assessment. For instance, 'damage extent' and 'consequences' in terms of fatalities corresponding to slow and fast sinking is updated with relevant developments in FLARE related to new damage breach distributions and ensuing direct assessments using verified numerical tools. A detailed explanation of the different nodes is provided next.

Level 1: Severity

For a given hazard and ship type, the severity of the accident is addressed in the form of the node 'severity'. In general, five potential class of severity can be identified, as shown in Figure 12. In the risk model, stages 1 and 2 (incident and non-serious) have been grouped into 'non serious', and stages – 3, 4, and 5 (serious, flood and sink) into 'serious' category as only 'serious' accidents are considered in project FLARE for risk assessment.

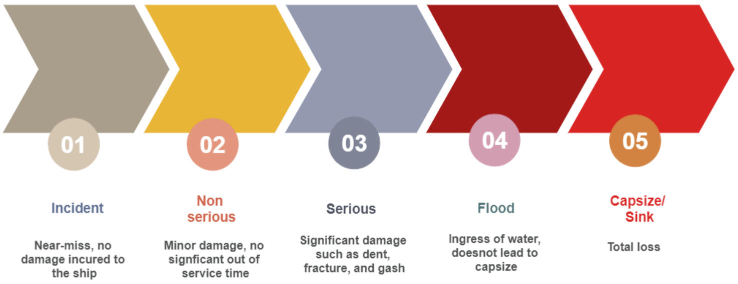


Figure 12. Classification of severity of ship flooding accidents

Level 2: Ship type

The first node in the risk model is assigned to ship type to distinguish the risk model for two types of passenger ships, namely Cruise ship and RoPax. Hence, presently, the category 'Cruise' includes Cruise and Pure passenger ships, whereas 'RoPax' includes RoRo passenger ships and Rail.

Level 3: Operational area

Following previous high level risk models, ship casualties in three operational areas have been identified for collision and grounding - open sea (at sea), terminal waters (such as port/harbour/dock/etc.), and restricted/limited waters. This follows the same categorisation used in the data taxonomy in the FLARE accident database. Three nodes are used to differentiate areas of ship operation [(terminal, restricted/limited waters, and at sea (or open sea)] instead of four categories [terminal, restricted/limited waters, coastal waters, and at sea (or open sea)], as in earlier models, consistent with the taxonomy used in the accident database as there is no sufficient data to feed a higher granularity in the model.

Level 4: Accident type

In the development of any risk model, in accordance with IMO FSA, the identification of hazards leading to ship flooding is the initial step in the risk model. In this respect, three hazards are considered, namely collision, side grounding, and bottom grounding. Side and bottom groundings are considered as a single node (level 5: bottom/side in Figure 14) in the grounding risk model, which again could be further differentiated based on results from pertinent numerical simulations.

For the remaining nodes, a similar structure to GOALDS/EMSA III models has been used, as explained next.

Level 5: Struck/striking ship (collision)

Following the GOALDS/EMSA III high level risk model for collision, a struck passenger ship is considered, and the striking ship is filtered out in serious accidents. Again, further differentiation could be considered, using pertinent numerical tools.

Hull breach and water ingress

These two nodes consider the probability of hull breach and water ingress for collision, side and bottom grounding accidents in three different operational areas.

Capsize/sink

The probability of capsize/sink is determined in previous models based on A-index. In this respect, the same A-index value has been used for ships damaged in different operational areas and are indifferent to hull breach. In FLARE, the casualty data are further filtered based on a direct method of assessment (survivability Index and p-factors, developed in FLARE) for related operational areas and corresponding hull breach.

Fatality rate

The node 'consequence' in the existing models is replaced with 'fatality rate' in the current model. For the ship capsize/sink, the fatalities and PoB are evaluated directly from the accident database to estimate the fatality rate. Therefore, the node 'fast/slow sinking' in case of capsizing, used in previous studies, is not considered here. In FLARE, instead of using the same assumed values as in GOALDS/EMSA III models, irrespective of operational area, the quantification of this node will come from direct assessment using numerical simulation tools, using agent-based simulations for the evacuation and abandon ship process.

At this stage of development, the number of accident cases in each node was estimated to obtain their conditional (dependent) probabilities and the consequence in terms of percentage of fatalities (fatality rate) with respect to the people on board (POB) (where ship capsize/sinking occurred).

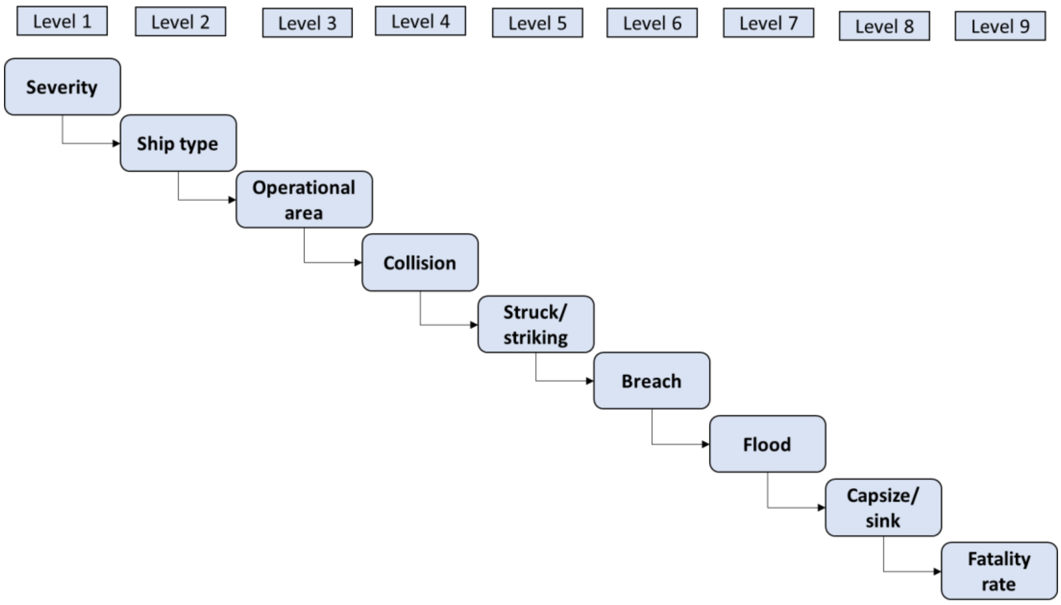


Figure 13. High-level event sequences in the current FLARE collision risk model

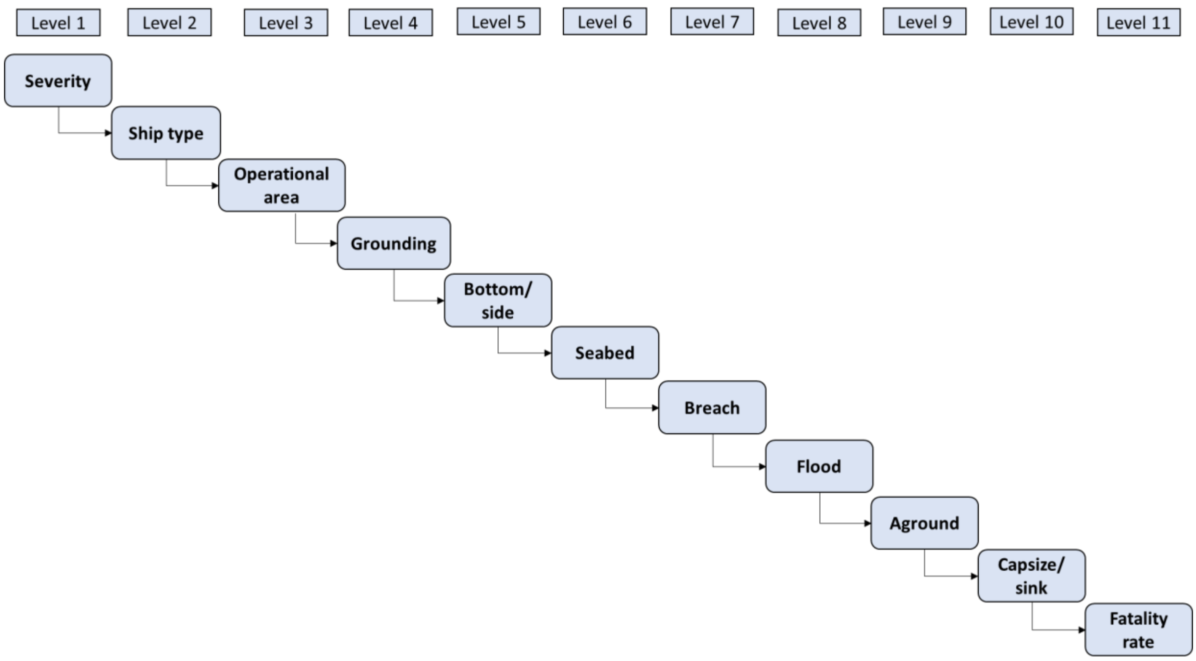


Figure 14. High-level event sequences in current FLARE grounding risk model

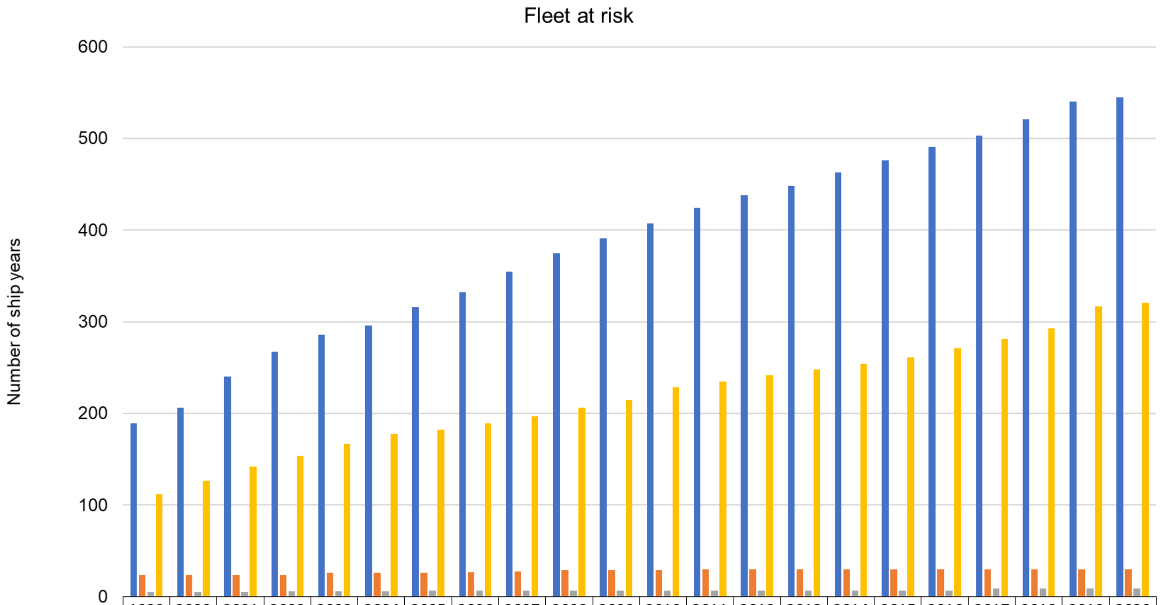
<u>Quantification of the high-level flooding risk model based on historical data</u>

Different nodes in the risk models are quantified using the data from the accident database, [94]. In this respect, the following filters are employed to extract the casualty data and fleet at risk:

- Accident period: 1999-01-01 to 2020-10-31
- Accident type: Collision and grounding (side and bottom groundings)

- Ship size: GT ≥ 3,500
- Ship length (overall): ≥ 80 m
- Ship type: Cruise, RoPAX, Pure passenger, and RoPax (Rail)
- Location: Worldwide
- Class type: IACS and non-IACS (for the fleet at risk)

The initial frequencies (probabilities) in the risk models are calculated based on a detailed analysis of fleet at risk data. Accordingly, the IHS Sea-web 'Ships' module has been utilised and the same filters as mentioned earlier, are used to derive fleet data. Figure 15 shows the annual distribution of ship years for different passenger ship types. As mentioned earlier, two ship type categories have been used - Cruise and RoPax., the former relating to cruise and pure passenger ships and the latter to RoPax and RoPax (Rail) with all relevant data merged accordingly. To filter large passenger ships from the database, a lower threshold value of 3,500 GT is selected, representing an average value based on a simple comparison of Cruise and RoPAX ships having an overall length of 100 m. It is, essentially, a compromise between having enough data in the database for meaningful statistical analysis while focusing on large passenger ships. For the same reason, the filter for the ship-built year in the accident period has not been applied in this study. Table 2 provides initial frequencies calculated for collision and grounding events with serious casualties. The data shows that the initial frequency is highest for RoPax ships involved in grounding accidents and lowest for cruise ships involved in collision accidents.



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
RoPAX	189	206	240	267	286	296	316	332	355	375	391	407	424	438	448	463	476	491	503	521	540	545
RoPAX (Rail)	24	24	24	24	26	26	26	27	28	29	29	29	30	30	30	30	30	30	30	30	30	30
Passenger	5	5	5	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	9	9	9	9
Cruise	112	127	142	154	167	178	182	189	197	206	215	229	235	242	248	254	261	271	281	293	317	321

Year

Figure 15. Yearly distribution of the number of fleets registered for different types of passenger ships

Table 2. Initial accident frequencies for different ship and accident types

Accident type	No. of casualties		Fleet at risk		Initial frequency		
	RoPAX	Cruise	RoPAX	Cruise	RoPAX	Cruise	Passenger ships (RoPax and Cruise)
Collision	59	9	9125	4974	6.47E-03	1.81E-03	8.28E-03
Grounding	120	44			1.32E-02	8.85E-03	2.2E-02

Table 3 summarises the total number of accidents for collision, side, and bottom grounding scenarios obtained for Cruise and RoPax, separately and collectively. To estimate the effect of combined accident type on ship safety, relative fractions (Pr_i) of the accident types are calculated, which may be considered as weighting factors of A-indices following the eSAFE proposal,[35], i.e.:

$$A = Pr_{CL}.A_{CL} + Pr_{GR-S}.A_{GR-S} + Pr_{GR-B}.A_{GR-B} \quad [16]$$

Table 4 provides similar results but only for those cases that involve serious flooding.

Table 3. Total number of accidents recorded and their respective weighting factors (irrespective on whether there is flooding)

Ship type	Collision (CL)	Side grounding (GR-S)	Bottom grounding (GR-B)	Pr_{CL}	Pr_{GR-S}	Pr_{GR-B}
RoPax	59	50	70	0.330	0.279	0.391
Cruise	9	15	29	0.170	0.283	0.547
Total	68	65	99	0.293	0.280	0.427

This yields the following expressions for cruise ships and RoPax:

$$A_{Total\_RoPAX} = 0.33A_{CL} + 0.28A_{GR-S} + 0.39A_{GR-B} \quad [17]$$

$$A_{Total\_Cruise} = 0.17A_{CL} + 0.28A_{GR-S} + 0.55A_{GR-B} \quad [18]$$

Table 4. Total number of accidents involving flooding and their respective weighting factors

Ship type	Collision (CL)	Side grounding (GR-S)	Bottom grounding (GR-B)	$\Pr_{CL}$	$\Pr_{GR-S}$	$\Pr_{GR-B}$
RoPax	15	25	21	0.246	0.410	0.344
Cruise	1	12	8	0.048	0.571	0.381
Total	16	37	29	0.208	0.481	0.377

On the basis that flooding is a taxonomizing factor, the respective weighting factors now become:

$$A_{Flood\_RoPAX} = 0.25A_{CL} + 0.41A_{GR-S} + 0.34A_{GR-B} \quad [19]$$

$$A_{Flood\_Cruise} = 0.05A_{CL} + 0.57A_{GR-S} + 0.38A_{GR-B} \quad [20]$$

This indicates that flooding incidents due to collision are the minority for both ship types and, for cruise, only a very small contribution (5%), indicating that current SOLAS is misrepresenting the real flooding risk, especially for cruise ships.

Figure 16 to Figure 21 depict the overall picture of high level risk models with different nodes and their associated probabilities for Cruise and RoPax ships at three different operational areas, based on the FLARE accident database, [94]. Table 5 and Table 6 show the number of samples totalled at each node of the risk model and the fatality rates (ratio of the actual number of fatalities recorded to POB) calculated for RoPax, and Cruise ships, respectively. In calculating the accident cases for different nodes, unknown/unspecified information in the dataset was disregarded. Therefore, the risk model is different for Cruise and RoPax ships.

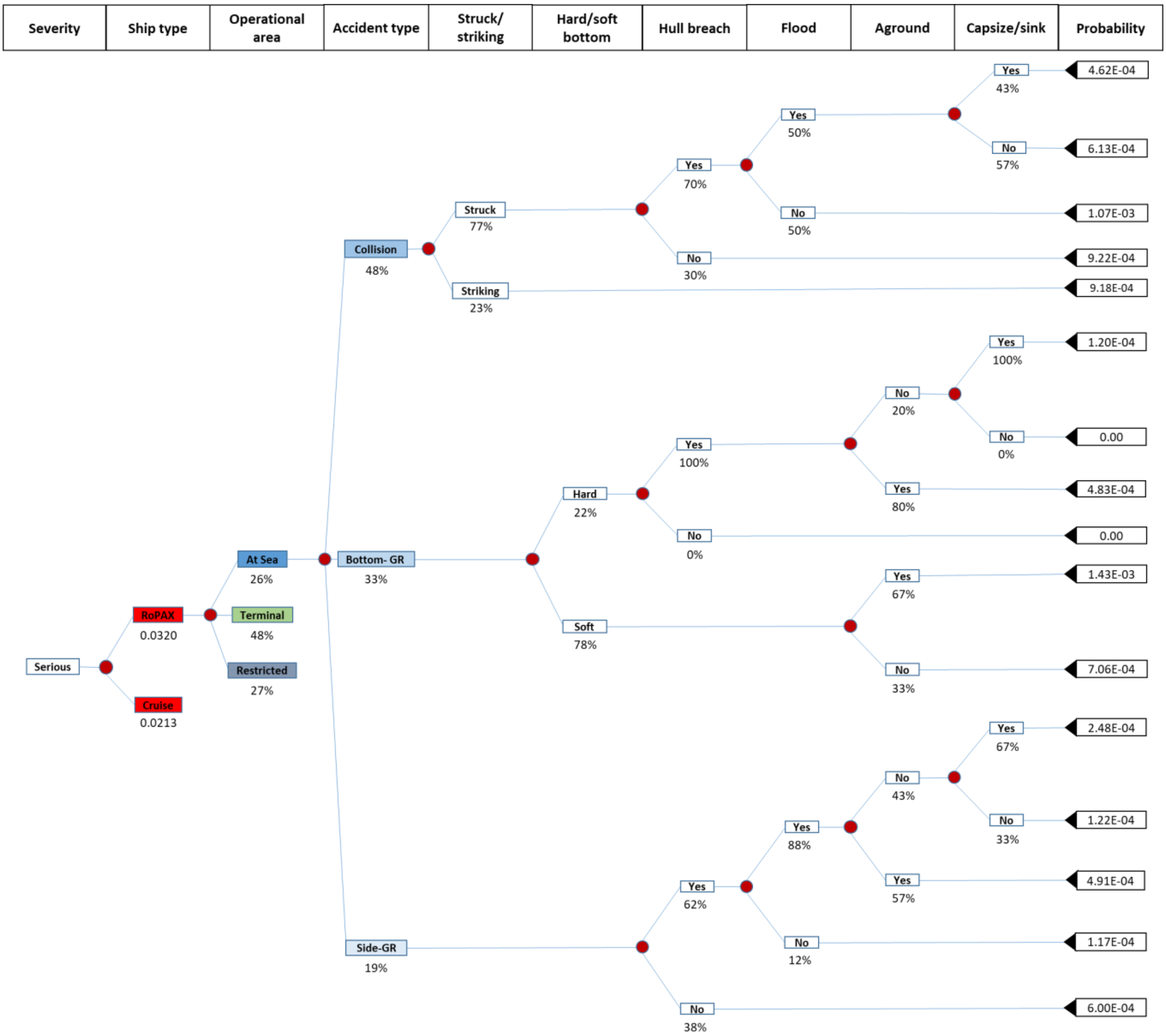


Figure 16. Probabilities determined in different branches in the flooding risk model for RoPax ships – open sea

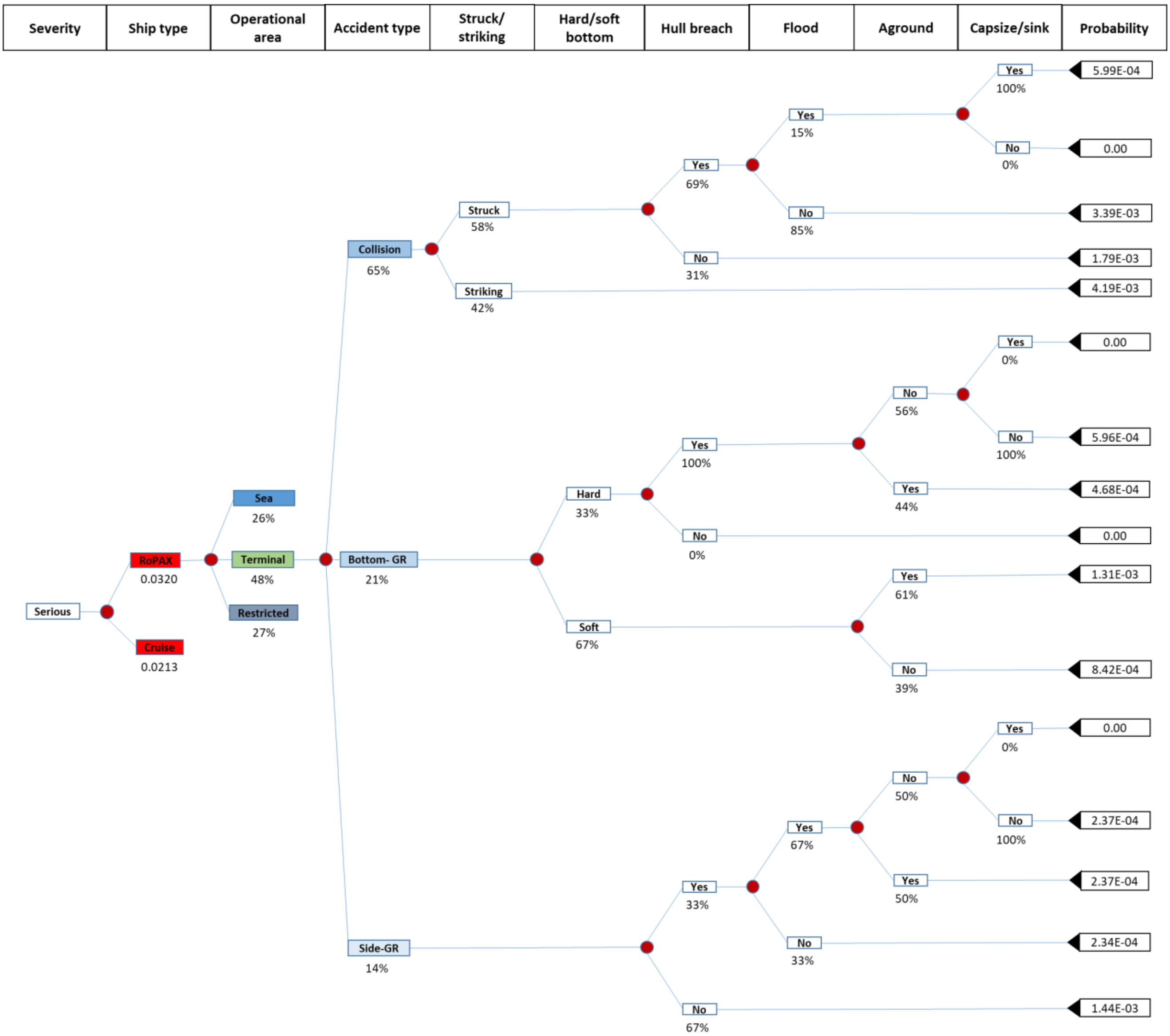


Figure 17. Probabilities determined in different branches in the flooding risk model for RoPax ships-terminal area

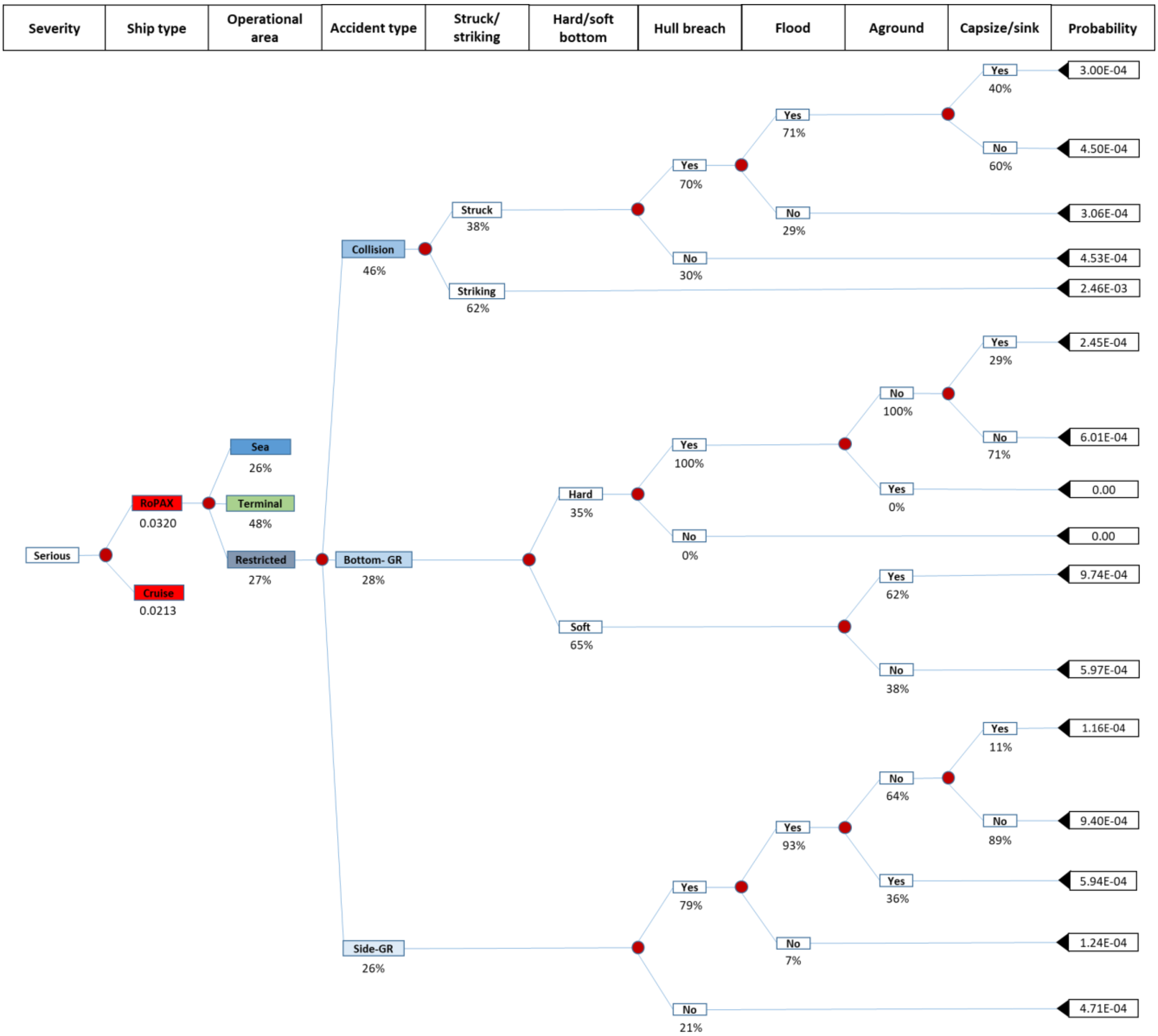


Figure 18. Probabilities determined in different branches in the flooding risk model for RoPax ships – restricted waters

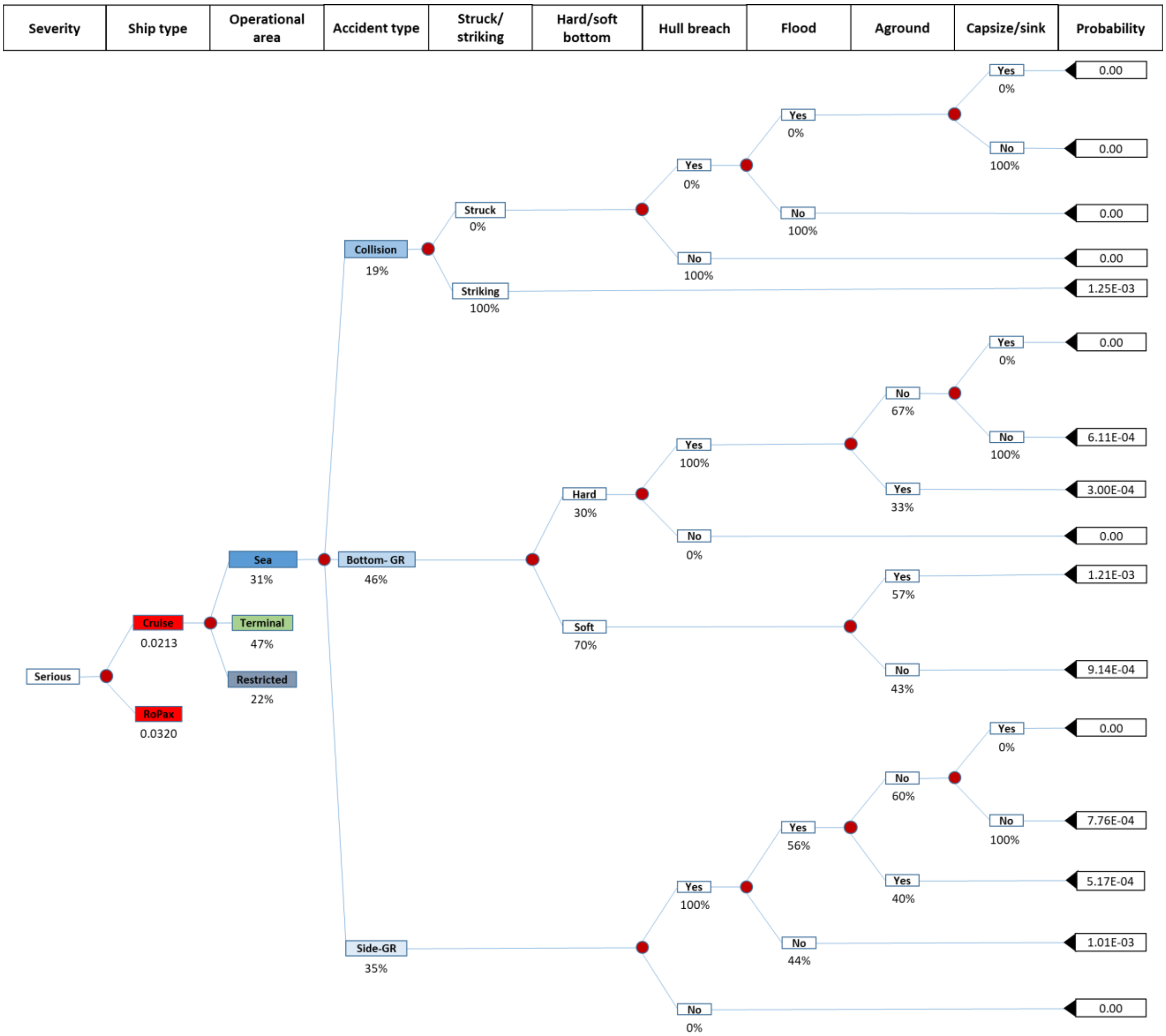


Figure 19. Probabilities determined in different branches in the flooding risk model for Cruise ships - open sea

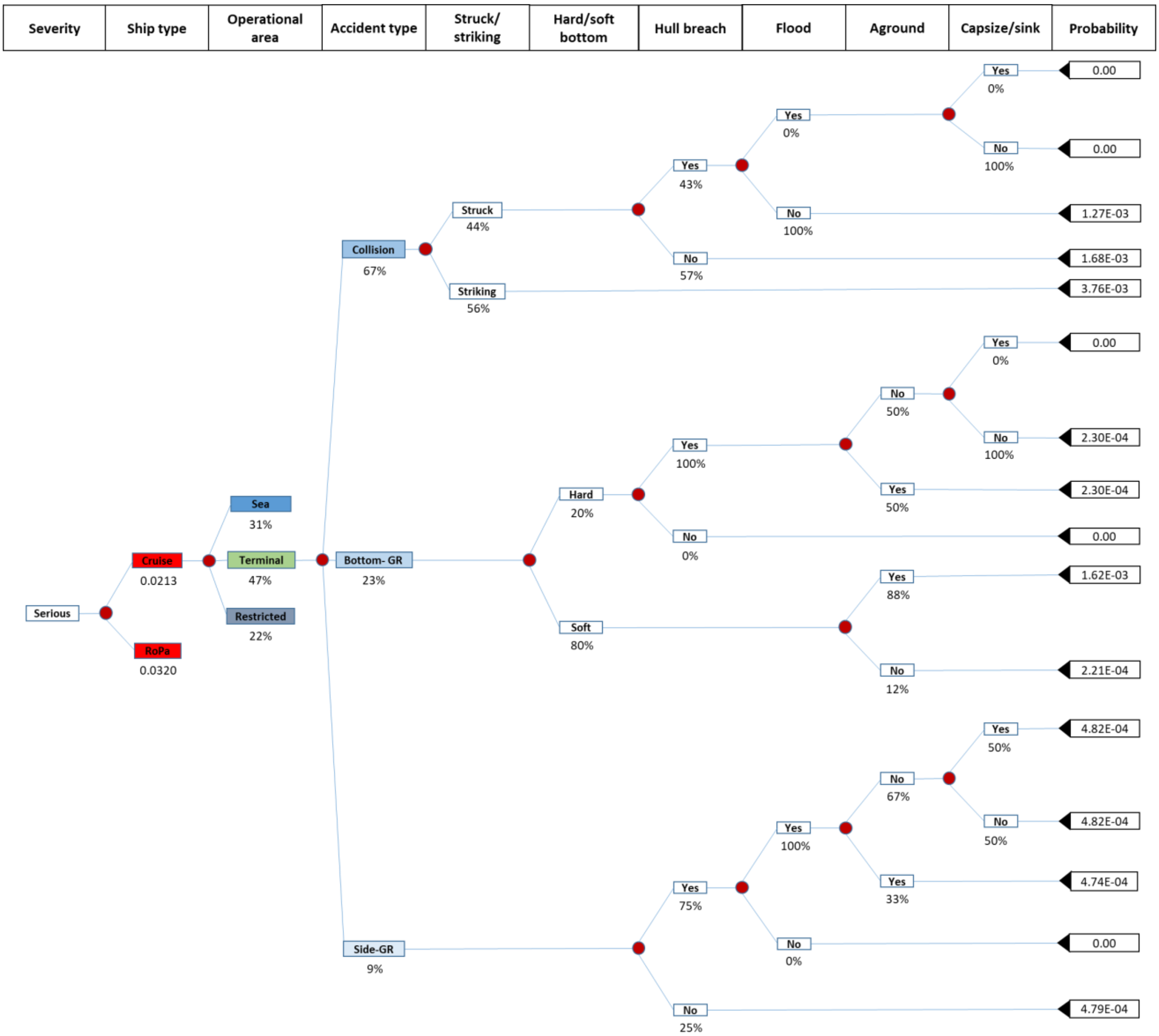


Figure 20. Probabilities determined in different branches in the flooding risk model for Cruise ships – terminal area

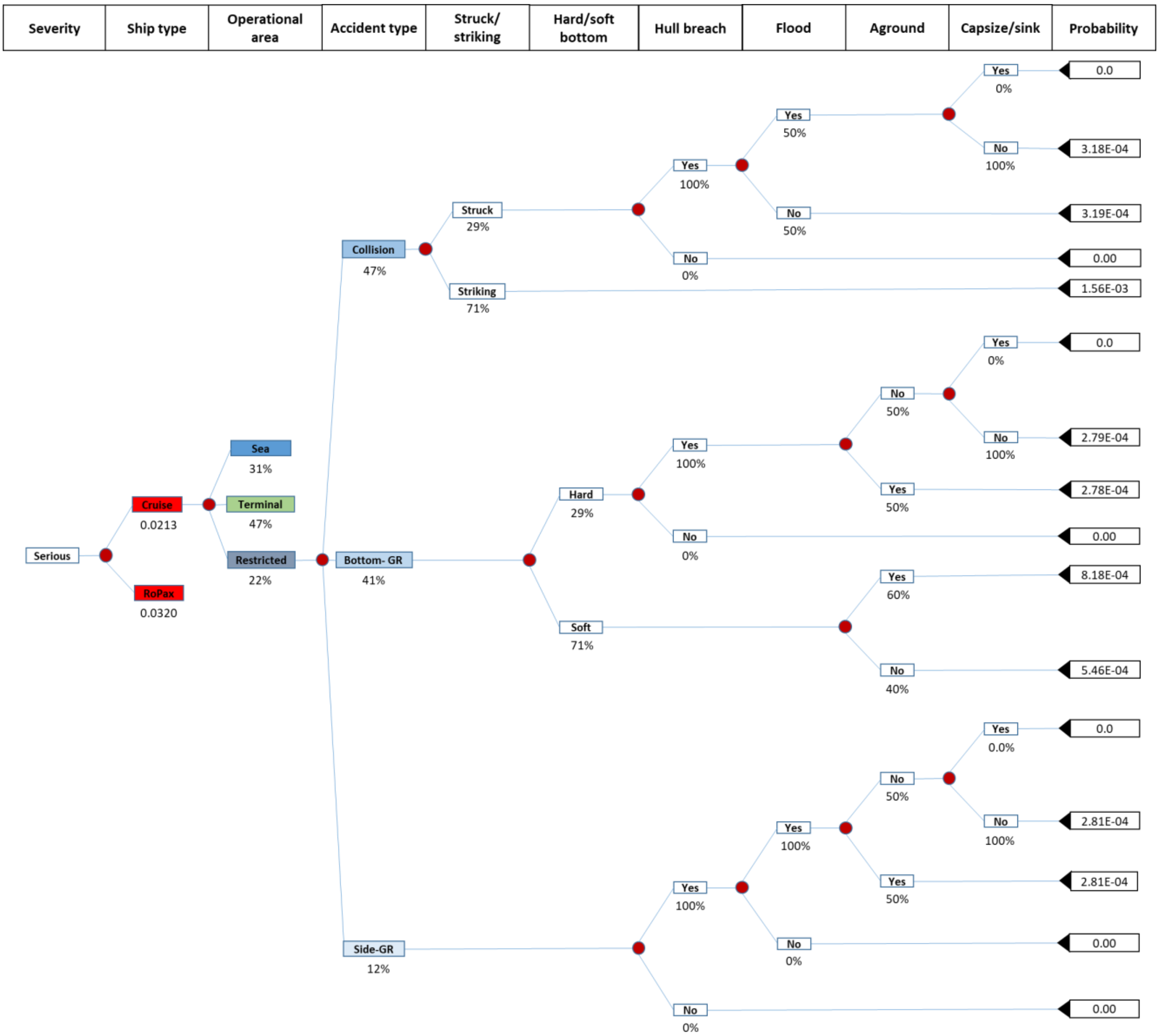


Figure 21. Probabilities determined in different branches in the flooding risk model for Cruise ships – restricted waters

Table 5. Total number of serious accident cases registered in the database fragmented in various stages of the risk model (RoPax)

RoPAX (292)

At sea								
71								
26%								
Side		Bottom				Collision		
13				23			33	
19%				33%			48%	
						Struck	Striking	
						20	6	
						77%	23%	
		Hard		Soft				
		5		18				
		22%		78%				
Breach		Breach				Breach		
8		5				14		
62%		100%				70%		
Flood						Flood		
7						7		
88%						50%		
Not Agrou	Aground	Not Agrou	Aground	Not Agrou	Aground			
3	4	1	4	6	12			
43%	57%	20%	80%	33%	67%			
Capsize		Capsize		Capsize		Capsize		
2		1		0		3		
67%		100%		0%		43%		
Fatality rate		Fatality rate		Fatality rate		Fatality rate		
96%		0%				7.98%		
0%						7.93%		

In port/harbour/dock/..								
133								
48%								
Side		Bottom				Collision		
18				27			84	
14%				21%			65%	
						Struck	Striking	
						29	21	
						58%	42%	
		Hard		Soft				
		9		18				
		33%		67%				
Breach		Breach				Breach		
6		9				20		
33%		100%				69%		
Flood						Flood		
4						3		
67%						15%		
Not Agrou	Aground	Not Agrou	Aground	Not Agrou	Aground			
2	2	5	4	7	11			
50%	50%	56%	44%	39%	61%			
Capsize		Capsize		Capsize		Capsize		
0		0		0		3		
0%		0%				100%		
Fatality rate		Fatality rate		Fatality rate		Fatality rate		
						12%		
						8%		

Restricted waters							
74							
27%							
Side		Bottom				Collision	
19				20			33
26%				28%			46%
						Struck	Striking
						10	16
						38%	62%
		Hard		Soft			
		7		13			
		35%		65%			
Breach		Breach				Breach	
15		7				7	
79%		100%				70%	
Flood						Flood	
14						5	
93%						71%	
Not Agrou	Aground	Not Agrou	Aground	Not Agrou	Aground		
9	5	7	0	5	8		
64%	36%	100%	0%	38%	62%		
Capsize		Capsize		Capsize		Capsize	
1		2		0		2	
11%		29%		0%		40%	
Fatality rate		Fatality rate		Fatality rate		Fatality rate	
0.625%		1.980%				0%	
		15.57%				16%	

Table 6. Total number of serious accident cases registered in the database fragmented in various stages of the risk model (Cruise)

Cruise (106)

At sea								
28								
31%								
Side		Bottom				Collision		
9			12				5	
35%				46%			19%	
						Struck	Striking	
						0	5	
						0%	100%	
		Hard		Soft				
		3		7				
		30%		70%				
Breach		Breach				Breach		
9		3				0		
100%		100%				0%		
Flood						Flood		
5						0		
56%						0%		
Not Agrou	Aground	Not Agrou	Aground	Not Agrou	Aground			
3	2	2	1	3	4			
60%	40%	67%	33%	43%	57%			
Capsize		Capsize		Capsize		Capsize		
0		0		0		0		
0%		0%				0%		
Fatality rate		Fatality rate		Fatality rate		Fatality rate		

In port/harbour/dock/..								
43								
47%								
Side		Bottom				Collision		
4				10			29	
9%				23%			67%	
						Struck	Striking	
						7	9	
						44%	56%	
		Hard		Soft				
		2		8				
		20%		80%				
Breach		Breach				Breach		
3		2				3		
75%		100%				43%		
Flood						Flood		
3						0		
100%						0%		
Not Agrou	Aground	Not Agrou	Aground	Not Agrou	Aground			
2	1	1	1	1	7			
67%	33%	50%	50%	12%	88%			
Capsize		Capsize		Capsize		Capsize		
1		0		0		0		
50%		0%		0%		0%		
Fatality rate		Fatality rate		Fatality rate		Fatality rate		
0.129%								

Restricted waters							
20							
22%							
Side		Bottom				Collision	
2				7			8
12%				41%			47%
						Struck	Striking
						2	5
						29%	71%
		Hard		Soft			
		2		5			
		29%		71%			
Breach		Breach				Breach	
2		2				2	
100%		100%				100%	
Flood						Flood	
2						1	
100%						50%	
Not Agrou	Aground	Not Agrou	Aground	not Agrou	Aground		
1	1	1	1	2	3		
50%	50%	50%	50%	40%	60%		
Capsize		Capsize		Capsize		Capsize	
0		0		0		0	
0%		0%		0%		0%	
Fatality rate		Fatality rate		Fatality rate		Fatality rate	

The simplified models can be obtained by combining relevant branches of risk models presented in Figure 16 to Figure 21, for instance, hazard-specific (collision, side grounding, and bottom grounding), operation area-specific (sea, terminal and restricted), and ship-specific (RoPax, Cruise, RoPax + Cruise). Table 7 and Table 8 summarises the hazard frequencies and operational area frequencies, respectively, and their relative fractions, obtained for different ships, ignoring 'capsize/sink' and 'fatality rate' nodes, as there are significantly fewer data to obtain any statistical inference. The probabilities of node 'capsize/sink' will be obtained from A-indices (or actual index) or the average survivability value obtained from the report D4.4. For the node 'fatality rate', the assumed value used in EMSA III models based on expert judgment (i.e., 80% for fast sinking and 5% for slow sinking), combined with the average fast/slow sinking ratio results from the flooding simulations, will be used. Finally, the risk in terms of PLL for a specific ship and for a given POB and exposure time is calculated from the following expression, eq. (20-1),

$$PLL = hazard\ frequency * (1 - A) * fatality\ rate * POB * exposure\ time\ (in\ years) \quad (20\text{-}1)$$

Table 7. Hazard frequencies of RoPAX, Cruise, and RoPAX + Cruise

Hazard type	RoPax		Cruise		RoPax + Cruise	
	Frequency (1/ship-year)	Relative fraction	Frequency (1/ship-year)	Relative fraction	Frequency (1/ship-year)	Relative fraction
Collision	2.42E-03	0.450	3.02E-04	0.127	1.68E-03	0.388
Side grounding	1.53E-03	0.285	1.21E-03	0.509	1.42E-03	0.328
Bottom grounding	1.42E-03	0.265	8.64E-04	0.364	1.23E-03	0.285
Total	5.38E-03	1.000	2.37E-03	1.000	4.33E-03	1.000

Table 8. Operational area frequencies of RoPAX, Cruise, and RoPAX + Cruise

Operational area	RoPAX		Cruise		RoPAX + Cruise	
	Frequency (per ship year)	Relative fraction	Frequency (per ship year)	Relative fraction	Frequency (per ship year)	Relative fraction
At sea	1.45E-03	0.262	1.17E-03	0.466	2.26E-03	0.706
Terminal + Restricted	3.99E-03	0.720	1.40E-03	0.556	3.08E-03	0.961
Total	5.54E-03	1.000	2.51E-03	1.000	3.21E-03	1.000

Risk-Based Safety Metric – SM (eSAFE (35))

This relates to the safety metric developed in eSAFE, which is updated here based on the new findings as reported in the foregoing. The reference risk models are relevant to both cruise ships and RoPax, the latter based on work conducted in FLARE, [93]. On this basis, the potential loss of life (PLL) associated with each type of accident can be determined as follows:

$$
\begin{cases}
PLL_{CL} = POB \cdot c_{CL} \cdot (1 - A_{CL}) \\
PLL_{GR-B} = POB \cdot c_{GR-B} \cdot (1 - A_{GR-B}) \\
PLL_{GR-S} = POB \cdot c_{GR-S} \cdot (1 - A_{GR-S})
\end{cases} \tag{21}
$$

Where, *POB* is the number of persons on board (crew and passengers, considering assumptions with respect to occupancy). The coefficients c_{CL}, $c_{GR\text{-}B}$ and $c_{GR\text{-}S}$ can be directly calculated from eqs. (25) and (26). The total PLL (PLL_{TOT}) can be obtained by summing up the risk contributions from the three types of accidents, i.e.

$$
\begin{aligned}
& PLL_{TOT} = PLL_{CL} + PLL_{GR-B} + PLL_{GR-S} = \\
& = POB \cdot \left[c_{CL} \cdot (1 - A_{CL}) + c_{GR-B} \cdot (1 - A_{GR-B}) + c_{GR-S} \cdot (1 - A_{GR-S}) \right]
\end{aligned} \tag{22}
$$

PLL_{TOT} represents the risk associated with a vessel with given *POB* and attained indices A_{CL}, $A_{GR\text{-}B}$ and $A_{GR\text{-}S}$, as measured based on the assumed reference risk models (eq. 19) and (eq. 20) for cruise ships and RoPax, respectively. The total societal risk PLL_{TOT} can be reformulated, leading to what is denoted as *SM*, which combines the impact from all three types of accidents, as follows, eq. (23):

$$
\begin{cases}
SM = k_{CL} \cdot A_{CL} + k_{GR-B} \cdot A_{GR-B} + k_{GR-S} \cdot A_{GR-S} \\
PLL_{TOT} = POB \cdot c_T \cdot (1 - SM) \\
\\
\text{where} \\
c_T = c_{CL} + c_{GR-B} + c_{GR-S} \\
k_{CL} = \dfrac{c_{CL}}{c_T} \quad ; \quad k_{GR-B} = \dfrac{c_{GR-B}}{c_T} \quad ; \quad k_{GR-S} = \dfrac{c_{GR-S}}{c_T}
\end{cases} \tag{23}
$$

It also follows that contributions to PLL_{TOT} from different types of accidents (collision, bottom, and side grounding) can be expressed as follows:

$$\begin{cases} PLL_{TOT} = PLL_{CL} + PLL_{GR-B} + PLL_{GR-S} \\ \text{where} \\ PLL_{CL} = POB \cdot c_T \cdot k_{CL} \cdot (1 - A_{CL}) \\ PLL_{GR-B} = POB \cdot c_T \cdot k_{GR-B} \cdot (1 - A_{GR-B}) \\ PLL_{GR-S} = POB \cdot c_T \cdot k_{GR-S} \cdot (1 - A_{GR-S}) \end{cases} \tag{24}$$

The main characteristic of this procedure is that the resulting weighting factors k_{CL}, $k_{GR\text{-}B}$ and $k_{GR\text{-}S}$ for the three attained indices in the safety metric *SM* are considering the relative contribution to risk stemming from different types of accidents with reference to cruise ships and RoPax. In this way, types of accident providing a large contribution to risk also provide a corresponding greater contribution in the combined safety metric *SM*. Numerical values of the coefficients, are summarised in Table 9, from which:

$$SM\ cruise\ ships\ = 0.127 \cdot A_{CL} + 0.364 \cdot A_{GR-B} + 0.509 \cdot A_{GR-S} \tag{25}$$

$$SM\ RoPax = 0.450 \cdot A_{CL} + 0.265 \cdot A_{GR-B} + 0.285 \cdot A_{GR-S} \tag{26}$$

Table 9. Risk-based safety metric SM for cruise ships and RoPax, based on FLARE risk models.

	k_{CL} [-]	k_{GR-B} [-]	k_{GR-S} [-]	c_T [1/ship-year]
Cruise ships	0.127	0.364	0.509	2.37E-03
RoPax	0.450	0.265	0.285	5.38E-03
	$$\begin{cases} SM = k_{CL} \cdot A_{CL} + k_{GR-B} \cdot A_{GR-B} + k_{GR-S} \cdot A_{GR-S} \\ PLL_{TOT} = POB \cdot c_T \cdot (1 - SM) = PLL_{CL} + PLL_{GR-B} + PLL_{GR-S} \\ PLL_{CL} = POB \cdot c_T \cdot k_{CL} \cdot (1 - A_{CL}) \\ PLL_{GR-B} = POB \cdot c_T \cdot k_{GR-B} \cdot (1 - A_{GR-B}) \\ PLL_{GR-S} = POB \cdot c_T \cdot k_{GR-S} \cdot (1 - A_{GR-S}) \end{cases}$$			

This concept, which has been summarised for the case of global indices, can be similarly applied to obtain safety metrics *SM* for each calculation draught by using corresponding partial A-indices.

Combined Attained Subdivision Index SM (eSAFE (35))

An alternative way, also developed in eSAFE, for the derivation of a safety metric considering all three types of accidents is through the definition of a Combined Attained Subdivision Index using appropriate weighting factors for the three individual A-Indices, based on the relative frequencies of the corresponding accidents. Like the A-Index (collision), the Combined A-index provides the conditional probability of survival given an accident with hull breach and potential water ingress had occurred, as shown in eq. (27).

$$\begin{aligned} A = & \Pr\{\text{collision}\} \cdot A_{CL} + \\ & + \Pr\{\text{bottom grounding}\} \cdot A_{GR-B} + \\ & + \Pr\{\text{side grounding/contact}\} \cdot A_{GR-S} \end{aligned} \tag{27}$$

where all probabilities of occurrence (Pr_i) of different types of accidents (collision, bottom grounding, and side grounding) in the previous formula are to be considered as conditional to the occurrence of an accident with hull breach, which can lead to water ingress. Such probabilities play the role of weighting factors in the Combined A-index, determined from the analysis of accidents statistics in FLARE database, as shown in Table 10. The relative frequencies for different types of accidents were determined considering accidents for both Cruise ships and RoPax, using the following filters:

- Cruise and RoPax ships
- Serious flooding
- IACS ships
- L_{oa}≥80m
- *GT≥3,500*
- Period 1999-2020

This led to a corresponding fleet at risk of 9,125 ship-years for RoPax and 4,974 ship-years for cruise ships. Moreover, accidents were selected for which a hull breach was explicitly reported. From the figures shown in Table 10, it can be deduced that the size of available accidents sample is very limited (e.g., 1 collision leading to flooding for cruise ships). As a result, this leads to large uncertainty, demonstrated in the reported confidence intervals for the estimators of the relative fractions.

Table 10. Number of accidents, absolute frequency, and relative fraction for different types of flooding accidents for Cruise ships and RoPax.

Type	Number of flooding accidents (Cruise Ship)	Number of flooding accidents (RoPax)	Frequency (1/ship-year) (cruise ship)	Frequency (1/ship-year) (1/ship-year) (RoPax)	Relative Fraction with 95% confidence interval (Cruise ship)	Relative fraction with 95% confidence interval (RoPax)
Collision	1	15	0.000201	0.00164	0.048	0.246 [7%,52%]
Bottom Grounding	8	21	0.001561	0.0023	0.381	0.344 [4%,46%]
Side Grounding	12	25	0.00241	0.00274	0.571	0.41 [30%,80%]

$$A\ combined\ cruise\ = 0.048 \cdot A_{CL} + 0.381 \cdot A_{GR-B} + 0.571 \cdot A_{GR-S} \quad (28)$$

$$A\ combined\ RoPax = 0.246 \cdot A_{CL} + 0.344 \cdot A_{GR-B} + 0.41 \cdot A_{GR-S} \quad (29)$$

The concept, which has been summarised for the case of global indices, can be applied in the same way to obtain Combined Partial Attained Subdivision Indices for each calculation draught.

4.1 Concluding Remarks

High level risk models provide an intuitive representation of the flooding process and pertinent influencing factors but lack granularity, especially for cruise ships, where the flooding process is much more complicated and hence difficult to capture in discrete steps, however, many such steps might be. For example, in a numerical model of the flooding process typically 1,000 scenarios are being considered in a ship geometric model that contains typically hundreds of spaces and thousands of openings. Trying to capture this with high level risk models might not lead to representatively useful results. It is also important to note that trying to build more complex high level risk models will complicate things still further without significantly improving the end result. An effort in this direction comprises the core of the FLARE project, early results in which are presented next.

5 Direct Assessment of Flooding Risk (FLARE, [93], SAFEDOR, [28])

Against the background of high-level flooding risk assessment approaches that have been followed to date, the FLARE project is making inroads towards a direct assessment of flooding risk, which is ship, operating environment, and accident type specific by addressing all the underlying elements from first principles. The framework and methodology are wide-reaching and most probably, the developments may take their time before they are institutionalised in the maritime industry but there is certainty and conviction that this is the way forward. The FLARE objectives, as described next, are clear in this respect:

The FLARE overriding objective is to develop a novel risk-based methodology beyond the existing state-of-the-art for 'live' flooding risk assessment and containment in line with IMO high level goals. Specific objectives include:

- Collate and analyse all pertinent accident data to create a flooding incident/accident database for the relevant type of ships and damages.
- Using this database, with support from flooding simulation tools and expert judgement, to develop a generic risk model for flooding incidents, accounting for collision and grounding.
- The risk model to be holistic (all flooding accident types, all modes of loss, active and passive measures, crashworthiness), hence with application potential to both newbuildings and existing ships.
- Facilitate real-time flooding risk evaluation for risk monitoring and effective control in emergencies.
- To consider an all-embracing, risk-aware approach post-flooding incidents by addressing the whole spectrum of risk from susceptibility to flooding to emergency response, including mustering and ship abandonment in pertinent flooding scenarios.
- To provide the technical basis and a proposal for the revision of relevant IMO regulations towards a risk-based approach to prevent, contain, and control flooding incidents.

What is presented in this section is methodology and progress in this direction, providing a flavour of things to come but also instilling belief in all concerned that all the effort expended in the past has not been in vain, meaning that this led to developing a true understanding of the problem at hand as well as the need and means for improvement.

A calculation procedure to assess this on a ship-specific, area of operation-specific or indeed on life cycle basis, like what is common practice in the offshore industry in the form of a safety case is of direct relevance to the objectives and methodology adopted in FLARE. The requisite high-level steps are shown in Figure 22.

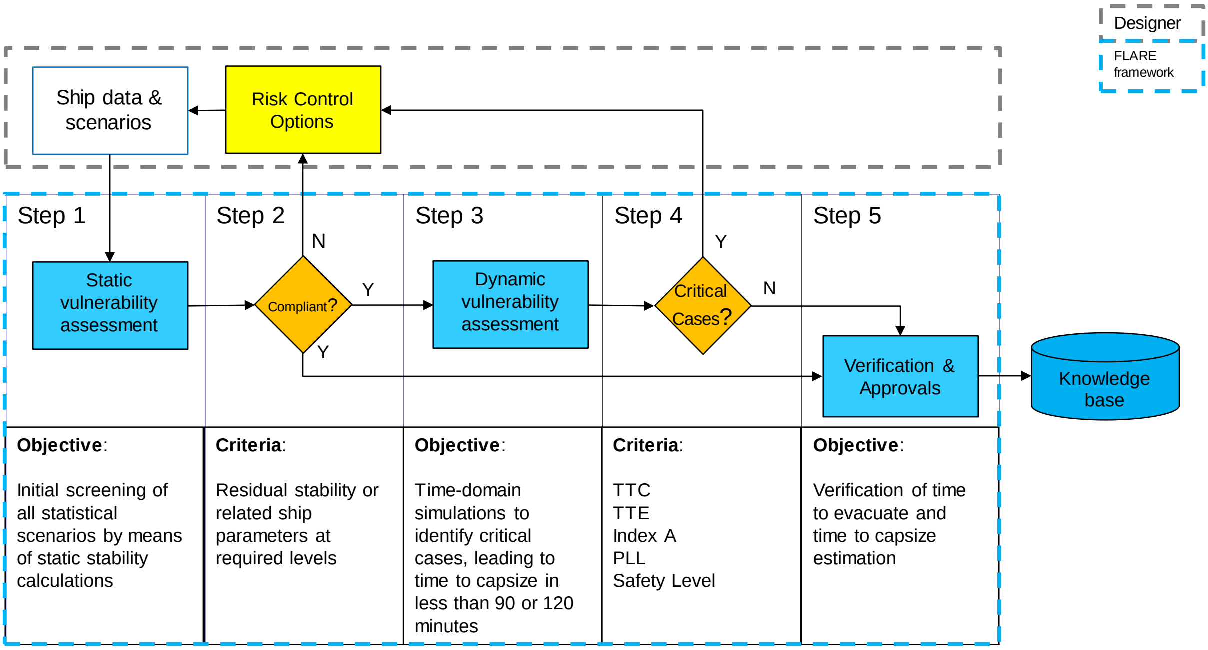


Figure 22. FLARE Framework for Direct Flooding Risk Estimation

5.1 Generic Flooding Risk Estimation

A common way of presenting graphically the chance of a loss (risk) in terms of fatalities is by using the so-called F-N diagram, the plot of cumulative frequency of N or more fatalities together with related criteria, [96],[97],[98], Figure 23. In addition, some form of aggregate information is used, such as the expected number of fatalities E(N), often referred to as Potential Loss of Life, PLL.

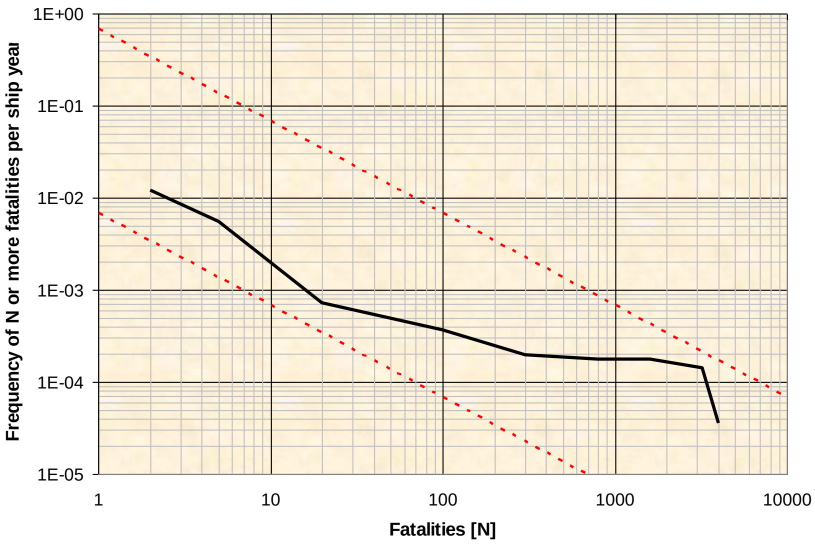


Figure 23. FSA cruise ships – Societal risk

Generic Flooding Risk Model

In generic form, risk may be expressed as follows, [99]:

$$Risk_{PLL} \equiv E(N) \equiv \sum_{i=1}^{N_{\max}} F_N(i) \tag{30}$$

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

$$F_N(N) = \sum_{i=N}^{N_{\max}} fr_N(i) \tag{31}$$

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

$$fr_N(N) = \sum_{j=1}^{n_{hz}} fr_{hz}(hz_j) \cdot pr_N(N|hz_j) \tag{32}$$

$$fr_{NCN}(N) = \sum_{j=1}^{n_{hz}} fr_{CNhz}(hz_j) \cdot pr_{NCN}(N|hz_j) \tag{33}$$

$$fr_{NGRB}(N) = \sum_{j=1}^{n_{hz}} fr_{GRBhz}(hz_j) \cdot pr_{NGRB}(N|hz_j) \tag{34}$$

$$fr_{NGRS}(N) = \sum_{j=1}^{n_{hz}} fr_{GRShz}(hz_j) \cdot pr_{NGRS}(N|hz_j) \tag{35}$$

Where, n_{hz} is the number of loss scenarios considered, and hz_j represents a loss scenario pertinent to any of the principal hazards; furthermore, $fr_{hz}(hz_j)$ is the frequency of occurrence of scenario hz_j per ship year, and $pr_N(N|hz_j)$ is the probability of occurrence of exactly N fatalities, given that loss scenario hz_j has occurred, each one of these related to the hazard in question (collision, bottom grounding, side grounding). As presented in the foregoing, frequency estimates for flooding hazards have been derived based on statistics, FLARE Accident Database, [94]. Efforts in the past to determine frequency of flooding events from first principles have not matured to an industry-accepted standard (e.g., [27]) but there is a renewed impetus to address this in FLARE, [93] and an outline of this effort is presented next.

Frequency Estimation of Flooding Events and Damage Breach Generation, [100], [101]

As part of the FLARE Project, [93], a direct assessment method for frequency estimation ($\boldsymbol{fr_{hz}(hz_j)}$) has been developed, and the methodology is shown in Figure 24. The basic elements comprise the following three steps:

- Step (i) – Ship Trajectories (STs) are reconstructed using AIS data that contain static voyage and dynamic navigation details for the Gulf of Finland, used in this specific example, as part of the research in FLARE. The process is used to cluster ship trajectories of the struck ships by using K-means for static voyage clustering and DB-SCAN for dynamic navigation features clustering (Figure 24).
- Step (ii) – Cluster collision scenarios are identified using the proposed avoidance behaviour-based collision detection model (ABCD-M). The collision probability in this study is estimated with focus on a RoPax vessel from the RoPax sample vessels used in FLARE (Figure 25).
- For each collision scenario, collision breaches are evaluated using the struck ship SHARP model (Figure 26 and Figure 27).

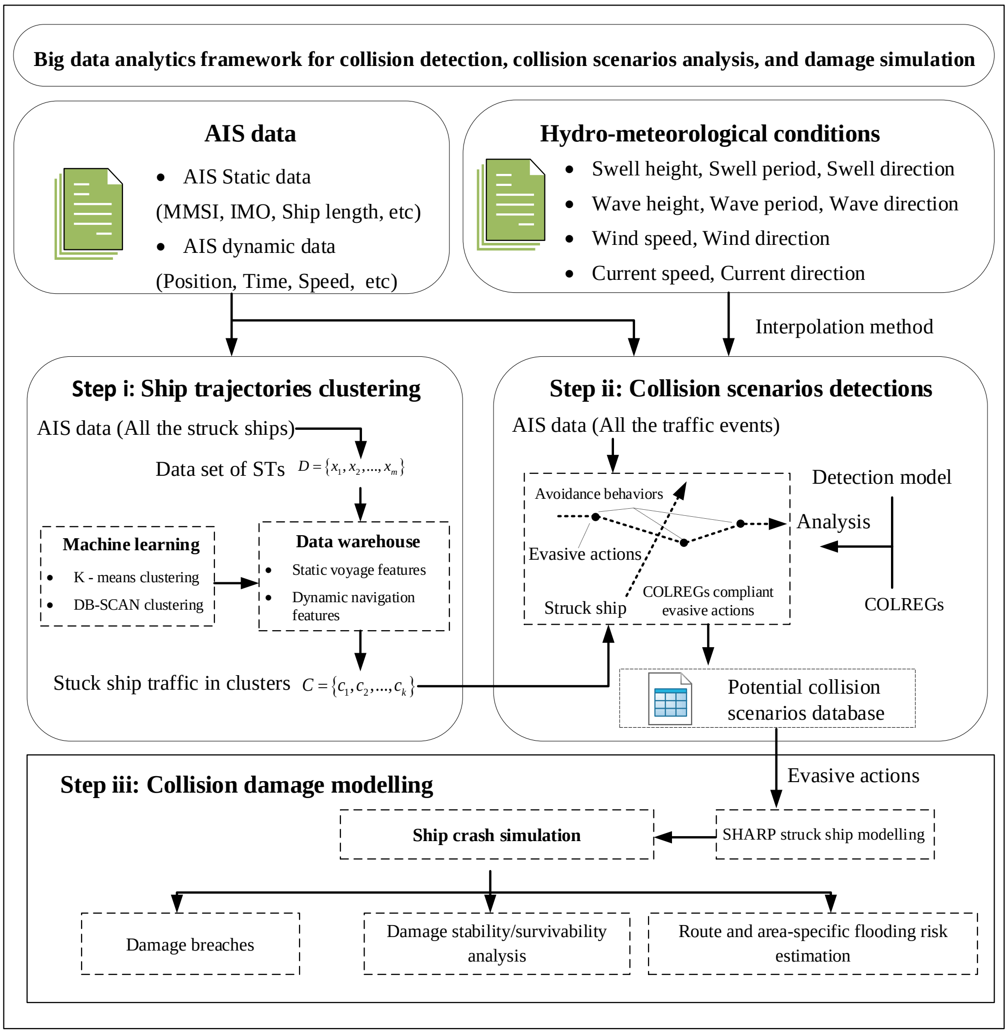


Figure 24. A Framework for Collision Risk Estimation using Big Data Analytics

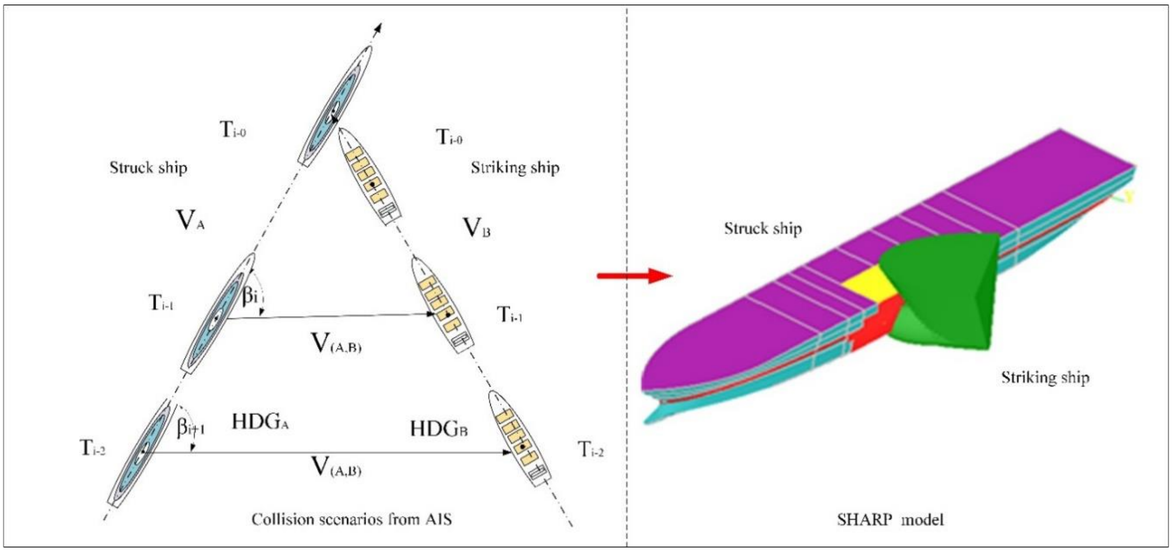


Figure 25. An Example of Collision Scenarios

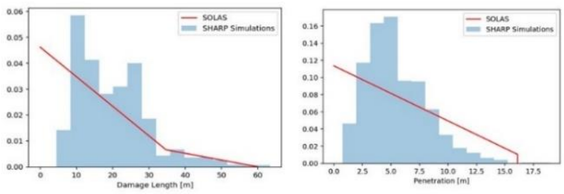


Figure 26. Damage normalized histogram for simulated damages (Left: Damage Length, Right: Penetration).

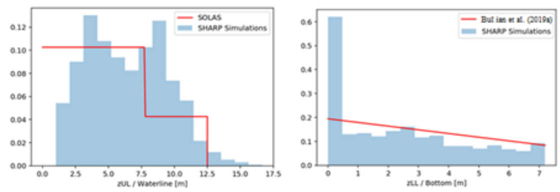
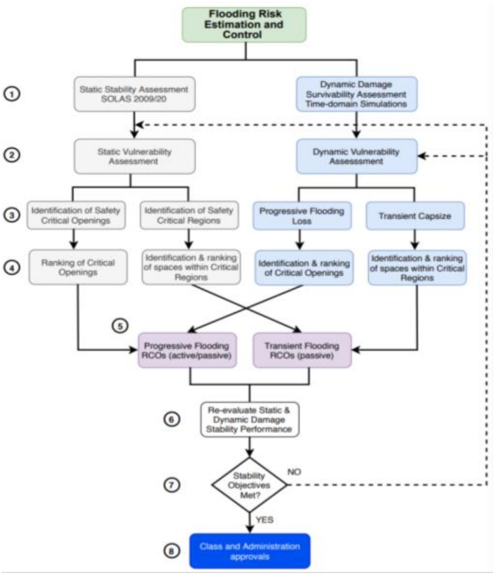


Figure 27. Damage breach vertical extent normalized histogram for simulated damages (Left: Upper limit, Right: Lower limit).

<u>Consequence Analysis</u> $\boldsymbol{pr_N(N|hz_j)}$

With frequency estimation in hand (for pertinent flooding scenarios), as described in the foregoing, the next step in the FLARE methodology for flooding risk assessment (as depicted in Figure 28) is to identify those scenarios where the vessel survival may be compromised (critical or loss scenarios) to inform the process of identifying pertinent risk control options (design measures) to alleviate these or at the very least attempt to increase time to capsize for pertinent scenarios during the design phase, Figure 28.

Those scenarios for which passive measures prove not to be cost-effective (e.g. structural crashworthiness), operational measures could then be employed for cost-effective flooding risk reduction and emergency response. The FLARE methodology is again displayed in Figure 29 with a pictorial explanation of the risk assessment process and flooding risk evaluation (Potential/Estimated Loss of Life). As explained in the foregoing and depicted in Figure 30, the two random variables essential for this estimation are Time to Capsize (TTC) and Time to Evacuate (TTE), where TTE includes mustering and abandonment process.



1. Input information(WP2)
2. Static/dynamic stability assessment (WP3/WP5)
3. Static/dynamic vulnerability assessment (WP3/WP4/WP5)
4. Failure/Loss modalities (WP5)
5. Forensic analysis of loss scenarios (WP5)
6. RCO selection (WP6/WP7)
7. RCO implementation (WP7)
8. Impact assessment/ Recommendations (WP8)

Figure 28. FLARE Methodology for Identification of Critical Flooding Scenarios [102]

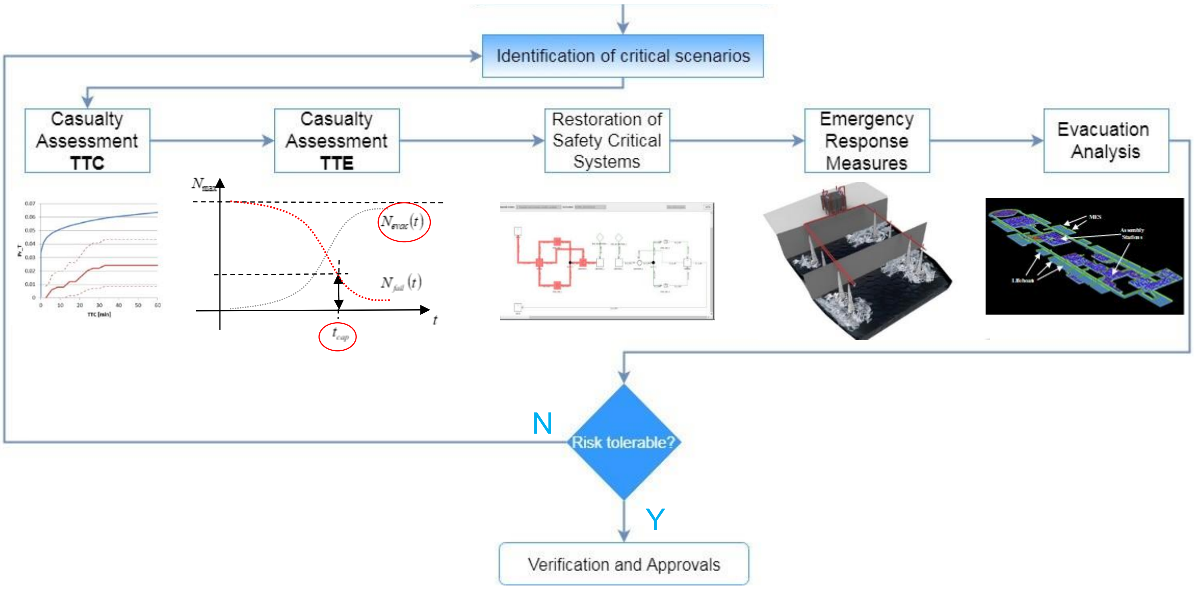


Figure 29. FLARE Methodology for Emergency Response and Risk Assessment.

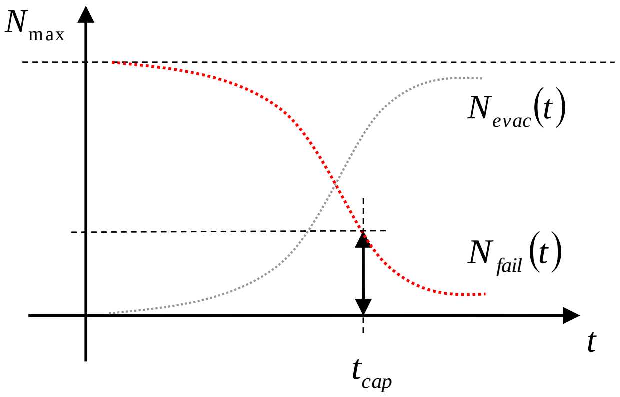


Figure 30. Fundamentals for Flooding Risk (Potential Loss of Life) Evacuation (Time to Evacuate; Time to Capsize)

Time To Capsize (TTC)

This relates to identifying those flooding scenarios where damage survivability is compromised (loss scenarios) and evaluating the time it takes for the vessel to capsize/sink. The process involves generating many flooding scenarios by sampling the random variables comprising loading conditions, sea states and damage characteristics (location, length, height, penetration) according to damage statistics adopted in the IMO probabilistic regulations in SOLAS, using Monte Carlo sampling. Each damage scenario is then simulated using explicit dynamic flooding simulation, e.g., PROTEUS, [83], aiming to identify potential loss scenarios, Figure 31 and Figure 32.

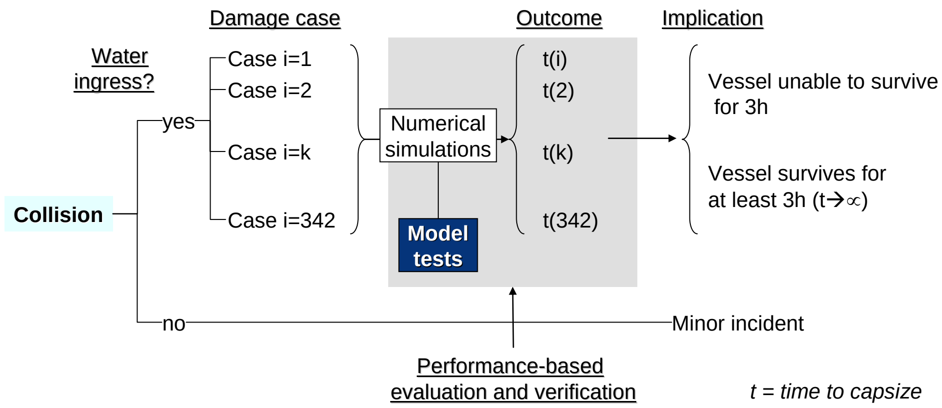


Figure 31. Monte Carlo simulation scheme – collision

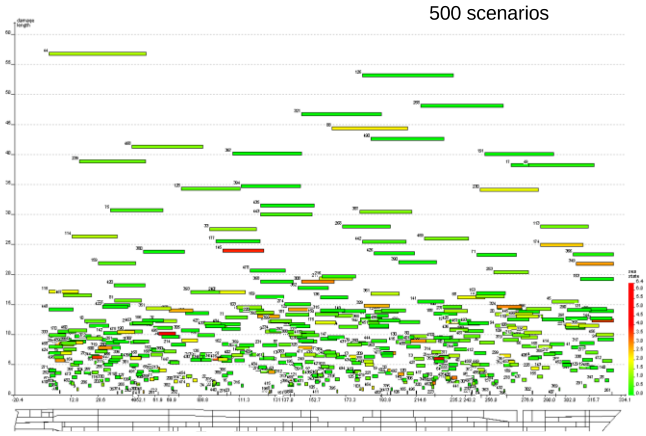


Figure 32. Monte Carlo simulation set up – collision, [84]

The results of the flooding simulations allow the vessel Survivability Index to be determined, which simply represents the ratio of cases survived to cases lost. This is a time-conditional value, depicted as the cumulative distribution function of Time to Capsize (TTC), shown in Figure 33 for a cruise vessel. Here, the probability of vessel capsizing can be observed with respect to time. The complement of this value then represents the vessel probability of survival, or **Survivability Index**, conditional on exposure time. In addition, through observation of the shape of the CDF, one can learn a great deal about the modality of the loss scenarios giving rise to the capsize risk (transient loss or progressive flooding loss). The CDF of a vessel with a higher propensity for transient capsize will demonstrate a sharp increase within the lower time range, after which only a gradual increase in capsize probability will be observed. Alternatively, a vessel with a higher propensity for progressive flooding will possess a CDF with only a slight increase within the lower time range, following which the curve will take on a much sharper incline towards longer exposure times. In addition, the CDF is also shown with 95% confidence intervals, determined in accordance with eq. (36). This accounts for statistical uncertainty and provides an upper and lower bound for the Survivability Index.

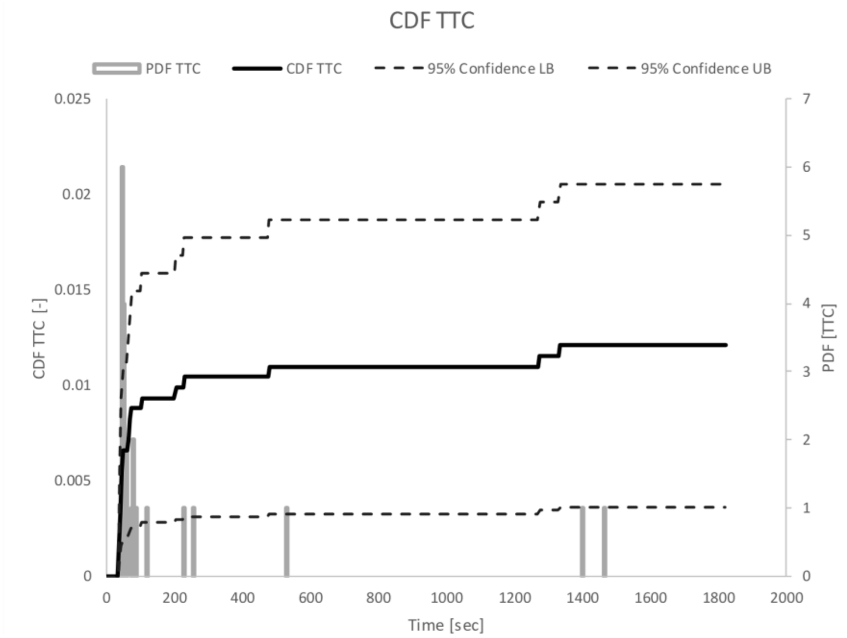


Figure 33. CDF for Time to Capsize

$$SE = \frac{\sigma}{\sqrt{n}} \tag{36}$$

Where,

σ = sample standard deviation

n = number of samples

In addition to considering the Standard Error, confidence intervals can also be derived for each sample to illustrate the range of confidence across the sample CDF. For this purpose, the Dvoretzky–Kiefer–Wolfowitz inequality (Dvoretzky, Kiefer, & Wolfowitz, 1956) may be utilised, which allows different rates in violation to be identified across the range of the distribution, see eq. 37 and eq. 38.

$$F_n(x) - \varepsilon \leq F(x) \leq F_n(x) + \varepsilon \tag{37}$$

$$\varepsilon = \sqrt{\frac{ln\frac{2}{\alpha}}{2n}} \tag{38}$$

Where,

$F(x)$ = the true sample CDF

$F_n(x)$ = lower and upper bounds

$1 - \alpha$ = Level of confidence, i.e., $\alpha = 0.05$ for 95% confidence

Time to Evacuate (TTE):

This relates to the time required for orderly evacuation of passengers and crew in any given flooding emergency scenario, identified in the estimation for TTC, which pertains to the last line of defence following flooding and fire ship casualties, namely the evacuation (mustering + abandonment) process, as depicted in Figure 34.

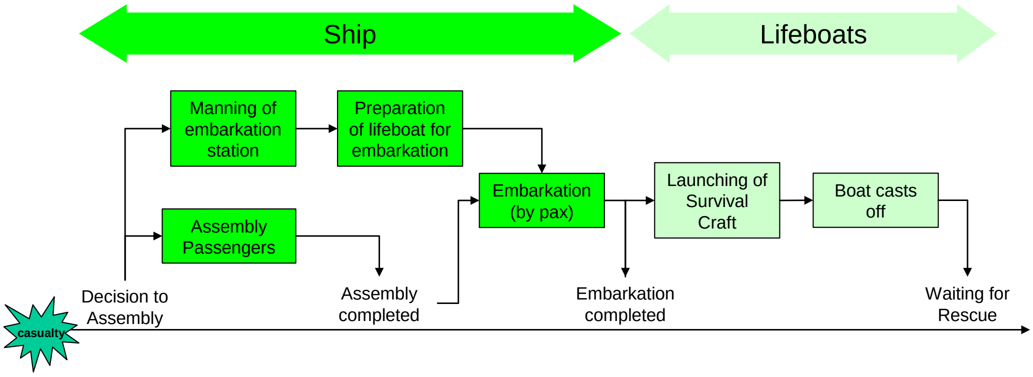


Figure 34. The Evacuation Process

The statutory requirements pertinent to flooding and evacuation of passenger ships are shown in Table 11, [89], the main reference for evacuation being IMO MSC (2016) – MSC.1/Circ. 1533, [90] concerning revised guidelines for evacuation analysis of new (after 01/01/2020) and existing passenger ships. Such guidelines still relate to simplified day and night scenarios in the absence of the main hazards being considered in FLARE, related to flooding and motions of the damaged ship. Hence, definition of pertinent scenarios and impact on analysis need further clarification.

Table 11. Summary of relevant regulations on flooding and evacuation of passenger ships

Statutory document	Relevant topics
SOLAS Ch. II-1 Part B-1, and	Stability, i.e. damage stability
SOLAS Ch. II-1 Part B-2 (after 01/01/2020 incl. SOLAS ammendments from MSC 98th session)	Subdivision, watertight & weathertight integrity *New ammendments include revised guidance for watertight doors on passenger ships, see MSC (2019)*
SOLAS Ch. II-2 Part D	Escape, esp. Reg. 13: Means of escape *Points to* [5]
SOLAS Ch. III (after 01/01/2020 incl. LSA Code ammendments from MSC 98th session)	Life-saving appliances & arrangements
MSC.1/Circ. 1533 (after 01/01/2020 mandatory ∀ PAX)	Revised guidelines on evacuation analysis for new and existing passenger ships *Replaces MSC (2007) and points to* [6]
FSS Code: MSC.98 (73) Annex Ch. 13 Part 2 Passenger ships	Definition of benchmark scenarios, i.e. pax/crew distributions Requirements concerning stairways, doors, corridors, evacuation routes & means of escape plans

Considering the FLARE objectives and scope, advanced evacuation analysis is recommended, meaning:

- Computer-based simulation
- Use of microscopic analysis
- Each occupant represented as an individual (agent-based)
- Detailed representation of the layout (not limited to escape routes, but including also public spaces and assembly stations)
- Interaction between passengers & crew and layout
- Less conservative results

The total evacuation time of a passenger is to be calculated following the procedure shown in Figure 35, repeated at least 50 times to account for the random elements involved in the analysis (e.g., passenger distribution, reaction times, etc.), Figure 36.

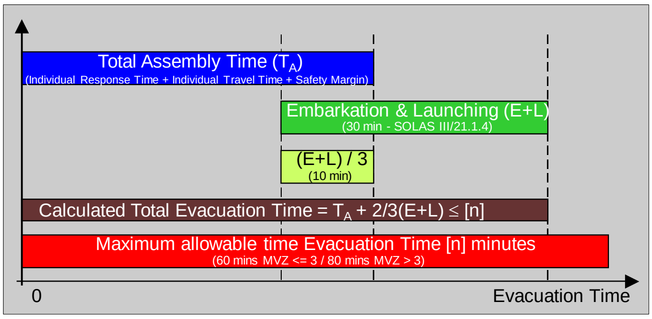


Figure 35. "Advanced" Evacuation Time (MSC 2016) – MSC.1/Circ. 1533 Revised guidelines on evacuation analysis for new (after 01/01/2020) and existing passenger ships.

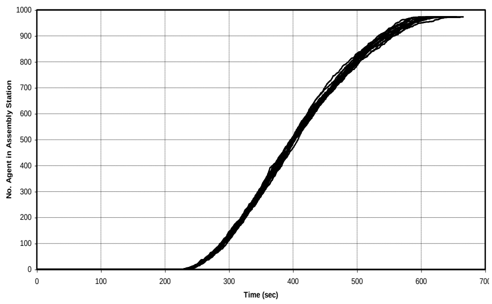


Figure 36. Typical Evacuation Completion Curve (Analysis repeated 50 times).

The IMO evacuation analysis for new cruise and existing passenger ships, allows for assessment at the design stage of passive safety (in-built) of the ship evacuation systems only, while operational safety, 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. The IMO evacuation scenarios address issues relating to layout and availability of primary evacuation routes as well as passenger distribution and response times. These however, do not address any real emergencies and hence the need to prepare for such through better planning, training, and decision support, all related to the functionality of the crew onboard, a factor as crucial to passenger mustering as a good layout of the escape routes. The Class Notation developed in [87] aims at assessing the effectiveness of crew functionality by comparing the evacuation performance of a ship in several specific scenarios (in addition to the 4 IMO scenarios), pertaining to social events, ship at berth and owner specified scenarios to reflect real emergencies with and without crew assistance. This new concept makes evacuation analysis much more relevant offering a "means" for enhancing passenger evacuation performance as well as incentivising passenger ship owners to improve emergency procedures. Stemming from these developments, evacuation analysis in emergency situations through numerical simulations could be undertaken more meaningfully using advanced evacuation tools, especially when such analysis is fused with technological developments to reduce uncertainty in crisis situations, Project SAFEPASS, [91].

Notwithstanding these developments, use is already made of advanced evacuation simulation software, for example EVI, [85], [86], [87], [88]. EVI has been developed specifically for the marine industry with focus on large passenger ships. Hence, it accepts any accommodation layout in .DXF format and converts this to 3D VR environment. It is based on mesoscopic multi-agent modelling, accounting for behavioural and environmental characteristics and their interaction and can handle any passenger/crew/sea scenario. The term Evacuability has been coined to reflect ability to evacuate a ship environment within a given time and for given initial conditions, defined as follows:

$$E=f\{\text{env,d,r(t),s[evacplan,crew,mii(g,y,hci)];t}\} \quad (39)$$

Thus, Evacuability is a function of a set of initial conditions: ship environment (env), passenger distribution (d), passenger initial and in-situ response r(t) and evacuation dynamics, s(ni), pertaining to evacuation plan, crew functionality, passenger mobility characteristics related to gender, age and mobility impairment depending on various handicaps, as depicted in Figure 37 next.

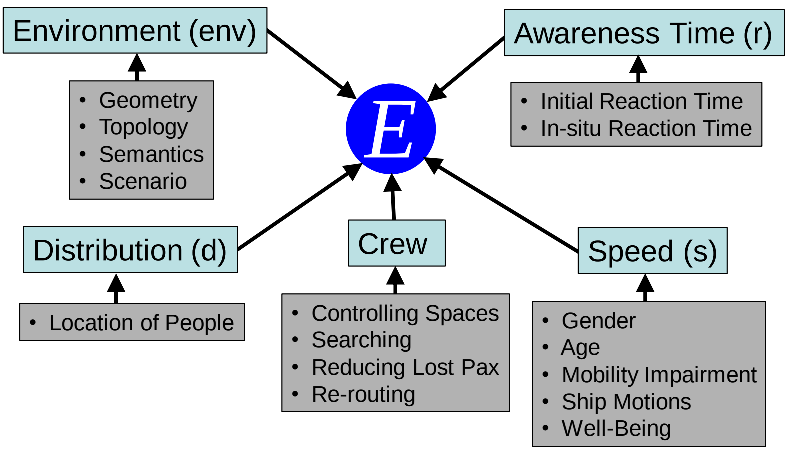


Figure 37. Parameter set for the advanced evacuation simulation software EVI

Evacuability analysis provides a probability measure of passenger evacuation in a ship-sea environment. More importantly, EVI uniquely incorporates capability to estimate the effect of flooding in the evacuation process. In flooding scenarios pertinent to FLARE, data from PROTEUS for the identified flooding loss scenarios are imported into EVI evacuation simulation environment, in the form of time series, as additional semantic information for the agents (evacuees). The agent model considers human behaviour in an evacuation according to a small set of crucial characteristics, such as speed and awareness. A hazard within the evacuation environment will, therefore, affect these characteristics, changing the performance of the agents. More specifically, EVI imports motion and floodwater data from PROTEUS, pertaining to the flooding scenario being considered, which are processed to provide deck inclination to the horizontal (level) position. Using inclination, a correction factor is applied to the walking speed of the evacuee (agent) based on the results of research undertaken in the MEPDesign project. This has been described in detail in [86]. Thus, flooding data are used to affect the awareness and walking speed of agents, reducing it as they become affected by (walking in) floodwater, as described below, and illustrated in Figure 38, [87], [88].

Deck inclination: asymmetric flooding will cause the ship to heel, making it more difficult for evacuees to walk, thus reducing the speed of agents (Figure 38).

Ship motions: ship motion will affect people orientation and movement; consequently, agents will advance more slowly, make wrong decisions, or fall over.

Inaccessibility: flooding renders some areas of the ship inaccessible; this entails that for people on lower decks, certain evacuation routes may become unavailable, and this will impact evacuation completion time.

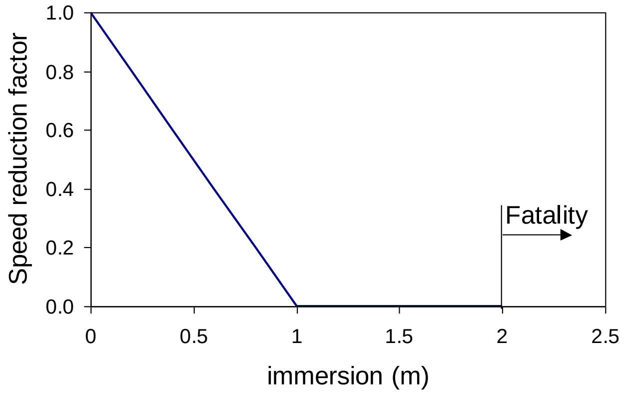
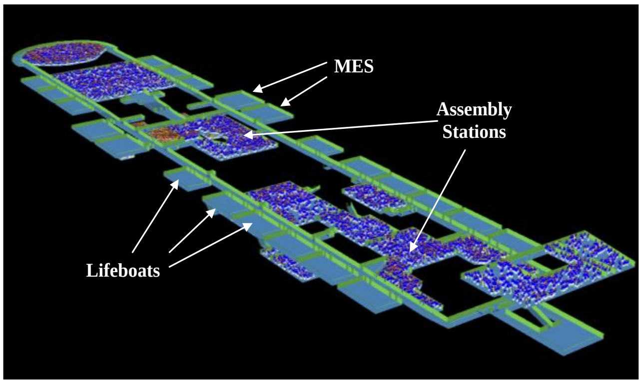


Figure 38. Effect of flooding hazards on the speed of evacuees

For each loss scenario identified as described in the foregoing, evacuation simulation determines the time to evacuate (TTE).



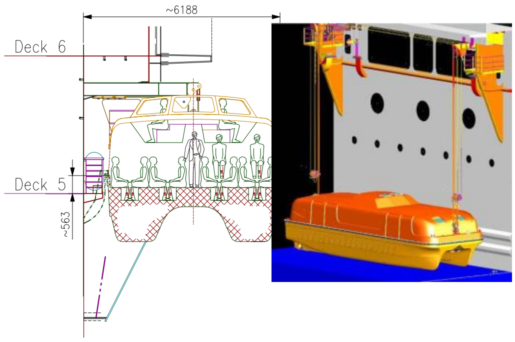


Figure 39. Mustering and Abandonment Simulations with Evi.

Deriving from the foregoing, Figure 39 illustrates the evaluation of the (estimated) potential loss of life through passenger evacuation advanced simulation tools, taking as input the available Time To Capsize (TTC) deriving from flooding simulation analysis, as described above. Figure 40 shows a typical passenger objective completion curve and the quantification of the ensuing risk in terms of estimated loss of human life (shaded area).

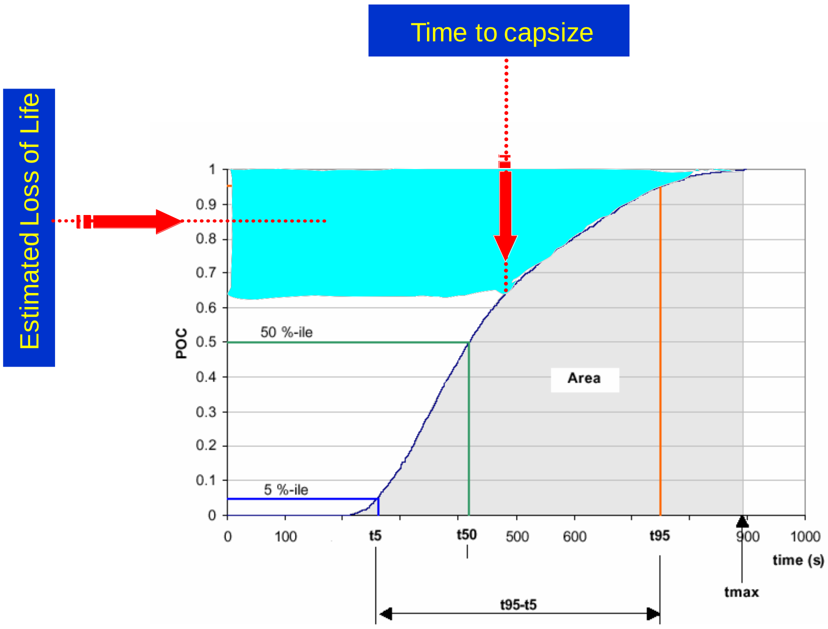


Figure 40. Consequence Analysis of Flooding Loss Scenario (Risk Quantification)

5.2 Concluding Remarks

Following considerable effort in flooding risk estimation for all ship types, we have reached a good understanding concerning the differentiating features between passenger and cargo ships and, in particular the need for attention at a different level of detail for ships with complex internal environments such as cruise ships. In the latter, empirical high lever models or generalised statistical models lack granularity and information capable of differentiating between different ship designs, area of operation and risk level for the different hazards being considered. There are still many specific developments and need for implementation of the FLARE process and methodology before direct flooding risk estimation is properly tested, adopted, regulated, and institutionalised. BUT we are certainly on the right track and we are gaining momentum.

6 REFERENCES

[1] Archimedes: "The Works of Archimedes", edited by T.L. Heath, 2002. Dover Publ., Mineola, N.Y.

[2] Horst, N., 2007. "Leonard Euler and the Theory of Ships", University of Michigan College of Engineering, Department of Naval Architecture and Marine Engineering.

[3] Hoste, P., 1697. "Théorie de la construction des vaisseaux" ("Theory of Ship Construction"), Arisson & Posule, Lyon.

[4] King, J., 1998. "Origins of the theory of ship stability", The Royal Institution of Naval Architects.

[5] Bouguer P., 1746. "Traité du Navire, de sa Construction et de ses Mouvemens", Jombert, Paris.

[6] Euler L., 1749. "Scientia Navalis seu Tractatus de Construendis ac Dirigendis Navibus", 2 vols., St. Petersburg. Reprinted in Euler's Opera Omnia [6], Series II, vols. 18 and 19, Zurich and Basel, 1967 and 1972.

[7] Atwood G., Clairbois, M. Vial de., 1798 "A Disquisition on the Stability of Ships. By George Atwood, Esq. F. R. S.", *Philosophical Transactions of the Royal Society of London*, Vol. 88, pp. vi-310.

[8] Vassalos, D., 1999. "Shaping ship safety: the face of the future", J. Marine technology, Vol. 36, No. 2, pp 61-74.

[9] 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.

[10] 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, Webb Institute.

[11] MSC 82/24/Add.1, "Adoption of amendments to the International Convention for the safety of life at sea, 1974", Resolution MSC 216 (82), adopted on 8th December 2006.

[12] Tagg R., Tuzcu C., 2003. "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, ISSW, New York, USA, 13–16 October 2002.

[13] Wendel, K., 1960. "Die Wahrscheinlichkeit des Uberstehens von Verletzungen", Schiffstechnik, Vol 7, No 36, pp.47-61.

[14] Wendel, K., 1968. "Subdivision of Ships", Proceedings of the 1968 Diamond Jubilee International Meeting – 75th Anniversary, SNAME, paper No 12, 27pp, New York

[15] Vassalos, D., 2008. (Chapter 2: Risk-Based Ship Design) in Papanikolaou, A (Editor): "Risk-Based Ship Design – Methods, Tools and Applications", Springer, October 2008, ISBN 978-3-540-89042-6, pp 17-98.

[16] Vassalos, D., 2012. “Design for Safety, Risk-Based Design, Life-Cycle Risk Management”, Keynote Address, International Marine Design Conference, June 2012, Glasgow, UK.

[17] CSC 1913. International Conference on Safety of Life at Sea, Committee on safety of construction, report and minutes. In: AVIATION, M. O. T. A. C. (ed.).

[18] UKG 1929. International convention for the safety of life at sea, treaty series No 34. In: IMO (ed.). London.

[19] UKG 1948. International convention for the safety of life at sea, 1948, treaty series no 1 (1953). In: MARITIME (ed.). London.

[20] UKG 1960. International convention for the Safety of Life At Sea (SOLAS), 1960, treaty series no 65 (1965). In: MARITIME (ed.). London: Majesty's stationery office.

[21] IMO 1974. Regulations on subdivision and stability of passenger Ships. As an equivalent to Part B of Chapter II of the International Convention for the Safety of Life at Sea, Resolution A265. In: ORGANISATION, I. M. (ed.). London.

[22] IMO 1996. Resolution 14 Agreement Concerning Specific Stability Requirements for Ro-Ro Passenger Ships Undertaking Regular Scheduled International Voyages Between or To or From Designated Ports in North West Europe and the Baltic Sea. In: ORGANISATION, I. M. (ed.). London.

[23] Vassalos, D., & Turan, O., 1994. Damage survivability of passenger ships. SNAME transactions, 102.

[24] Vassalos, D., 1995. Capsizal resistance prediction of a damaged ship in a random sea. The RINA symposium on RoRo Ship survivability, London, 2.

[25] Velschou, S., and Schindler, M., 1994. RoRo passenger ferry damage stability studies - a continuation of model tests for a typical ferry. RINA trans, on RoRo ship survivability, 2.

[26] Jasionowski, A., and Vassalos, D., 2002. Shedding light into the loss of M.V. Estonia. International conference - Learning from marine accidents, London, 2.

[27] HARDER 1999-2003. Harmonization of Rules and Design Rational”. Project funded by the European Commission, DG XII-BRITE.

[28] SAFEDOR 2005-2009. Design, Operation and Regulation for Safety, EU project, FP6-516278.

[29] IMO 2010. Resolution MSC.216(82), amendments to the international convention for the safety of life at sea, 1974. In: ORGANISATION, I. M. (ed.). London.

[30] IMO 2010. MSC. 1/Circ. 1369, Interim explanatory notes for the assessment of passenger ship systems' capabilities after a fire or flooding casualty. International Maritime Organisation. London.

[31] IMO 2019. MSC. 1/Circ. 1212/Rev. 1, Revised guidelines on alternative design and arrangements for SOLAS chapters II-1 and III. International Maritime Organisation. London.

[32] Papanikolaou, A., Bulian, G., Cichowicz, J., Mains, C., Olufsen, O., Szalek, R., Vassalos, D. & Zaraphonitis, G. GOALDS - Goal Based Damage Stability - A new approach to passenger

ship damage stability and safety. 4th International Maritime Conference on Design for Safety and 3rd Workshop on Risk-Based Approaches in the Marine Industries, 2010 Trieste, Italy.

[33] GOALDS 2009-2012. Goal-based Damage Stability", Project funded by the European 13th Commission, FP7- DG Research, Grant Agreement 233876.

[34] Miller, G. 2017. Five years after Costa Concordia: Assessing the safety legacy.

[35] Luhmann, H., Bulian, G., Vassalos, D., Olufsen, O., Seglem, I. & Pottgen, J. 2018a. eSAFE-D4.3.2 – Executive summary, Joint Industry Project "eSAFE - enhanced Stability After a Flooding Event – A joint industry project on Damage Stability for Cruise Ships", rev.3. Available from: https://cssf.cruising.org/projects.

[36] DGMOVE 2016. Proposal for Assessment of specific EU stability requirements for ro-ro passenger ships, European commission DGMOVE SRD /MOVE/D.2/2016-243 V4.0.

[37] Cichowicz, J., Tsakalakis, N., Vassalos, D. & Jasionowski, A. 2016. Damage survivability of passenger ships - Re-engineering the safety factor. Safety MDPI, 2.

[38] Cichowicz, J., Tsakalakis, N., Vassalos, D., 2012. Survivability of passenger vessels – re-engineering of the s-factor, Proceedings of the 12th International Ship Stability Workshop. Webb Institute, USA.

[39] IMO 2017. Resolution MSC.429(98) (adopted on 9 June 2017) Revised explanatory notes to the SOLAS chapter II-1 subdivision and damage stability regulations. London.

[40] Vassalos, D. and Guarin, L., 2009. Designing for damage stability and survivability - Contemporary developments and implementation. Ship science and technology, 1, 59-71.

[41] IMO 2009b. SOLAS- International Convention for the Safety of Life at Sea, London, IMO.

[42] Jasionowski, A., 2009a. Study of the specific damage stability parameters of Ro-Ro passenger vessels according to SOLAS 2009 including water on deck calculation. Lisbon: European Maritime Safety Agency.

[43] Jasionowski, A., 2009b. Study of the specific damage stability parameters of Ro-Ro passenger vessels according to SOLAS 2009 including water on deck calculation, 2nd EMSA study on damage stability of RoPax vessels, Project No EMSA/OP/08/2009. Ship Stability Research Centre, University of Strathclyde.

[44] Tsakalakis, N., Cichowicz, J. & Vassalos, D., 2010. The concept of the capsize band revisited. Proceedings of the11th International Ship Stability Workshop, 21–23 June, Wageningen, The Netherlands

[45] IMO 1976. Resolution A.265(VIII). Regulations on Subdivision and Stability of Passenger Ships as an Equivalent to Part B of Chapter II of the International Convention for Safety of Life at Sea, 1960. In: ORGANISATION, I. M. (ed.). London.

[46] Bird, H. & Browne, R. P., 1973. Damage stability model experiments. The Transactions of RINA, 69-91.

[47] Middleton, E. and Numata, E., 1970. Tests of a damaged stability model in waves SNAME transactions, Washington DC, 7.

[48] IMCO 1973. Resolution A265 VIII, regulations on subdivision and stability of passenger ships as equivalent to part b of chapter II of the international convention for the safety of life at sea, 1960. London, UK, Adopted November 1973.

[49] Vassalos, D., and Papanikolaou, A., 2002a. Stockholm Agreement - Past, Present and Future (Part 2). Marine Technology, 39, 199-210.

[50] Vassalos, D., and Papanikolaou, A., 2002b. Stockholm Agreement - Past, Present, Future (Part 1). Marine Technology, 39, 137-158.

[51] Vassalos, D., Pawlowski, M. and Turan, O., 1995. Criteria for survival in damaged condition. Ship hydromechanics and structures, Delft technical University.

[52] Tuzcu, C. 2003. Development of factor s: the damage survival probability. Proceedings of the 8th International Conference on the Stability of Ships and Ocean Vehicles, STAB2003, 15–19 September, Madrid, Spain.

[53] Jasionowski, A., 2005. Survival criteria for large passenger ships, SAFENVSHIP project final report. Glasgow: Safety at Sea.

[54] Vassalos, D., York, A., Jasionowski, A., Kanerva, M. & Scott, A., 2007. Design implications of the new harmonised probabilistic damage stability regulations. International shipbuilding progress, 339-361.

[55] Vassalos, D. & Jasionowski, A., 2011. SOLAS 2009 - Raising the Alarm. In: NEVES, M. (ed.) Contemporary Ideas on Ship Stability and Capsizing in Waves. Fluid Mechanics and Its Applications: Springer science.

[56] Spanos, D. & Papanikolaou, A., 2011. Considerations on the survivability assessment of damaged ships. Proceedings of the 12th International ship stability workshop ISSW, 12-15 June, Washington DC, USA

[57] Pawlowski, M., 2010b. Developing the s-factor. Proceedings of the 10th International conference on stability of ships and ocean vehicles, STAB2009, 22-26 June, St. Petersburg, Russia.

[58] Heimvik, N. 2001. "Wave Height Distribution According to Damage Statistics", HARDER No: GRD1-1999-10721, 2001-11-29, Report No 3-33-W-2001-01-0. Hovik: DNV.9

[59] Tagg, R., 2014. Comparison of survivability between SOLAS 90/95 and SOLAS 2009 ships - A retrospective view of 10 years on from project HARDER. Proceedings of the 14th International Ship Stability Workshop, ISSW2014, 29 September–1 October, Kuala Lumpur, Malaysia.

[60] Jasionowski, A., 2009a. Study of the specific damage stability parameters of Ro-Ro passenger vessels according to SOLAS 2009 including water on deck calculation. Lisbon: European Maritime Safety Agency.

[61] Jasionowski, A., 2009b. Study of the specific damage stability parameters of Ro-Ro passenger vessels according to SOLAS 2009 including water on deck calculation, 2nd EMSA study on damage stability of RoPax vessels, Project No EMSA/OP/08/2009. Ship Stability Research Centre, University of Strathclyde.

[62] Papanikolaou, A., Hamann, R., Lee, B. S., Mains, C., Olufsen, O., Tvedt, E., Vassalos, D., Zaraphonitis, G., GOALDS – Goal Based Damage Stability of Passenger Ships, Trans. SNAME, Vol. 121, 2013, pp 251-293 (SNAME Archival Paper)

[63] Vassalos, D., and Turan, O., 1992. "Development of Survival Criteria for Ro-Ro Passenger Ships – A Theoretical Approach". Final Report on the S0T Ro-Ro Damage Stability Programme, University of Strathclyde.

[64] Vassalos, D., Letizia, L., 1995. "Formulation of a non-linear mathematical model for a damaged ship subject to flooding", Sevastianov Symposium, Kaliningrad, 1995.

[65] Kat, J de, 1996. "Dynamics of a ship with partially flooded compartment", 2nd Stability Workshop, Japan.

[66] Zaraphonitis, G., Papanikolaou, A. and Spanos, D., 1997. "On a 3D Mathematical Model of the Damage Stability of Ships in Waves", STAB, Bulgaria.

[67] NEREUS (1999-2002). "First-Principles Design for Damage Resistance against Capsize": EC Project CONTRACT No. G3RD-CT 1999-00029.

[68] ROROPROB (1999-2002). "Probabilistic Rules-Based Optimal Design for Ro-Ro Passenger Ships": EU FP5 RTD Project G3RD-CT-2000-00030.

[69] Jasionowski, A and Vassalos, D., 2001. "Benchmark Study on the Capsizing of a Damaged Ro-Ro Passenger Ship in Waves", Final Report to the ITTC Specialist Committee on the Prediction of Extreme Motions & Capsizing.

[70] Vassalos, D., Jasionowski, A., 2002. "Damaged Ship Hydrodynamics", Proceedings of the 6th International Ship Stability Workshop, Webb Institute, New York, October 2002.

[71] Van den Bosh, J.J and Vugts, J.H: "Roll damping by free surface", Report no. 134, Shipbuilding Laboratory, Delft.

[72] Hamlin, N.A., Lou, Y.K., Maclean, W.M., Seibold, F., Chandras, L.M., 1986. "Liquid sloshing in slack ship tanks - theory, observations and experiments", SNAME Transactions, Vol. 94, pp. 159-195.

[73] Mikelis, N.E., Miller, J.K., Taylor, K.V., 1984. "Sloshing in partially filed liquid tanks and its effect on ship motions: numerical simulations and experimental verification", RINA Spring Meetings, Paper No. 7.

[74] Francescutto, A., Contento, G., 1994. "An experimental study of the coupling between roll motion and sloshing in a compartment", ISOPE'94, Osaka, Paper N. 94-YI1-4.

[75] Bass, D., Cumming, D., (2000)]: "An experimental and numerical investigation of the effects of water trapped on the deck", STAB, Launceston, Tasmania, Australia.

[76] Daalen, E.F.G. van, Kleefsman, K.M.T, Gerrits, J., Luth, H.R, Veldman, A.E.P., 2000. "Anti-roll tank simulations with a volume of fluid (VOF) based Navier-Stokes Solver", 23rd Symposium on Naval Hydrodynamics.

[77] Veer, R Van't, Kat Jan de., 2000. "Experimental and numerical investigation on progressive flooding and sloshing in complex compartment geometries", STAB, Launceston, Tasmania, Australia.

[78] Woodburn, P, Letizia, L and Gallagher, P., 2002. "Fundamentals of Damaged Ship Survivability", RINA Transactions.

[79] VIRTUE (2005, 2009): "The Virtual basin", EC FP6 IP, Project 516201, TIP5-CT-2005-516201.

[80] Vassalos, D, Jasionowski, A, Dodworth, K, Allan, T, Matthewson, B and Paloyannidis, P., 1998. "Time-based Survival Criteria for Ro-Ro Vessels", RINA Spring Meeting.

[81] Vassalos, D., Turan, O. and Pawlowski, M., 1997. "Dynamic Stability Assessment of Damaged Ships and Proposal of Rational Survival Criteria", Journal of Marine Technology, Vol. 34, No. 4, pp 241-269.

[82] Tsakalakis, N, Cichowicz, J, Vassalos, D and Jasionowski, A., 2011. "The Capsize Band Concept Re-visited", Proceedings of the 11th Ship Stability Workshop, Washington DC, USA.

[83] Jasionowski, A., 2001. "An Integrated Approach to Damage Ship Survivability Assessment", PhD dissertation, University of Strathclyde.

[84] Vassalos, D., 2020. "The Role of Damaged Ship Dynamics in Addressing the Risk of Flooding", Ships and Offshore Structures. DOI: 10.1080/17445302.2020.1827639.

[85] Vassalos D, Kim H, Christiansen G and Majumder J., 2001. "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.

[86] Vassalos, D., Kim, H. S., Christiansen, G. and Majumder, J., 2002. A mesoscopic model for passenger evacuation simulation in a virtual ship-sea environment and performance-based evaluation, in Pedestrian and Evacuation Dynamics, Proceedings of the 1st International Conference on Pedestrian and Evacuation Dynamics, Springer-Verlag, Berlin, Heidelberg, New York, 369–391.

[87] Dogliani, M, Vassalos, D and Strang, T., 2004. "Evacuation notation: A New Concept to boost Passenger Evacuation Effectiveness in the Cruise industry", Proceedings, 3rd International Euro-Conference on Computer Applications and Information Technology in the Marine Industries (COMPIT), May, Parador Siguenza, Spain.

[88] Guarin, L., Majumder, J., Shigunov, V., Vassalos, G., and Vassalos, D., 2004. "Fire and Flooding Risk Assessment in Ship Design for Ease of Evacuation", Proceedings of the 2nd International Conference on Design for Safety, October, Osaka, Japan.

[89] Ilus, M., 2019. "Combination of Time Domain Flooding and Evacuation Simulation", MSc Thesis, Institute of Ship Design and Ship Safety, TUHH.

[90] MSC 2016. Maritime Safety Committee: MSC.1/Circular 1533 - Revised Guidelines on Evacuation Analysis for New and Existing Passenger Ships.

[91] SAFEPASS, EU H2020 MG2.2 (2019-2022). "Next generation of life Saving appliances and systems for saFE and swift evacuation operations on high capacity PASSenger ships in extreme scenarios and conditions".

[92] EMSA III/OP/10/2013, 2014. "Risk Level and Acceptance Criteria for Passenger Ships", European Maritime Safety Agency.

[93] FLARE, EU H2020 – MG2.2 (2019-2022). "Flooding Accident Response".

[94] Mujeeb-Ahmed M.P., Vassalos, D, Boulougouris, E., 2021. "Development of Collision and Grounding Accident Database for Large Passenger Ships", Proceedings of the STAB&S Conference, 7-11 June 202, Glasgow, UK.

[95] Mujeeb-Ahmed M.P., Vassalos, D, Boulougouris, E., 2021. "Probabilistic Damage Distribution and Risk Modelling of Collison and Grounding Accidents for Large Passenger Ships", Proceedings of the STAB&S Conference, 7-11 June 2021, Glasgow, UK.

[96] IMO 2008. MSC 85/17/1. Formal Safety Assessment, FSA – Cruise ships. Submitted by Denmark, International Maritime Organisation, London

[97] IMO 2008. MSC 85/17/2, 2008. Formal Safety Assessment, FSA – RoPax ships. Submitted by Denmark, International Maritime Organisation, London

[98] IMO MSC 85, 2009. "FSA Cruise Ships", submitted by Denmark.

[99] Vassalos, D., 2008. (Chapter 2: Risk-Based Ship Design) in Papanikolaou, A (Editor): "Risk-Based Ship Design – Methods, Tools and Applications", Springer, October 2008, ISBN 978-3-540-89042-6, pp 17-98.

[100] Zhang, M, Fabien Conti, F, Vassalos, D, Kujala, P, Lindroth, D and Hirdaris, S. 2021. "Direct Assessment of Ship Collision Damage and Flooding Risk", Ocean Engineering, (accepted).

[101] Zhang, M, Fabien Conti, F, Vassalos, D, Kujala, P, Lindroth, D and Hirdaris, S, 2021. "On the estimation of collision frequency and generation of collision scenarios from AIS big-data analysis", Proceedings of the STAB&S Conference, 7-11 June, Glasgow, UK.

[102] Vassalos, D and Paterson, D. 2021. "Towards Unsinkable Ships", Ocean Engineering, Vol 232, 109096.

Appendix A

Early Developments

The question as to how to measure ship stability is a long-standing issue and was first addressed in the period around 250 B.C. by Archimedes, [1] and [2]. However, it was not until the 17th/18th century before the first attempts to crystallise these principles were made. Notably, in 1698, Paul Hoste introduced the concept of metacentric height as a measure of ship stability, or GM as it is commonly known today [3], [4], [5]. Pierre Bouguer, who introduced in 1746 the actual term "metacentre", later elaborated this concept further in a more widely acknowledged exposition [6]. Leonhard Euler focused in 1749 on the righting moment at a particular angle of heel as a better measure of stability,[7], but it was George Atwood who eventually demonstrated in 1798 that such measure can be derived for any angle, [8], inventing thereby the GZ curve. Other milestones on stability quantification, achieved thereafter, include Canon Moseley's concept of using the area under a GZ curve as a better measure of ship stability in 1850, [3]. Further still, 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 [9]. The emphasis, however, was on global ship parameters rather than the detail of the internal ship environment, which is the key determinant of subdivision/configuration of such environment for passenger ships. Despite the significant contribution by Rahola, his approach influenced subsequent developments for all ship types, an issue, which Rahola could not possibly have conceived 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 a "legal" safety instrument was realised for many centuries. First attempts to introduce governmental intervention were in place from 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 even as late as the 18th century. Other examples include the first recorded regulations on load line in middle ages (cross marked on each ship) in Venice in 1255, or the first system of survey inspections imposed by The Recesses of the Diet of the Hanseatic League of 1412.

However, it was only during 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 dimension 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 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, which obliged the Board of Trade to monitor, regulate and control all aspects of safety and working conditions of seamen. The latter also implemented the load line requirements, which were applied to all vessels, including foreign ships 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 transatlantic voyage to New York. In this one 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, which gained international recognition. 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 factor of subdivision in addressing the state of a damaged ship, the Convention did not even mention the concept of stability. Instead, all focus was on intuitive/empirical subdivision as opposed to informed reconfiguration by stability calculations. It was the third Convention of 1948, which referred to stability explicitly in Chapter II-B Regulation 7, and subsequently SOLAS 1960, which prescribed a specific requirement on one parameter of stability after flooding (Residual GM of 1 cm). Finally, SOLAS 1974, adopted Rahola's proposals of using properties of the GZ curve to measure stability. In principle, Rahola's approach forms the basis for amendments of technical requirements on stability ever since,[10], 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,[11], [12]. This can easily escape attention, since the overall damage stability assessment framework, based on Kurt Wendel's concepts of probabilistic index of subdivision A, [13], [14], is rather a complex mathematical construct, with the basic details not discernible. This framework is also a major step-change in the philosophy of stability standardisation and measurement.

As indicated above, it seems that such implicit reliance on Rahola's measures is a major obstacle for 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 clear explanation as to what is implied if the criterion is met, or in which 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 when 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, [15], [16], which will form the basis for the flooding risk estimation in FLARE.