A Multi-Level Approach to Flooding Risk Estimation of Passenger Ships

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ABSTRACT

Against the background of using the Index of Subdivision as a reference to address the safety level of ships when damaged, following primarily collision incidents, the EC-funded 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, using a two-level approach; level 1 being semi-empirical with risk models informed through a newly composed accident database and level 2 with flooding risk, in the form of Potential Loss of Life, calculated from first principles, using time-domain flooding simulation tools and evacuation analyses in pertinent emergencies. In addition to addressing all accident types and modes of loss, the FLARE framework and methodology target active and passive measures of risk prevention and control, hence with application potential to both newbuildings and existing ships as well as facilitate real-time flooding risk evaluation for risk monitoring and effective control in emergencies. A key objective of the FLARE project is to provide the technical basis and a proposal for the revision of relevant IMO regulations towards a risk-based approach to contain and control flooding emergencies. The paper provides a complete example of one cruise ship and one RoPax where levels 1 and 2 of flooding risk evaluation are presented and discussed, and a summary of results for a further 8 sample ships from Project FLARE, leading to conclusions on the progress made and recommendations for the way forward.

KEY WORDS

Damage stability, evacuation, flooding risk, passenger ships, multi-level approach

INTRODUCTION

The question on how to measure ship stability is a long-standing issue, dating back around 250 B.C. by Archimedes, (Archimedes, 2002) and (Nowacki, 2007). Credit for the first significant contemporary development addressing how to measure damage stability of ships goes to Jaakko Rahola who made propositions to use a function of the GZ curve to express the ability of a ship to stay in functional equilibrium after flooding (Rahola, 1939). 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 (Rahola, 1939). In principle, Rahola's approach forms the basis for amendments of technical requirements on stability ever since. Womack (2002), applied in various frameworks for adherence to the SOLAS '74 goal "The subdivision of passenger ships into watertight compartments must be such that after an assumed damage to the ship's hull the vessel will remain afloat and stable". Further still, Rahola's use of GZ curve properties to guide subdivision and to quantify stability are at the core of even the most modern amendments to SOLAS 1974 criteria of ship stability in the damaged condition, (IMO, 2006), (Tagg and Tuzcu, 2003). This can easily escape attention, since the overall damage stability assessment framework, based on Kurt Wendel's concepts of the probabilistic index of subdivision A, (Wendel, 1960), (Wendel, 1968), is rather a complex mathematical construct, with the basic details not 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 having been judged to be sufficient or not in investigations of accidents that have occurred". This then leads one to ask, "what is sufficient?" and unfortunately today's standards do not offer an explicit answer. The profession seems to be content with an implicit comparative criterion, whereby a Required Index R is put forward as an acceptance instrument (ultimately as "a" stability measure). However, this is offered without a clear explanation as to what is implied if the criterion is met, or in 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, (Vassalos, 2008), (Vassalos, 2012), which forms the basis for the flooding risk estimation in the EU-funded project FLARE, (FLARE, (2019-2022). However, the journey has been long, confidently addressing two major elements of the process, namely, on developing numerical tools, aiming at the improvement of damage stability/survivability, which enable the maritime community to better understand survivability as a function of time, as well as the ability for passengers to evacuate a ship in the time available when the ship is compromised, following a flooding incident. A good critical review on the first is provided in (Vassalos and Paterson, 2019) and, on the second, (Guarin et.al., 2014).

Notwithstanding the aforementioned developments, facilitating forensic examination of the flooding process, there are more serious implications when addressing the risk of flooding in passenger ships with the current framework, namely, it only addresses the flooding risk pertaining to collisions only. However, collisions are not the only hazard constituting the flooding risk for a ship, especially for passenger ships. For the latter, lack of due consideration at IMO for grounding (side and bottom) hazards over the past few decades, only catering for these through deterministic requirements, has shifted the flooding risk focus with side and bottom groundings now constituting the majority of the flooding risk for passenger ships. SOLAS is becoming less and less relevant and in need of urgent revision by adopting a more holistic regulatory framework accounting suitably for all pertinent hazards. Figure 1 from Project FLARE is indicative of the current situation with flooding hazards for passenger ships.

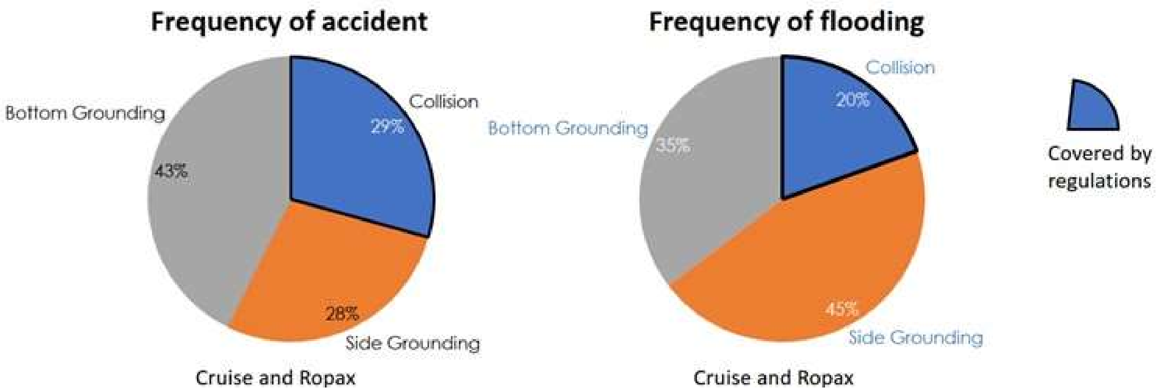


Figure 1. Recent statistics on the flooding risk of passenger ships, Project FLARE

Notwithstanding this, research on the topic of grounding hazards has not been dormant, with significant developments ranging from an accident database addressing all hazards (Mujeeb-Ahmed et al., 2021a) and leading to new damage breach distributions (Mujeeb-Ahmed et al., 2021b) as well as probabilistic damage stability calculations following a non-zonal approach for breach generation, e.g., (Zaraphonitis, et al., 2015) and (Bulian, et al., 2016) as well as calculations of all pertinent indices and their combination, based on the current IMO framework and accounting consistently for all hazards (Zaraphonitis, et al., 2017) and (Bulian, et al., 2020). Armed with this knowledge and accounting for recent developments in intact ship stability where a multi-level approach has been developed and adopted at IMO concerning second-generation intact stability criteria, (Francescutto, 2019), a multi-level approach flooding risk estimation has also been adopted in FLARE. Based on the same principles, a two-level approach has been formulated for damage stability, in this case considering flooding risk, with Level 1 comprising a semi-empirical approach deriving from the current SOLAS probabilistic framework, supplemented by accident statistics, and Level 2 based on using first-principles tools to enable a direct approach to flooding risk estimation, as detailed in the next section. Like the intact stability framework, Level 2 entails a more rigorous approach, hence the calculated Potential Loss of Life (PLL) should be less than in the simplified approach. This requirement forms one of the conditions in using such an approach.

THE FLARE FRAMEWORK FOR FLOODING RISK ASSESSMENT

The FLARE Framework is a methodology, or a process, for conducting a comprehensive and quantitative assessment of flooding, with consideration addressing the full lifecycle of the ship, namely from its design phase and its operational phase to the emergency response phase. The framework articulates its different elements and provides the flow of requisite information from one stage to the next, as indicated in Figures 2 and 3, and further explained in this section.

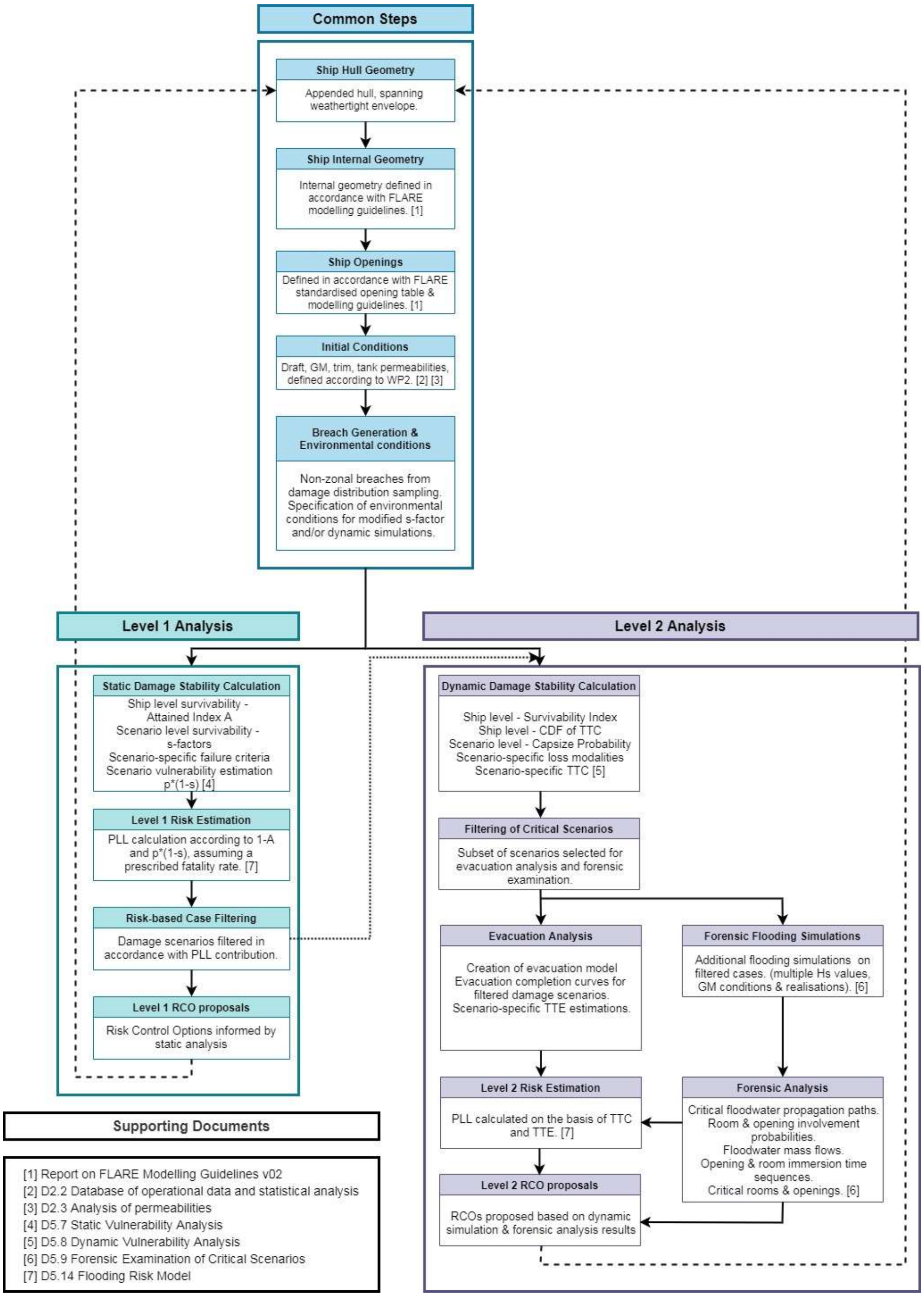


Figure 2: Diagrammatic Representation of the FLARE FRAMEWORK for flooding risk estimation (each stage is linked to specific deliverables of Project FLARE, as indicated in the lower left side of the figure, and provided in the REFERENCES chapter)

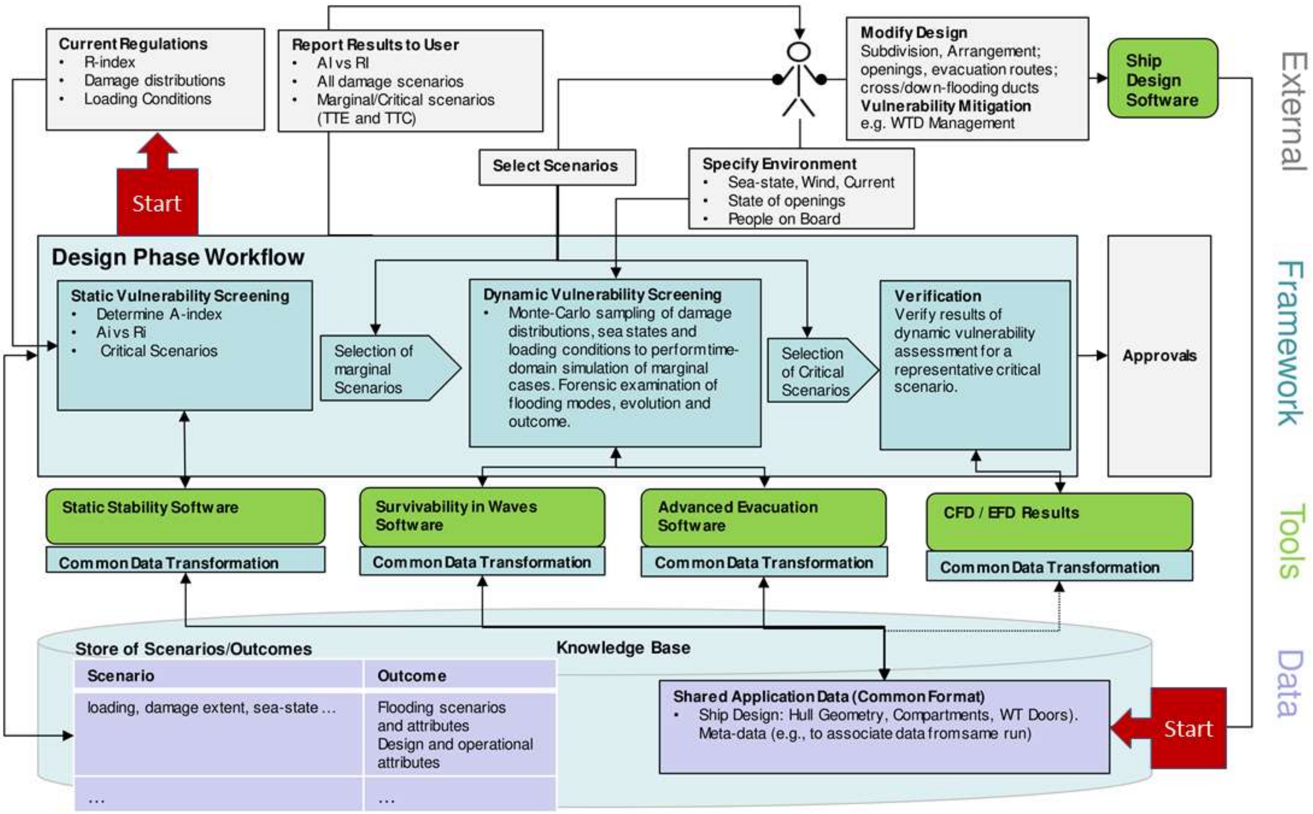


Figure 3. Overall architecture of the FLARE Framework

The FLARE Framework is a methodology for conducting a comprehensive and quantitative assessment of flooding over the vessel lifecycle, including design, operation, and emergency response phases. It involves using different software tools, catering for different determinants of flooding risk, at the different stages of the assessment process. It culminates in the identification of risk control options and quantitative risk measures (Vassalos et al, 2021). The overall architecture of the Framework is shown in Figure 3. The assessment process itself, with the various elements that the Framework links together comprise the following:

- **Software tools** used at the different stages of the process
- **Data** that the software tools operate on
- **Input** provided by the user of the Framework
- **Output** which is reported to the user

Software tools

The three pillars of the flooding risk assessment in the framework are three successive numerical analyses: static damage stability analysis, dynamic damage stability analysis, and evacuability analysis. Each of these offers a different insight into flooding risk and with an increasing degree of detail and information. Pertinent analyses can be carried out with a variety of software tools, and the Framework does not prescribe specific ones. The user of the Framework is free to carry out each analysis with the assessment program they normally use for this task, for instance:

- NAPA for the static analysis, (NAPA, 2021)
- PROTEUS for the dynamic analysis (Jasionowski, 2001)
- EVI for the evacuability analysis (Guarin, et al, 2014)

Data

The primary data used by the software tools relate to the geometrical models of the ship under investigation. These models are typically 3D models and data tables. They include the hull geometry model, the internal geometry models, and the tables of internal openings (for static dynamic stability assessment). Here, it is worth noting that the flooding risk assessment process in the FLARE Framework is not meant to be performed only once, but to be repeated on successive iterations of the geometrical design of the same ship. Each assessment should lead the user of the Framework to modify the geometrical design of the ship, based on identified risk control options until the risk is as low as reasonably practicable. It is worth noting that not all three numerical analyses must be conducted for all design datasets. This depends on which level of risk assessment is being pursued. For Level 1 alone, it is sufficient to perform an only static assessment to identify pertinent risk control options and proceed to the next design iteration. In that case, the corresponding design dataset would only possess static analysis results whilst a Level 2 assessment would involve static, dynamic, and evacuability analyses. Ultimately, the user of the Framework has discretion in the choice of analysis to carry out on a given design dataset. More specifically, in preparing the ship model for Levels 1 and 2 flooding risk estimation the following information is required as input:

- Hull Geometry: The ship hull geometry for both static and dynamic analysis, should be the appended hull modelled up to 3 decks above and including the bulkhead deck.
- Internal Geometry: The vessel internal geometry should be common to both static analysis and dynamic analysis. Modelling should include all features liable to impact the flooding process in a significant manner such as watertight (WT) structure, partial bulkheads, A-class divisions, lift trunks, escape trunks, stairwells, and cold room storage areas. In addition, necessary "virtual" subdivisions should be employed where necessary to support flooding simulations based on Bernoulli models. All the aforementioned should be conducted in line with the agreed-upon FLARE modelling guidelines.

Input

In addition to the data related to the geometrical design of the ship, the software tools require input data describing the damage cases involved in the analysis. A damage case, or damage scenario, is the set of input parameters for a particular numerical analysis, pertaining to the following:

- Internal Openings: One common table of openings should be produced in a standardised format, containing all pertinent information on the openings required for static and dynamic analysis. What differs here between each approach is the manner in which this information is used. Where the dynamic model will include all openings in their geometric form and with their assigned flow properties, the static analysis will require compartment connections, flooding stages and flooding phases that reflect the openings within the internal geometry, in addition to the definition of certain openings as a single point.
- Initial Conditions
  For both Level 1 and Level 2 risk estimation, initial conditions should be generated in accordance with the findings of FLARE deliverable D2.2. Here, relative to the SOLAS assumed draft range, for passenger ships, non-dimensional drafts at 0.45 and 0.75 should be considered under limiting GM conditions and weighted equally.
- Generation of breaches
  Breaches are to be generated through a sampling of pertinent damage distributions to create non-zonal damage scenarios. This should be conducted using a Monte Carlo sampling scheme or the Quasi-Monte Carlo sampling method proposed during FLARE to reduce the number of scenarios required in order to accurately reflect the underlying probability distributions (Mauro, F, 2021). Damage p-factors should be determined on the basis of the number of unique damage cases found within the damage sample and their frequency within the sample.

The above approach can be utilised for any or all the damage hazards, simply by considering the hazard-specific damage distributions (collision, side-grounding, bottom-grounding).

Output

The primary output of the software tools depends on the tools themselves, of course. The output generated by the software tools should include or make it possible to calculate quantitative measures of vulnerability to flooding, such as the Attained Subdivision Index, Static Analysis (A-index), the Attained Survivability Index, Dynamic Analysis (S-index), the list of critical openings, the distribution (A-Index) of loss modalities, and other important parameters such as Time To Capsize (TTC) and the Time To Evacuate (TTE), in each scenario (Vassalos and Paterson, 2019), leading to flooding risk estimation in terms of Potential Loss of Life at Levels 1 (Statistical/Semi-empirical Analysis) and Level 2 (Direct Approach, using first-principles tools) as explained later in the paper. These components in flooding risk estimation, will guide the user of the Framework to identify risk control options (RCOs) to contain and control flooding risk. In this respect, the assessment process should be repeated until the user is satisfied with a final ship design which renders flooding risk As Low As Reasonably Practicable (ALARP), Figure 5, (IMO MSC 72/16, 2000).

FLOODING RISK ESTIMATION – GENERAL CONCEPT

Pipeline of Developments

Even though implementation of developments in flooding risk estimation is not reflected directly in the IMO regulatory framework, they have been at the heart of evolutionary developments in flooding risk estimation with significant developments through EC-funded research involving industry and academia working together and making significant progress, which is currently culminating in having developed direct approaches for flooding risk estimation. The key research projects with related contributions and pipeline of development are listed next and demonstrated in Figure 4.

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

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

GOALDS (2009-2013): analysis of accident data for collision and grounding for passenger ships high-level risk model for flooding.

EMSA III (2013-2016): review of the risk model (including an 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): combination of collision, bottom and side grounding hazards based on EMSA III high-risk models; safety metric for combined collision and grounding (side and bottom) events.

FLARE (2019-2022): revision of high-level risk model, leading to a new structure; development of a new open accident database; revision of the frequencies for colleen and groundings.

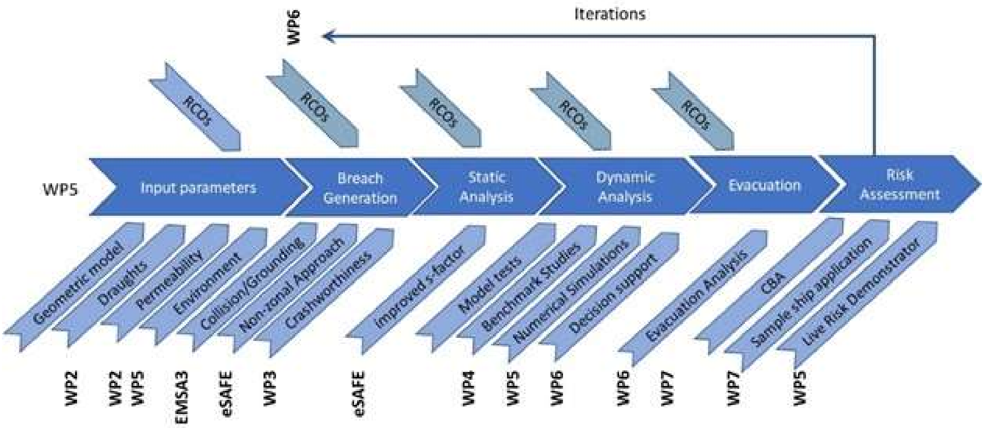


Figure 4: Pipeline of development in flooding risk estimation (Luhmann, et al., 2022)

Flooding Risk Estimation – FN Curves

A common way risk can be further evaluated and regulated against is by using some form of aggregate information, such as the expected number of fatalities, often referred to as the PLL. More specifically, by using so-called F-N diagrams, showing the relationship between the cumulative frequency of an accident and the expected number of fatalities. Such diagrams are often plotted relative to upper and lower bounds representing the limits of societal risk acceptance. These limits are determined as a function of the fatality rate relative to the economic importance of the activity in question (fatalities per billion $ turnover), as outlined within (IMO MSC72/16, 2000), Figure5 and demonstrated in Figure 6 for cruise ships, (IMO MSC85, 2009).

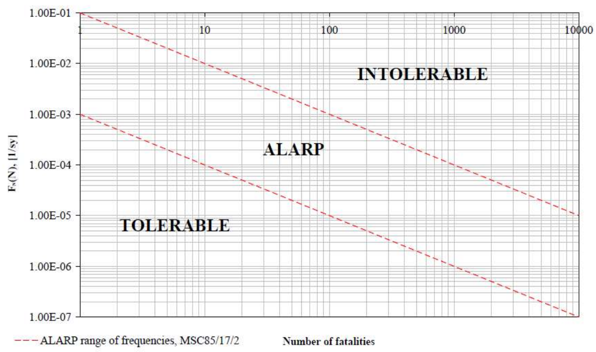


Figure 5: Societal Criteria (IMO MSC 72, 2006)

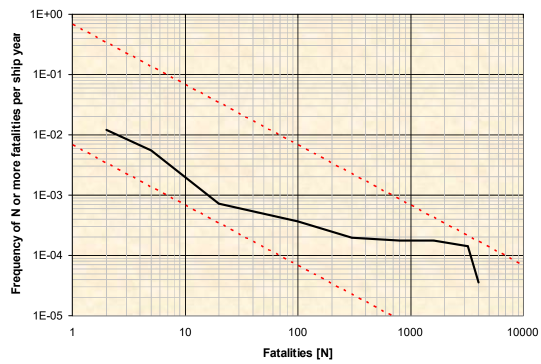


Figure 6: FSA Cruise Ships (IMO MSC 85, 2009)

Applying such criteria creates, three distinct zones are defined, as follows:

- Intolerable: Region where risk cannot be justified and must be reduced.
- ALARP: Region where risk must be reduced as low as reasonably practicable.
- Negligible: Region where risk is at an acceptable/tolerable level.

Considering Figure 5, there are two elements of the risk estimation that need to be addressed. One relates to estimating the risk of one ship or the population of this ship type, e.g., passenger ships, which by drawing from earlier practice at IMO, we refer to as the Attained PLL (PLL_A) whilst the risk level at the regulator level we refer to as the Required PLL (PLL_R). The key information that is needed to construct this curve is the number of people exposed to a particular hazard at scenario level, which is not considered in FLARE. This consideration can be addressed by accounting for POB seasonal variation to simplify the process and making it more amenable for practical applications, as explained later in the paper or, conservatively, considering the maximum allowable number of people onboard in all scenarios, an approach adopted in FLARE. In so doing, the result on an F-N diagram will be only a point.

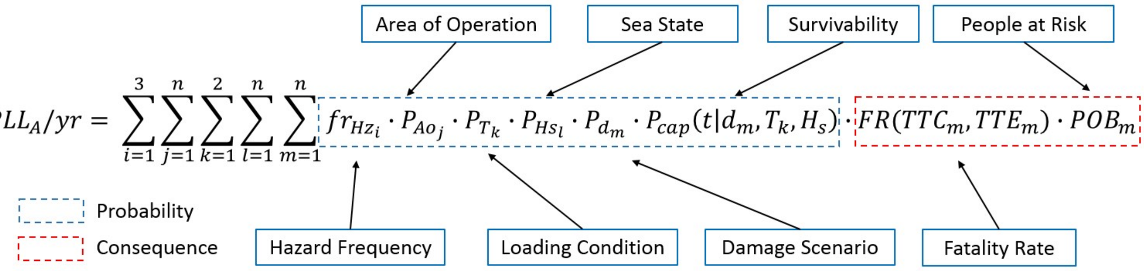
FLOODING RISK ESTIMATION - RISK MODELLING

Genial Considerations

A generalised way of considering flooding risk in the form of PLL_A is given in equations (2) and (3) next.

$$PLL = Probabilty \times Consequence \qquad (1)$$

$$PLL_A/yr = \sum_{i=1}^{3}\sum_{j=1}^{n}\sum_{k=1}^{2}\sum_{l=1}^{n}\sum_{m=1}^{n} fr_{Hz_i} \cdot P_{Ao_j} \cdot P_{T_k} \cdot P_{Hs_l} \cdot P_{d_m} \cdot P_{cap}(t|d_m, T_k, H_s) \cdot FR(TTC_m, TTE_m) \cdot POB_n$$



$$PLL_A/yr = \sum_{i=1}^{3}\sum_{j=1}^{n}\sum_{k=1}^{2}\sum_{l=1}^{n}\sum_{m=1}^{n} fr_{Hz_i} \cdot P_{Ao_j} \cdot P_{T_k} \cdot P_{Hs_l} \cdot P_{d_m} \cdot P_{cap}(t|d_m, T_k, H_s) \cdot FR(TTC_m, TTE_m) \cdot POB_m \qquad (2)$$

Where,

i	denotes hazard (1=collision, 2=side grounding, 3=bottom grounding from the accident database, FLARE Deliverable (D2.6, 2021)
j	denotes area of operation (e.g., open sea, restricted, port)
k	denotes loading condition for non-dimensional draft range values (T_1=0.45 and T_2=0.75)
l	denotes the 99th percentile of Hs subject to the area of operation
m	denotes a particular damage scenario up to the nth scenario of the sample
$FR(TTC_m, TTE_m)$	denotes Fatality Rate for each loss modality (transient, progressive, failure criteria, e.g., IMO/ITTC capsize criteria)
POB_m	denotes persons on board (people at risk) at each scenario
PPL_A/yr	denotes Attained Potential Loss of Life per year of exposure at each scenario; hence PLL_A for life cycle needs to account for years in service. In so doing, the annual variation of PLL needs to be accounted for.

For singular values of the variables i, j, k, l, m, (i.e., at scenario level) equation (2) becomes

$$PLL_A/yr = \ hazardfequency\ x\ breach\ frequency\ x\ capsize\ probability\ x\ fatality\ rate\ x\ people\ on\ board \qquad (3)$$

The process itself and the various terms depicted in Eq. (2) are expanded upon in the following. One observation here of particular importance, especially in deriving the FN curve for the ship in question, concerns the people onboard (POB). In the FLARE project, it is assumed that POB is constant for all scenarios and all years of service (exposure), which will lead to a conservative estimate of PLL. Further elaboration on this, is provided in the following.

Flooding Risk Estimation – Initial Parameters

<u>Sample ships</u>

The shipyards involved in the FLARE project made proposals for suitable designs of cruise ships and RoPax ferries and out of this set of possible designs, the sample ships shown in Table 1 have been selected.

Table 1. FLARE Project sample ships (D2.1, 2019)

Sample ship No	Type	GT	POB	Comment

1	Cruise	230,000	10,000	LNG-fuelled, S2020
2	Cruise	130,000	4,500	LNG-fuelled, S2020
3	Cruise	95,900	~3,700	S2009, updated to S2020
4	Cruise	41,000	~1,300	S2009, updated to S2020
5	Cruise	11,800	478	S2009, updated to S2020 (EMSA, 2015)
6	RoPax	28,500	2000	LNG-fuelled, S2020
7	RoPax	70,000	3700	S2009, updated to S2020 (GOALDS, 2016)
8	RoPax	50,000	2,800	S2009+SA, LNG-fuelled, updated to S2020
9	Cruise	69,490	2,800	SOLAS90
10	RoPax	36822	2,400	SOLAS90 + SA

Eight ships are designed to comply with the latest SOLAS amendments (SOLAS2020) and due to their size with Safe Return to Port (SRtP) requirements whilst ships 9 and 10 are designed to SOLAS90 requirements (the latter also complies with Stock Agreement). Four ships are designed with LNG as primary fuel, while two designs (ships 5 and 7) have been used in earlier research projects. This may allow a transparent view on the development of damage stability requirements from SOLAS2009 to SOLAS2020, offering a wider perspective, concerning the findings of research in the Project FLARE. Moreover, with this selection of ships, the fleet of cruise ships and RoPax ferries is well represented as shown in Figures 7 and 8, thus allowing for generalisation of the findings for use in, for example, in any Formal Safety Assessment (FSA) considerations.

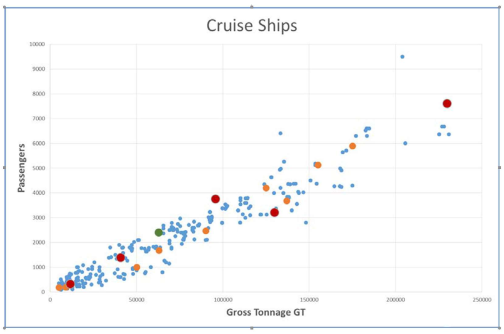


Figure 7: Sample cruise ships Vs world fleet

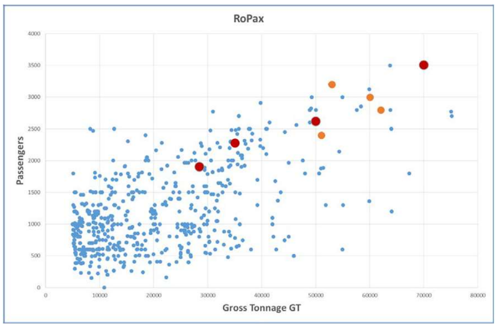


Figure 8: Sample RoPax Vs world fleet

Limiting GM~~, FLARE Deliverable (D7.1, 2022)~~

The FLARE GM limiting curve is obtained by keeping constant the GM for nondimensional draughts below 0.45 and above 0.75, Figure 9. This approach is in line with the Explanatory Notes of the current SOLAS, where also the extreme GM values are extrapolated horizontally for draughts outside the calculated draught range. Having said this, IMO is not the Gospel, as a more procedurally correct approach could be to consider GM values at A=R, since this is the guideline in the assessment of damage stability; GM is only one of the inputs.

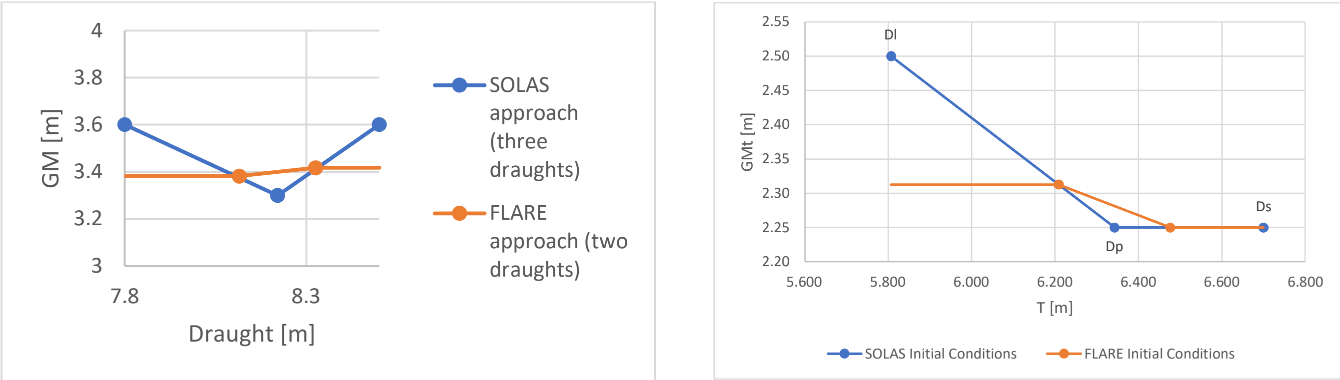


Figure 9: Example of GM limiting curve with new FLARE draughts (left, cruise ship; right, RoPax)

Permeability

Deriving from the FLARE Deliverable (D2.3, 2020), the figures shown in the last two columns of Table 2 are used for the permeability of the cruise ships.

Table 2: Permeability of cruise ships according to SOLAS and FLARE

Rooms	**SOLAS permeability**	**FLARE permeability T0.45**	**FLARE permeability T0.75**
Engine rooms	0.85	0.90	0.90
Auxiliary machinery spaces	0.95	0.90	0.90
Stores	0.60	0.90	0.90
Accommodation (cabin areas, galleys, offices, workshops) etc)	0.95	0.90	0.90
Public spaces, crew mess, corridors, staircases	0.95	0.95	0.95
Fuel Oil, LNG, Marine Gas Oil, Lube Oil, Potable Water, Wastewater, Technical water, Water ballast, Misc.	0.95	0.541	0.508
Heeling tanks	0.95	0.51	0.51
Void spaces	0.95	0.95	0.95

For RoPax, the SOLAS figures are used except for heeling tanks where 0.51 is used (Table 3).

Table 3: Permeability of Ro-pax ships according to SOLAS and FLARE

Rooms	**SOLAS permeability**	**FLARE permeability T0.45**	**FLARE permeability T0.75**
Engine rooms	0.85	0.90	0.90
Auxiliary machinery spaces	0.95	0.90	0.90
Stores	0.60	0.90	0.90
Accommodation (cabin areas, galleys, offices, workshops) etc)	0.95	0.90	0.90
Public spaces, crew mess, corridors, staircases	0.95	0.95	0.95
Fuel Oil, LNG, Marine Gas Oil, Lube Oil, Potable Water, Wastewater, Technical water, Water ballast, Misc.	0.95	0.95	0.95
Heeling tanks	0.95	0.51	0.51
Void spaces	0.95	0.95	0.95
Ro-Ro spaces	0.95-0.90	0.9125	0.90

Frequency estimation of a loss scenario

1. Hazard frequency: Ideally, this needs to be ship and area-specific as well as hazard-specific. In the absence of all the requisite information, we can take frequencies from the database pertaining to ship type and the hazard in question (collision, bottom grounding, side grounding), as shown in Table 4.

   Table 4. Hazard frequencies of RoPax, Cruise, and RoPax + Cruise, FLARE (D5.14, 2021)

	RoPax	**Cruise**	**RoPax + Cruise**

Hazard type	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	0.284
Total	5.38E-03	1.000	2.37E-03	1.000	4.33E-03	1.000

2. Scenario frequency: This is the frequency of a given scenario occurring, conditional on the hazard being addressed, as defined by the p-factor. The product of 1 and 2 gives the frequency of the loss scenario being considered.

PLL_A Level 1 Estimation

Consequence estimation of a loss scenario

As the expected number of fatalities depends on the time to capsize and static analysis does not account for time, some approximation is called for at this stage to estimate the fatality rate. This is conditional on fast or slow capsize and assumptions relating to the percentage of passengers lost. To simplify the methodology and to account for the dependencies between survivability and fatality rate, the following simplifying assumptions are made:

If s-factor < 1 → Fatality rate = 80% (4)

If s-factor = 1 → Fatality rate= 0% (5)

This simple and conservative approach is in line with the method used in the EMSA III Project for capsizing, for the development of SOLAS2020. Moreover, research in FLARE, as reported in FLARE Deliverable (D4.4, 2021), indicate that collated information from time-domain simulations on cruises and RoPax vessels provide some evidence in support of this assumption in that 80% of damage scenarios in a survivability assessment are transients in which case no time for evacuation is available (on average 5 minutes for RoPax and 10 minutes for Cruise ships).

Ship level PLL can be calculated by substituting scenario-specific 1-s values, with the compliment of the Attained Index as an estimation of the capsizing probability.

Main assumptions and considerations

Drawing from Section 2, and in particular Eq. (2), the following main assumptions are made in Level 1 risk estimation:

i	All hazards are considered (1=collision, 2=side grounding, 3=bottom grounding)
j	Only open sea is considered with Hs=4m
k	Two loading conditions are accounted for the non-dimensional draft range values (T_1=0.45 and T_2=0.75)
l	One seastate is accounted for with Hs =4m (the 99th percentile where collisions have taken place, as per SOLAS)
m	10,000 scenarios are considered, sampled from SOLAS distributions
$FR(s)$	Fatality Rate as a function of s-factor according to eq. (4) and eq. (5)
POB	Persons on board (people at risk) at each scenario, assumed conservatively to be constant, as provided in Table 2
$PLL_{A/yr}$	Attained Potential Loss of Life per year of exposure.

On the basis of the above, Eq. (2), now becomes:

$$PLL_{A/yr} = \sum_{i=1}^{3} \sum_{k=1}^{2} \sum_{m=1}^{10,000} fr_{Hz_i} \cdot P_{T_k} \cdot P_{d_m} \cdot (1 - s_m) \cdot FR(s) \cdot POB \quad (6)$$

Furthermore, with all the variables set to unit values, i.e., PLL per each hazard, loading condition and scenario, eq. (6) becomes,

$$PLL_{A/yr} = hazard\ frequency\ x\ scenario\ ferequency \times capsize\ probability \times\ fatality\ rate\ \times\ POB \quad (7)$$

Where,
- Hazard frequency is taken from Table 4

- Scenario frequency is the p-factor corresponding to the breach being examined (damage scenario)
- Capsize probability is the complement of the scenario s-factor, i.e., (1-s)
- EMSAIII breach distributions are used for side grounding/contact and bottom grounding (Zaraphonitis, et al., 2013)
- SOLAS breach distribution is used for collision, (Luhmann, H et al., 2018)
- Calculations by software NAPA rel.2020.2 (NAPA, 2020)
- Hazard frequency for RoPax + Cruise (Table 4).

Although direct comparisons may not be drawn between indices and risk, as discussed earlier, the combined Index for all hazards is also calculated, using frequencies from Table 1, and Eq. (8), as reported in FLARE Deliverable (D2.6, 2020).

$$FLARE\ Combined\ Index = 0.388\ A_{CL} + 0.328A_{GR-S} + 0.284A_{GR-} \quad (8)$$

Where,

A_{CL} is the FLARE Attained Index for collision
$A_{GR\text{-}S}$ is the FLARE Attained Index for side grounding
$A_{GR\text{-}B}$ is the FLARE Attained Index for bottom grounding

Having said this, it is important to highlight that this route should be seriously discouraged. If we are struggling to understand and convey the risk content of the A index, then a "soup" of indices will make progressively less sense. This is perhaps the reason why the hazard of grounding did not make inroad at IMO, as some people understood that this was not the right avenue for progress. More importantly, in the strife to consider grounding hazards at IMO, adding more indices to the current framework will foster continuation in the current state of affairs and undermine all the escort at FLARE to produce a meaningful framework to address flooding risk in a rational and practical manner with significant benefits to the industry as a whole.

Based on the aforementioned information and data, PLL_A Level 1 values are derived for all the sample ships as shown in Table 5 next.

Table 5: PLL_A Level 1 Risk Estimation for 10 FLARE Cruise/RoPax sample ships, FLARE Deliverable (D7.1, 2022)

Ship	**Ship 1**	**Ship 2**	**Ship 3**	**Ship 5**	**Ship 6**	**Ship 7**	**Ship 8**	**Ship 9**	**Ship 10**
Type	Cruise	Cruise	Cruise	Cruise	Ro-Pax	Ro-Pax	Ro-Pax	Cruise S90	Ro-Pax S90
POB	10000	4940	3750	478	2000	3500	2800	2074	2400
SOLAS 2020 R Index	0.9173	0.8935	0.8835	0.7323	0.8611	0.8811	0.8730	0.8624	0.8675
SOLAS A Index	0.9240	0.9067	0.9027	0.7436	0.8892	0.8948	0.8825	0.7691	0.8142
FLARE A_{CL}	0.9583	0.9508	0.9296	0.8043	0.9178	0.9144	0.8549	0.7781	0.8942
FLARE $A_{GR\text{-}S}$	0.9042	0.9309	0.8744	0.8681	0.9180	0.9768	0.8510	0.8683	0.9412
FLARE $A_{GR\text{-}B}$	0.9298	0.9394	0.9461	0.8978	0.9351	0.9656	0.9083	0.9396	0.9849
FLARE Combined Index	0.9324	0.9410	0.9162	0.8518	0.9228	0.9494	0.8688	0.8536	0.9354
PLL_A Level 1 (1/ship year)	**2.340**	**1.0091**	**1.0888**	**0.2454**	**0.5348**	**0.6132**	**1.2724**	**1.4204**	**0.5372**

PLL_A Level 2 Estimation

The key parameters for Level 2 flooding risk estimation are TTC (Time to Capsize) and TTE (Time to Evacuate), which are expanded upon in the following.

Time to Capsize (TTC), (Vassalos, D and Paterson, D, 2019)
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 (TTC). 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 or Quasi-Monte Carlo (Mauro, F, et. al., 2021)) sampling. Each damage scenario is then simulated using explicit dynamic flooding simulation, e.g., PROTEUS, aiming to identify potential loss scenarios, Figures 10 and 11.

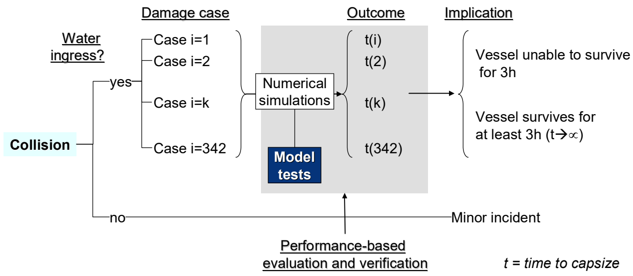


Figure 10. Monte Carlo simulation scheme – collision, (Vassalos, 2008)

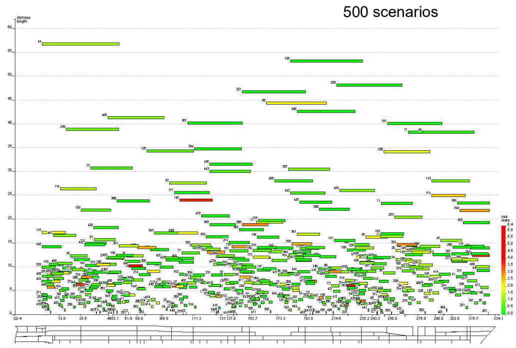


Figure 11. Monte Carlo simulation set up – collision, (Vassalos, 2008)

The results of the flooding simulations allow the vessel survivability to be determined, by considering 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 12 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, 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, accounting for statistical uncertainty (sampling error) and provides an upper and lower bound for the Survivability Index.

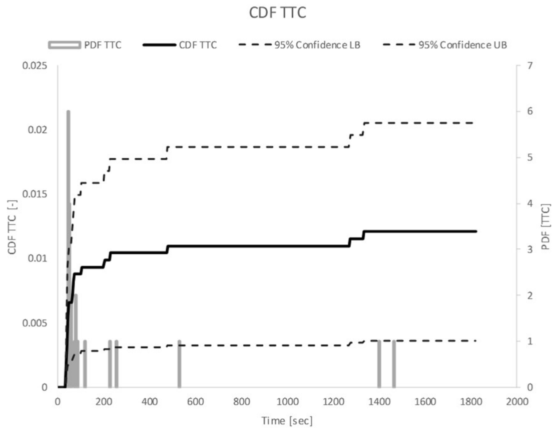


Figure 12. CDF for Time to Capsize

Considering the sampling process from a more mathematical (and hence rational) perspective, (Mauro, 2021) demonstrated that using a Randomised Quasi-Monte Carlo method, instead of Monte Carlo sampling of pertinent distributions ensures a faster convergence rate than the traditional Monte Carlo approach. Considering this in the case of application to damaged ship stability/survivability, a preliminary study, limited to Cruise RoPax bottom groundings, carried out for the non-zonal approach demonstrated that the sample size to achieve similar convergence to that achieved by Monte Carlo sampling can reduce the sample size tenfold. In simple terms, this method applies a weighted approach to sampling, which ensures that all the regions in the distribution are addressed with equal weights, including the extreme regions, hence capturing those scenarios of particular interest in addressing damage stability/survivability. What is important from the above description on sampling different distributions concerns sensitivity analysis, regarding PLL estimation, namely that unless we ensure that we capture the whole range of the distribution in question, any sensitivity analysis will be pointless as in the absence of any data in the extreme range of distribution, the result will be insensitive by default.

Time to Evacuate (TTE)
This relates to the time required for an orderly evacuation of passengers and crew in any given flooding emergency scenario, identified in the estimation for TTC (Vassalos et. al., 2021). For each loss scenario identified as described in the foregoing, evacuation simulation determines the time to evacuate (TTE). On this basis, Figure 13 illustrates the evaluation of the Potential Loss of Life through passenger evacuation advanced simulation tools, taking as input the Time To Capsize (TTC) deriving from flooding simulation analysis, as described above.

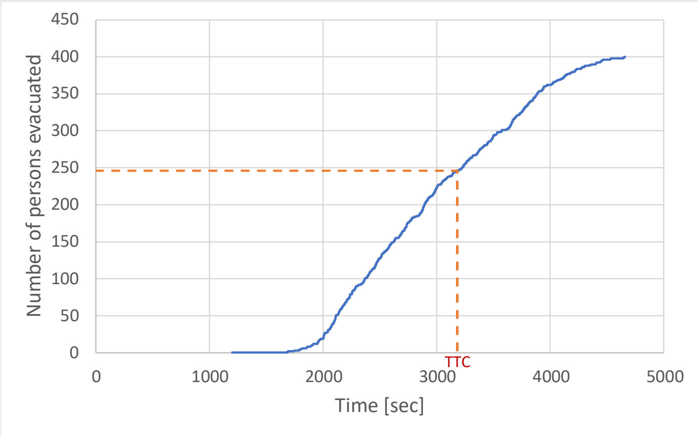


Figure 13. Level 2 consequence analysis of flooding loss scenario (PLL Level 2)

Calculating individual fatality probability (P_f):
The fatality probability (P_f) is conditional on the TTC and TTE. The fatality probability (P_f) can be calculated as the exceedance probability of TTE relative to TTC. To make this determination, we examine the TTE relative to the CDF of TTC, as shown in the example in Figure 14.

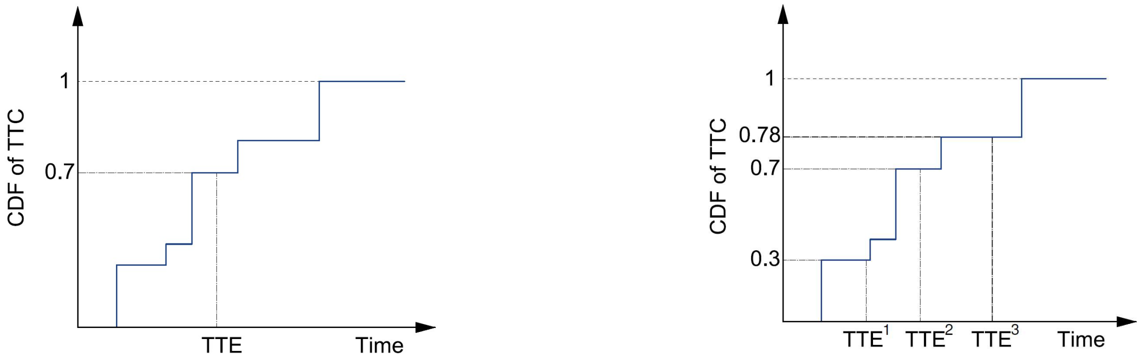


Figure 14: Calculating fatality probability based on TTC and TTE

In the above example (left), the estimated TTE exceeds the TTC 70% of the time, meaning that there is a 70% chance that the passenger is lost, i.e., $P_f = 0.7$. Therefore, adopting risk control options to increase TTE has a direct and significant impact on the risk estimation.

Moreover, in calculating PLL, though not directly represented in the formula for determining PLL, the relationship between these parameters dictates the fatality rate, which bears great influence on PLL. For example, if we consider a cruise vessel with a capacity of 5,000 persons, just 1% variation in the fatality rate could change the predicted casualty number by 50 persons. Traditionally, PLL has been determined on the basis of an assumed ratio of fast to slow sinking events, to which a further assumed fatality rate is applied. In (GOALDS, 2009-2012), this ratio was assumed to be 50% fast and 50% slow, with prescribed fatalities rates of 80% and 5% applied respectively. However, this is a considerable approximation given the importance that loss modality, and more specifically, time has on the fatality rate. By applying a blanket assumption to all passenger vessels, we fail to capture important risk information, such as:

- The differences between simple and complex internal ship environments, i.e., RoPax and cruise vessels.
- Ship-specific tendencies towards transient or progressive flooding loss.
- The impact of passenger capacity on evacuation time and subsequently the number of fatalities.
- The quality of a given vessel evacuation arrangement and LSAs.
- The manner and degree in which the floodwater evolution impairs evacuation.

In fact, recent studies would suggest that the ratio of transient to progressive flooding loss scenarios for cruise vessels is closer to 80%-20%, as opposed to the 50%-50% assumption made in the GOALDS risk model. On the surface, this might sound alarming, but we must remember that the residual risk is comprised of extreme damage scenarios, and this comes by virtue of increasingly safe designs. It, therefore, stands to reason that such scenarios would be severe in the outcome as we are dealing with the top 10%-15% worst-case scenarios. Furthermore, steps can be taken to improve upon the prescribed loss modality ratio and fatality rate values within existing flooding risk models. This can be achieved using flooding simulations coupled with evacuation analysis, the first of which allows the ratio of fast/slow sinking events to be determined directly and the latter allowing fatality rates to be calculated instead of assumed. While evacuation analysis of all capsize events would be a highly time-consuming endeavour, thus presenting difficulties from a practical perspective, it is possible to derive better estimates of the fatality rate by employing evacuation analysis in a targeted and sparing manner. The proposed approach is to select cases for further scrutiny under evacuation analysis by sampling cases across the range of TTC for a given vessel. Each of these cases will then result in a unique fatality rate, as shown in Figure 15(a). Linear regression can then be employed to derive a simple function describing the manner in which the fatality rate varies with respect to time. If this function is viewed relative to the CDF of TTC, appropriate fatality rate values for each loss scenario can then be calculated through interpolation of this function, see Figure 15(b).

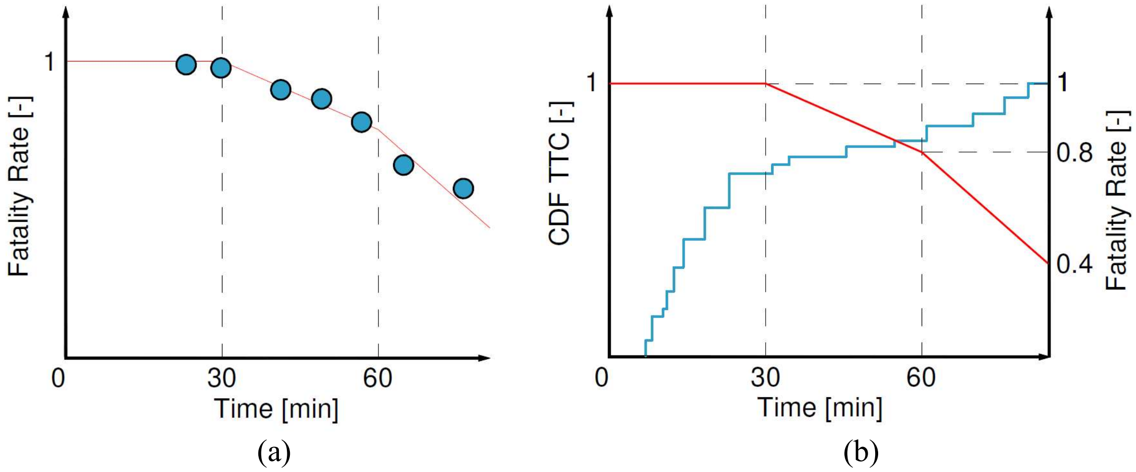


Figure 15. Level 2 consequence analysis of flooding loss scenario (PLL Level 2)

PLL$_A$ Level 2 formulation

Drawing from the above, and in particular Eq. (2), the following additional consideration is made in Level 2 risk estimation, concerning the number of damage scenarios and Fatality Rate:

m	1,000 scenarios are considered, sampled from SOLAS distributions
$FR(TTC_m, TTE_m)$	denotes Fatality Rate for each loss modality (transient, progressive and failure criteria, namely, IMO/ITTC capsize criteria), using time-domain simulations with PROTEUS to derive the TTC CDF, as described above, and EVI-based evacuation simulations to derive the TTE CDF, as described able and in FLARE Deliverable (D7.1, 2022). For the evacuation analysis, the IMO Circular 1455 is used for the evacuation analysis (IMO MSC, 2016)
s	The factor-s now denotes damage survivability in waves, as derived from time-domain simulations (Vassalos, D and Paterson, 2021)

On the basis of the above, Eq. (2), now becomes:

$$PLL_{A/yr} = \sum_{i=1}^{3} \sum_{k=1}^{2} \sum_{m=1}^{1,000} fr_{Hz_i} \cdot P_{T_k} \cdot P_{d_m} \cdot (1 - s_m) \cdot FR(TTC_m, TTE_m) \cdot POB \quad (9)$$

Furthermore, with all the variables set to unit values, i.e., PLL per each hazard, loading condition and scenario, eq. (9) attains the same form as Eq. (7).

PLL$_A$ Level 2 estimation

Only ships 9 and 10 have been subjected to evacuation analysis, thus allowing for PLL$_A$ Level 2 assessment. Results are shown in Table 6 and Table 7, put together for ease of making comparisons. Reference to PLL Level 2.1 pertains to a model in calculating fatality rates, using simplifying assumptions with reference to TTC, FLARE Deliverable (D7.1, 2022). The results clearly demonstrate that the multi-level PLL$_A$ methodology is consistent with the intention behind this methodology, namely adopting a more rigorous approach leads to a reduction in Level 2 PLL$_A$ estimation, in the absence of the simplifying assumptions adopted in Level 1, leads to a considerable reduction in PLL.

Table 6: PLL$_A$ Level 2 assessment for ship 9 (cruise ship)

Table 7: PLL$_A$ Level 2 assessment for ship 10 (RoPax)

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	6.209	6.477	6.209	6.477	6.209	6.477	
PLL L1 (1/ship year) (static assessment)	1.32E-01	2.09E-01	7.32E-02	8.71E-02	1.62E-02	1.95E-02	0.5372
	0.3412		0.1603		0.0357		
PLL L2.1 (1/ship year) (dynamic assessment)	1.21E-01	2.01E-01	3.35E-02	4.76E-02	4.22E-03	4.50E-03	0.4122
	0.3224		0.0811		0.0087		
PLL L2.1 vs L1 (variation percentage)	-5.5%		-49.4%		-75.6%		-23.3%
PLL L2.2 (1/ship year) (evacuation analysis)	**0.3222**		**0.0810**		**0.0086**		**0.4118**
PLL L2.2 vs L2.1 (variation percentage)	**-0.05%**		**-0.18%**		**-1.40%**		**-0.11%**

Damage Type	Collision		Side Grounding		Bottom Grounding		TOTAL
Frequency (1/ship-year)	1.68E-03		1.42E-03		1.23E-03		
Init condition	T0.45	T0.75	T0.45	T0.75	T0.45	T0.75	
Draught [m]	6.209	6.477	6.209	6.477	6.209	6.477	
PLL L1 (1/ship year) (static assessment)	1.32E-01	2.09E-01	7.32E-02	8.71E-02	1.62E-02	1.95E-02	0.5372
	0.3412		0.1603		0.0357		
PLL L2.1 (1/ship year) (dynamic assessment)	1.21E-01	2.01E-01	3.35E-02	4.76E-02	4.22E-03	4.50E-03	0.4122
	0.3224		0.0811		0.0087		
PLL L2.1 vs L1 (variation percentage)	-5.5%		-49.4%		-75.6%		-23.3%
PLL L2.2 (1/ship year) (evacuation analysis)	**0.3222**		**0.0810**		**0.0086**		**0.4118**
PLL L2.2 vs L2.1 (variation percentage)	**-0.05%**		**-0.18%**		**-1.40%**		**-0.11%**

Required PLL Estimation (PLL_R)

In line with earlier work (SAFEDOR, 2009), it was thought to be educational to use the work presented in this paper to derive FN curves as a means of further testing the multi-level flooding risk estimation in FLARE, in terms of the Attained PLL_A, through comparison with the Required PLL_R, the latter tested against the IMO Societal Criteria, as depicted in Figure 5. This will facilitate comparison with the level of the Required PLL (PLL_R) based on available societal criteria as well as test the consistency of the developed multi-level approach for flooding risk estimation Attained PLL (PLL_A). The outcome of this analysis is shown in Figure 16 (PLL Level 1) and Figure 17 (PLL Level 2) for FLARE sample ship 10, a medium-sized RoPax (SOLAS90 + Stockholm Agreement compliant) in the form of FN diagrams.

In Figure 16, the risk model has been informed by the results from a non-zonal hydrostatic damage stability assessment. This includes consideration of all hazard categories, namely collision, side-grounding and bottom grounding events. On the y-axis, the cumulative flooding event frequency is shown, based on individual damage case frequencies (Table 4), with the capsize probability determined as the compliment of the s-factor for all pertinent scenarios. On the x-axis, the number of fatalities relating to each flooding event is shown, calculated using the assumption that if the s-factor < 1 then fatality rate = 80%, or else the fatality rate=0%. The number of people on board, and thus persons at risk, has been determined by sampling a uniform distribution across a range relating to the maximum and minimum expected passenger occupancy. This is a simplistic assumption that has been made for the purposes of this demonstration, as in reality a distribution representative of the vessel operational profile should be employed for this purpose. The resultant FN curve shows that the majority of cases lie within the ALARP region, even though there is a significant number of cases in which the risk level lies within the intolerable region.

In the second figure, depicting results from Level 2 PLL assessment, the risk model has instead been informed by 1,000 flooding simulations, accounting again for collision, side-grounding, and bottom-grounding events. In this instance, the capsize probability has been determined in accordance with the simulation results and the fatality rate has been calculated with respect to TTC, as outlined in Eq.9. The resultant FN diagram shows that several cases lie within the intolerable region. However, they are significantly fewer in comparison to the Level 1 analysis. The reason for this comes from the simplified conservative assumptions made in static damage stability calculations, which were addressed when using more direct calculation methods such as flooding and evacuation simulations. Principle among these is the ability to account for time and thus TTC, which enables us to make a better informed and less conservative quantification of the fatality rate.

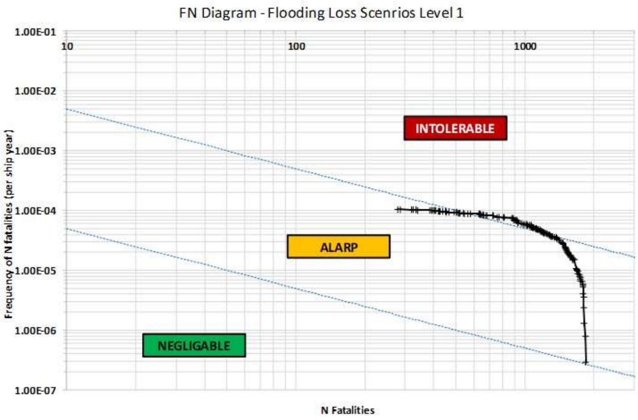


Figure 16: FN diagram resulting from PLL Level 1 analysis

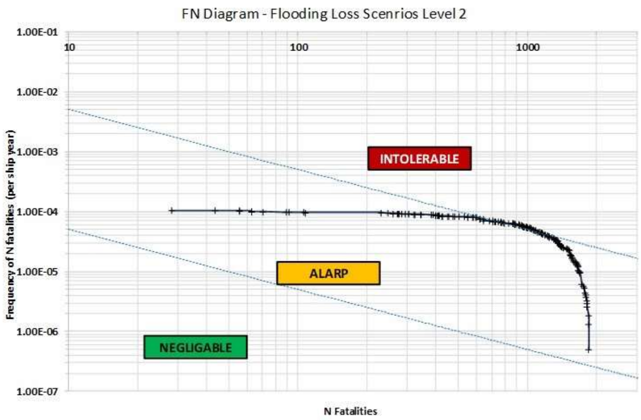


Figure 17: FN diagram resulting from PLL Level 2 analysis

CONCLUSIONS

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

- A monumental effort spanning over three decades, with major support by the European Commission in multi-million funded projects, has nurtured unprecedented collaboration between Industry, Government and Academia. This brought research teams together with varying insights, knowledge, and experience to help transform the landscape of maritime safety, especially passenger ships through the development of methods, tools, and processes to support safety enhancement through innovation, a key component of the passenger ship industry.
- Such developments are highlighted in the paper, providing a full landscape of maritime safety research and the impact brought to IMO regulations, design/shipbuilding, and passenger ship operators.
- Key among those is the effort in support of regulations at IMO, driving a shift from experiential to risk-inform regulations and rational decision making on safety matters in ship design and operation; Risk-Based Design, Operation, and Regulations.
- This effort culminated in Project FARE, with a focus on damage stability and flooding hazards, in a series of unique developments addressing current gaps at IMO (e.g., focus only on the hazard of collision) and paving the way for a new regulatory framework where all hazards are addressed as well as developing design and operational measures to contain, control and mitigate flooding risk with application to new and existing ships.
- To this end, deviating completely from the current practice at IMO of using Indices as measures of damage stability and passenger ship safety, a methodology has been developed in addressing directly flooding risk.
- The methodology has been applied to 10 sample ships, involving all major yards building passenger ships in Europe, to demonstrate that the developed methodology could readily be implemented in daily design work, following significant efforts by all parties involved, and that it leads to meaningful results in line with expectations, current knowledge, and best practice.
- This, of course, is the first step in the transformational process, being driven by Project FLARE. Engagement with the wider industry, Government and Academia are key for instigating and promoting the requisite cultural shift in maritime safety. An engagement process is already taking place through directly involving Administrations and Regulators in the process and through wider dissemination of the FLARE results.
- This paper is one of these building blocks.

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