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Modernisation of Domestic Ro-Ro Passenger Ships Operating in the Philippines

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ABSTRACT

This paper forms part of a wider study in the form of a Formal Safety Assessment of the domestic passenger ships operating in the Philippines, undertaken on behalf of the Philippines Government, and financed by the World Bank and the International Maritime Organisation. The paper focuses on design deficiencies of the domestic RoPax ships, primarily in damage stability. The process of ship selection for representation of the wider fleet risk assessment is explained, leading to one medium RoPax and one large RoPax, typical of some 500 of these ships, serving the open sea domestic trade in the Philippines. To this end, the selected designs have been subjected to a systematic process of damage stability and flooding risk analysis in order to identify design vulnerabilities, leading to risk estimation in the form of Potential Loss of Life. A number of risk control options have then been identified, enabling a thorough risk assessment and identification of cost-effective RCOs, as well as impact assessment, using IMO risk acceptance criteria as basis. Despite the poor state of the domestic Ro-Ro passenger vessels operating in the Philippines, many of these aged, badly retrofitted, poorly maintained, and operated, it has been possible to identify cost-effective design solutions to raise the damage stability (and safety) standard of these ships to international standards of newly designed ships; it seems an unprecedented achievement, but evidently true. This presents the Philippine Government and the owners of these vessels with a unique opportunity to upgrade their domestic fleet of RoPax vessels and showcase these against the best in the world. Because of the similarity in the approach, the selection of risk control options and the overall analysis adopted, only one of the typical RoPax vessels selected is presented in this paper.

KEY WORDS

Domestic Ro-Ro Passenger Ships; Damage Stability Failure; Flooding Risk; Cost-effective Risk Control Options

INTRODUCTION

One way of ensuring that action is taken before a disaster occurred is to use a process known as a Formal Safety Assessment (FSA, MSC-MEPC.2/Circ.12/Rev.2.). This has been described as "a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of IMO's options for reducing these risks.". Such options have invariably been extended to other stakeholders (Flags, Administrations, Class, Shipyards and Ship operators), aiming at identifying cost-effective solutions to improve the safety standards of existing ships and new buildings. As the nature of this undertaking is highly technical, it is vitally important that the proposed solutions in the form of recommendations are properly communicated to ensure that all stakeholders gain sufficient information at a level that is readily understood to support effective decision-making (Vassalos et al., 2022a). One way to achieve this is by comparing proposed changes with existing standards, targeting life-cycle implications (design, operation, emergencies) to enable a balance to be drawn between technical and operational issues, including the human element as well as between safety (Delta Risk) and cost (Delta cost) in the implementation of the proposed recommendations (Goerlandt, F. & Montewka, J., 2015, Puisa et al., 2021).
This paper focuses on describing the process of assessing the risk (Aven, 2012, 2022), as well as identifying and implementing cost-effective solutions for the design of new ships or for retrofitting existing ships (Vassalos et al., 2021,2022b) to achieve

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higher safety standards with focus on the highest risk contributor, as previously identified, namely inadequate damage stability and the ensuing risk to human life (Vassalos, 2012). To this end, following a ship selection process of representative ships from the whole fleet currently engaged in domestic voyages in the Philippines, three ships have been selected, namely (a) a small motor banca; (b) a medium-sized modern RoPax and (c) a large older design RoPax. In this paper, only the two latter categories are being addressed. The process of risk analysis and risk assessment is detailed, the latter providing a cost-benefit assessment to aid decision-making in the Risk Control Options (RCOs) selection, practical implementation, and impact.

ADOPTED METHODOLOGY FOR FLOODING RISK ESTIMATION

Survivability Assessment

The methodology adopted in the FSA Philippines project, has been tailored to cater for flooding risk estimation (using different risk metrics), pertinent to static assessment and statutory requirements, leading to risk-informed performance in relevant conditions and environments. This, in turn, facilitates the design and implementation of pertinent RCOs to prevent, mitigate and control flooding risk in domestic passenger ships and is comprised of eight distinct phases, as elaborated in the following and shown in Figure 1. The process begins by addressing damage stability assessment based upon conventional hydrostatic techniques (Bulian et al., 2016, Ruponen et al., 2019, Mauro & Vassalos, 2022). Such assessment is conducted in accordance with applicable IMO statutory instruments, which vary depending on vessel age, type, and size. When assessing new build vessels engaged in international voyage, this relates to the requirements of either SOLAS 2009 (IMO, 2009) or SOLAS 2020 (IMO, 2020), as applicable. This form of assessment enables a quantifiable baseline risk level to be established from which the impact of RCOs can then be measured and compared (Vassalos et al., 2022b). Unfortunately, a great deal of existing ships and domestic vessels are regulated based on older prescriptive regimes, with an implicit but not explicitly quantifiable safety level. This is by using the Index of Subdivision (A-Index) as the risk metric to facilitate comparisons in the attained "risk" level and for evaluation of various design options to enhance ship damage stability. This means that the choice of risk control options is somewhat shaped by the elements of assumption, generalisation and simplification that are commonplace within technical standards.

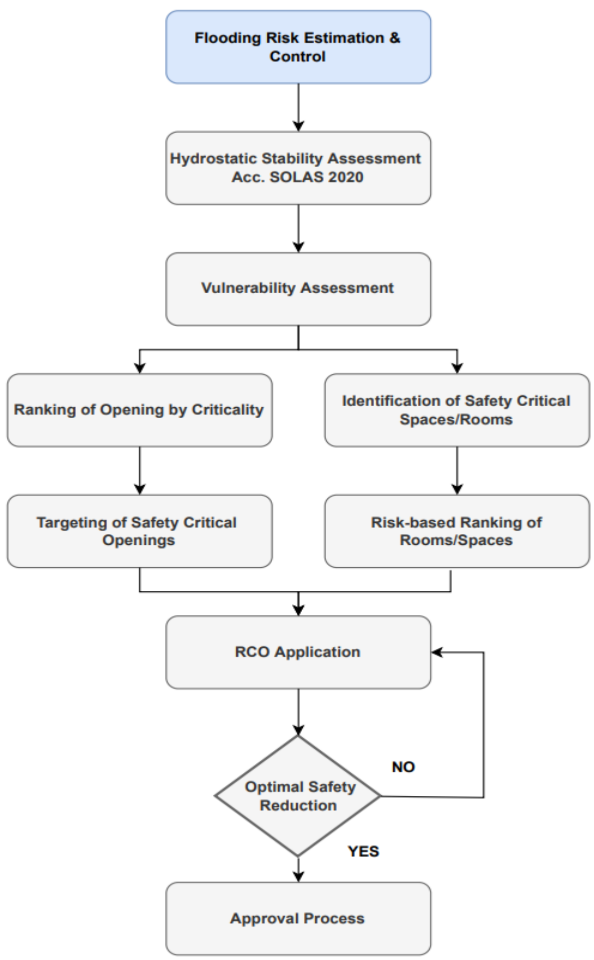

Figure 1: Methodology Adopted

Risk Assessment

Building upon the developments in risk models over the past 30 years, a generic risk quantification process and modelling is presented in this section, geared towards domestic passenger ships operating in the Philippines. In this respect, a generalised way of considering flooding risk in the form of Potential Loss of Life (pertinent to design evaluation; hence PLL Attamed, PLL_A) is given in equations [1] and [2], with a description in Figure 1.

$$PLL = Probabilty \times Consequence \quad [1]$$

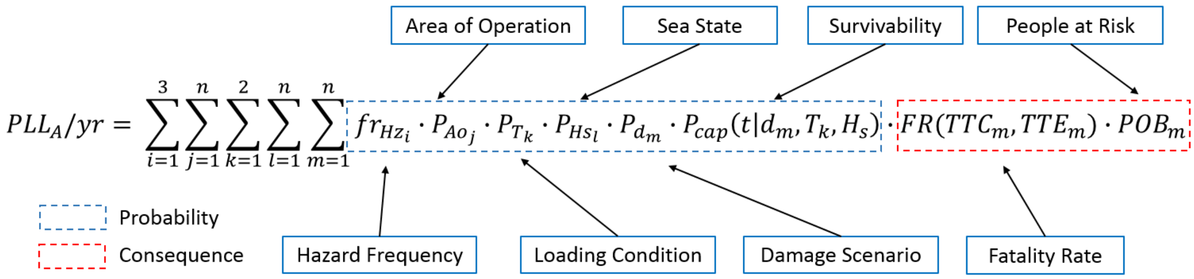

Figure 1: Description of Risk Estimation (PLL) Components

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

Where,

i	denotes hazard (1=collision, 2=side grounding, 3=bottom grounding from the accident database devethe undertaking of this project
j	denotes area of operation (e.g., open sea, restricted, port)
k	denotes loading condition for the 3 SOLAS drafts (D_L D_S D_P)
l	denotes the 99th percentile of Hs pertinent 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 Potential Loss of Life per year of exposure at each scenario; hence PLL for life cycle needs to account for years, duration in service and POB in each.

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

$$\frac{PLL_A}{yr} = hazardfequency\ xbreach\ frequency\ x\ capzize\ probability\ x\ fatality\ rate\ x\ PoB \quad [3]$$

The process itself and the various terms depicted in Eq. [2] are expanded upon in the following.

Flooding Risk Quantification – Input Data and Parameters

Sample ships – Initial ship data and preliminary analysis

The first item considered in analysing domestic passenger fleet data pertaining to the Philippines, has been to observe the fleet demographics in terms of ship type and age, as shown in Figure 3.

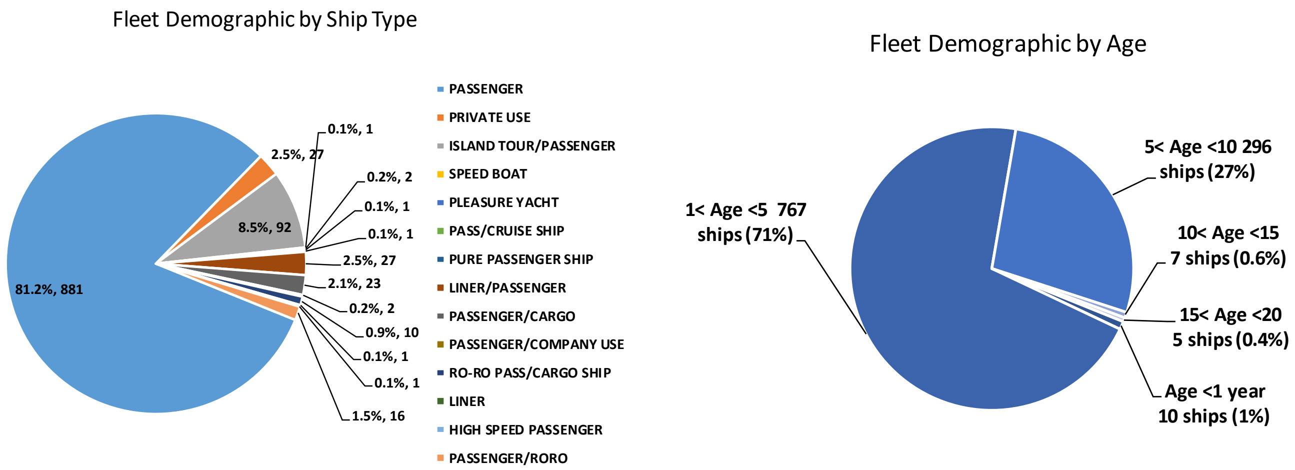

Figure 2: Ship Demographics by Ship Type and Ship Age

Here, the following key observations can be made:

- 93% of the fleet is less than 100 GT;
- 98% of the fleet is less than 1,000 GT;
- 37% of the fleet is less than 10 m length;
- 83% of the fleet is less than 20 m length.

In addition, the domestic passenger vessel fleet has also been analysed in terms of PAX capacity, Gross Tonnage and Length, as shown in Figure 3, Figure 4 and Figure 5.

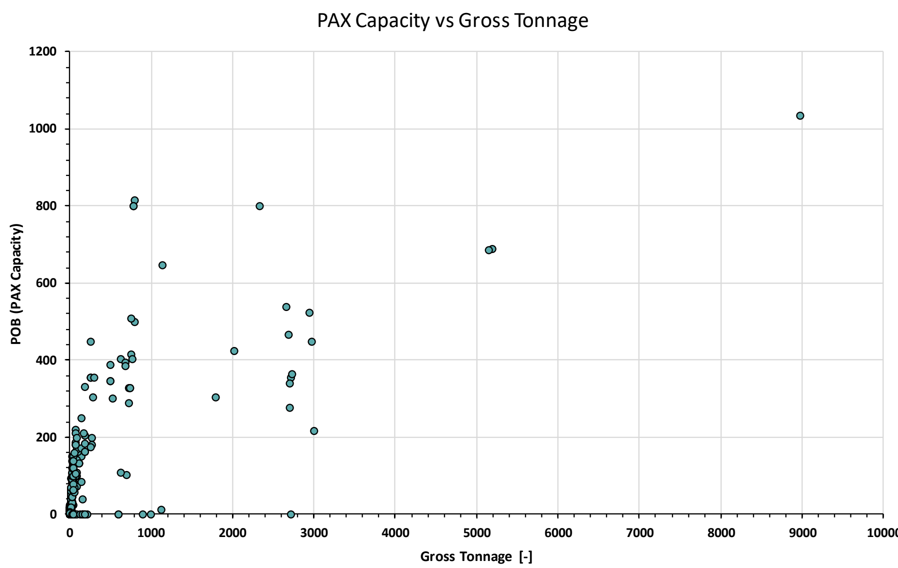

Figure 3: Fleet at Risk – PAX capacity Vs Gross Tonnage

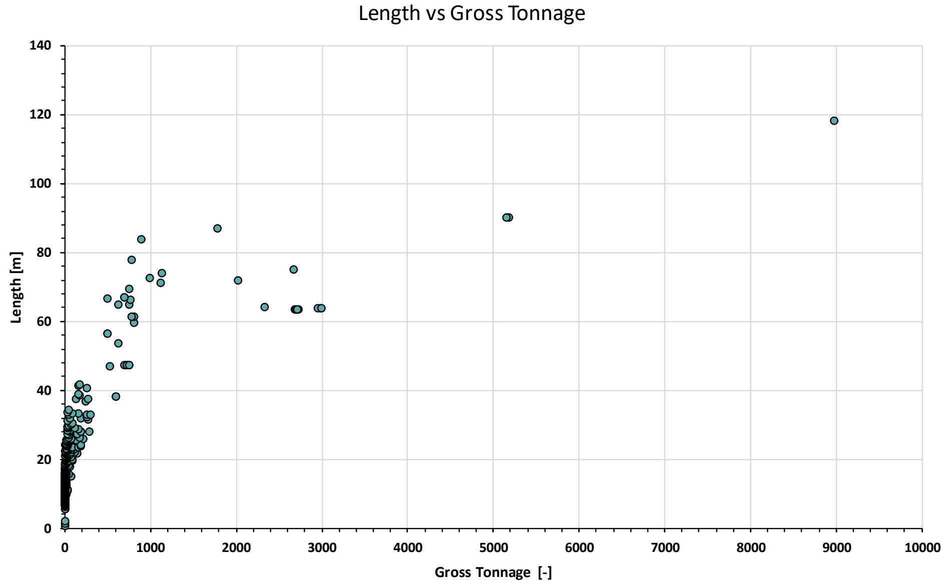

Figure 4: Fleet at Risk – Length Vs Gross Tonnage

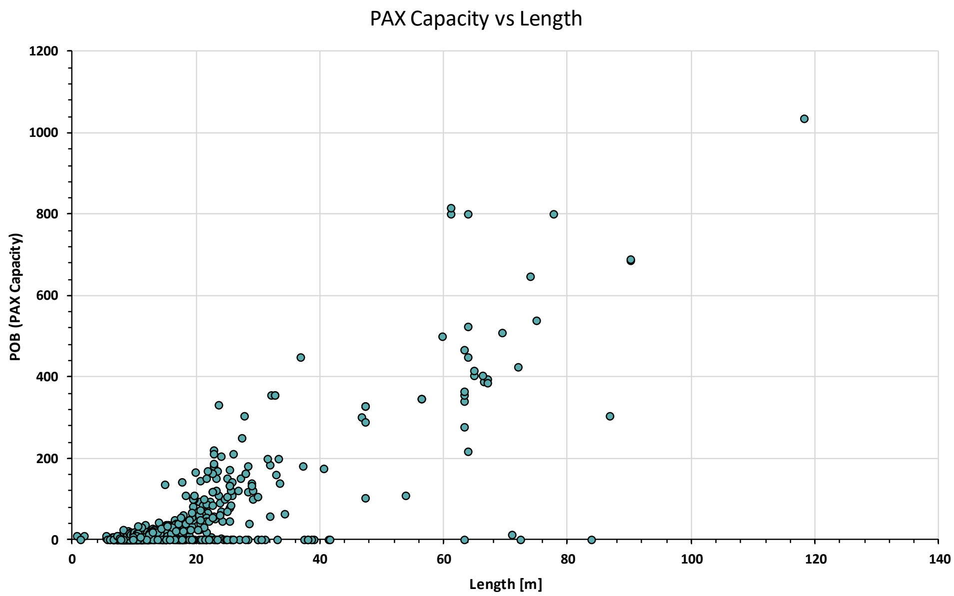

Figure 5: Fleet at Risk – Pax Capacity Vs Length

Sample ships selection

Figure 7 outlines the vessels selected for the FSA study, representing the full size-range, on the basis of which quantitative risk assessment will be undertaken, in particular damage stability calculations and risk analysis in the FSA study. The red markers in the figure are the ships selected in order to provide a representative picture of the whole range of vessels comprising the fleet at risk. This, in turn, supports the argument that a weighted (based on the number of ships in each of the four selected bands) risk evaluation will suitably represent the whole fleet at risk. However, it should be noted that the vessels selected have also been influenced by the availability of requisite information on the vessels to support calculations. Instead, the nearest representative vessels have been selected in such instances.

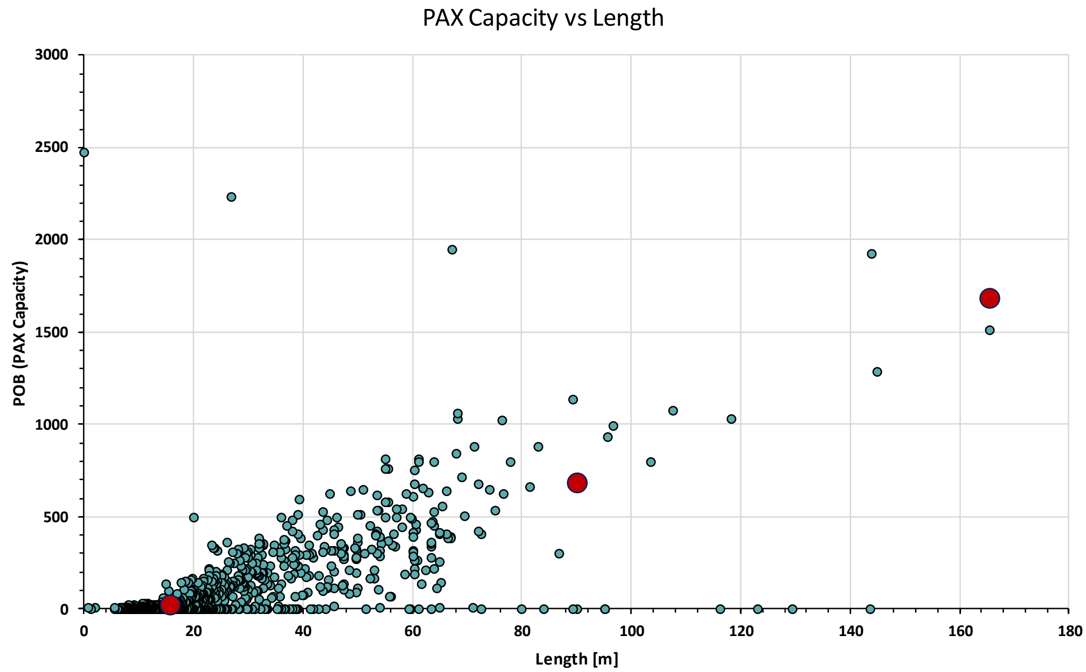

Figure 6: Vessel selection for the FSA study

Table 1: Representative ships and associated characteristics selected for the FSA study

Name	Service	Homeport	Registry	Build Yr.	Rig	Hull	Length	Breadth	GRT	PoB
Kate Alleson	Passenger	Surigao City	Surigao City	2019	MBCA	WOOD	15.75	1.24	3.86	24
Starlite Venus	Passenger	Batangas	Batangas	2020	MV	STEEL	90.11	16.3	1616	688
ST. Pope John Paul II	Passenger/Cargo	Manila	CEBU	1984	MV	STEEL	165.31	26.8	1931	1688

Frequency estimation of a loss scenario

1. Hazard frequency: 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 accident database, developed in the project purposely for the Philippines Domestic Passenger Ships, pertaining to each hazard in question (collision, bottom grounding, side grounding).

Table 2: Hazard frequencies for the domestic ferries in the Philippines (only collision has been considered)

Hazard type	**Domestic Ferries in the Philippines**	
	Frequency 1/ship year	
	Motor Banca	RoPax
Collision	4.55E-04	1.68E-03

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

PLL_A Quantification

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 to estimate the fatality rate. This is conditional on fast or slow capsize and assumptions relating to the percentage of People On Board (POB) lost. To simplify the methodology and to account for the dependencies between survivability and fatality rate, the following simplifying assumptions are made (based on work performed in Project FLARE), Eq. [4] and Eq. [5]:

If 0 < s-factor < 1 → Fatality rate = 5% [4]

If s-factor = 0 → Fatality rate= 80% [5]

This simple and conservative approach is in line with the method used in the EMSA III Project for capsizing and the development of SOLAS2020. Moreover, research in Project FLARE (Cardinale et al., 2022) indicated that collated information from time-domain simulations on cruise and RoPax vessels that the majority of damage scenarios in a survivability assessment are transient capsize cases, in which case no time for evacuation is available (on average 5 minutes for RoPax). In the absence of other evidence, it is assumed that for domestic ferries this value also applies.

Main assumptions and considerations

Drawing from Eq. [2], the following main assumptions are made for risk estimation:

i	Only collision is considered (1=collision)
j	Area of operation is considered with Hs=4 m, as per SOLAS
k	Three loading conditions are accounted for
$FR(s)$	Fatality Rate as a function of s-factor according to eq. [4] and eq. [5]
POB	Persons on board (people at risk) according for the operational profile of each selected vessel
$PLL_{A/yr}$	Attained Potential Loss of Life per year of exposure.

On the basis of the above, Eq. [2], with all the variables set to unit values, i.e., PLL for collision, per loading condition and scenario, becomes:

$$\frac{PLL_A}{yr} = hazardfequency\ x\ scenario\ frequency\ x\ capzize\ probability\ x\ fatality\ rate\ x\ PoB \qquad [7]$$

Where,

- Hazard frequency for domestic ferries in the Philippines (
- Table 2).
- 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)
- SOLAS breach distribution is used for collision.
- Calculations by software NAPA rel.2020.2

In the following sections, all three case studies are described in detail, including the initial damage stability evaluation, the process of implementing and measuring the impact of RCOs, and finally the approach adopted in judging the efficacy of each RCO.

CASE STUDY – MEDIUM SIZE ROPAX VESSEL

Vessel Principal Particulars

The following section details the vessel principal particulars, as outlined within
Table 3. Here, it is observed that the vessel is a moderately large Ro-Pax, with a length nearing 100 m and a capacity of 688 persons.

Table 3: Vessel Particulars

Property	Value
Length (O.A.)	97.78 m
Length (B.P.)	89.80 m
Breadth (MLD.)	16.30 m
Depth (MLD.)	9.90 m
Design Draft	4.90 m
GM	3.40 m
Deadweight	1094.89 ton
Passenger Capacity	688 persons
No. of Crew	50 persons

Coordinate System

A right-handed coordinate system has been used in defining the vessel stability model, as shown in Figure 7. The origin is located at frame #0, and locations in the ship are designated in accordance with a Cartesian coordinate system, where the axes are placed as follows:

- X-axis: longitudinal coordinate, positive in the direction of the bow, zero at frame #0,
- Y-axis: transverse coordinate, positive direction to port side, zero at the centre line,
- Z-axis: vertical coordinate, positive upwards, zero at the baseline.

In addition, trim is positive to stern and negative to bow.
The heeling angle is positive when the vessel heels to the port side.

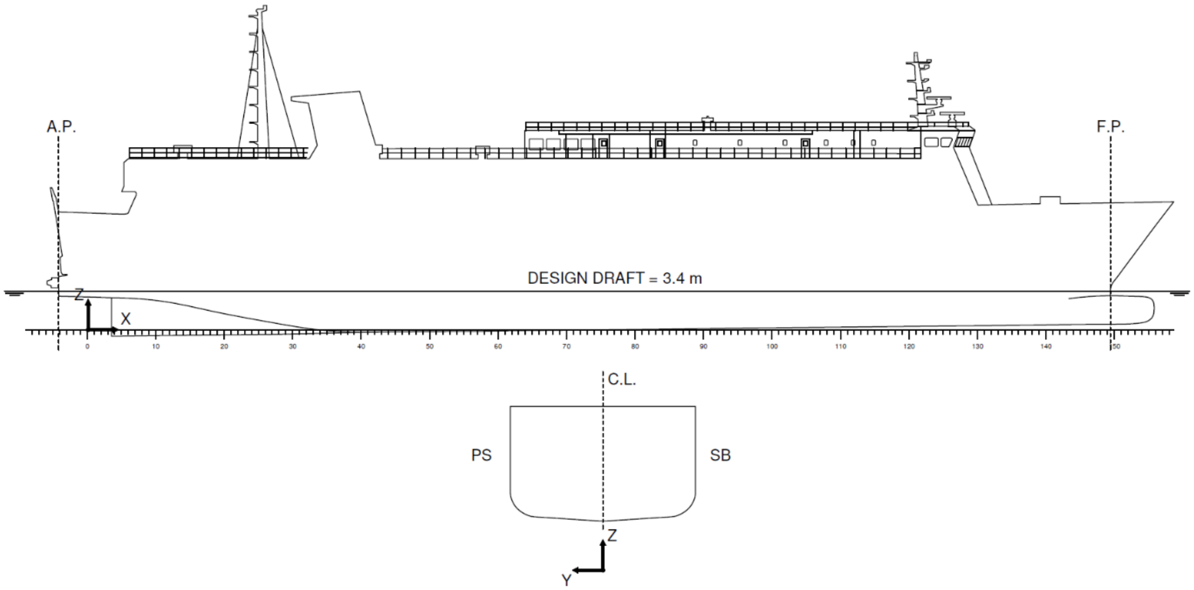

Figure 7: coordinate system

Stability Model

The ship model used in the damage stability calculations has been defined from the baseline up to, and including, the vessel ro-ro deck (9.9 m A.B.L.). In addition, one bow thruster has been reduced from the buoyant volume in the fore of the vessel. The resultant calculation sections of the model are shown in Figure 8 below, with the profile and body plan illustrated in Figure 9, and General Arrangement plan in Figure 10.

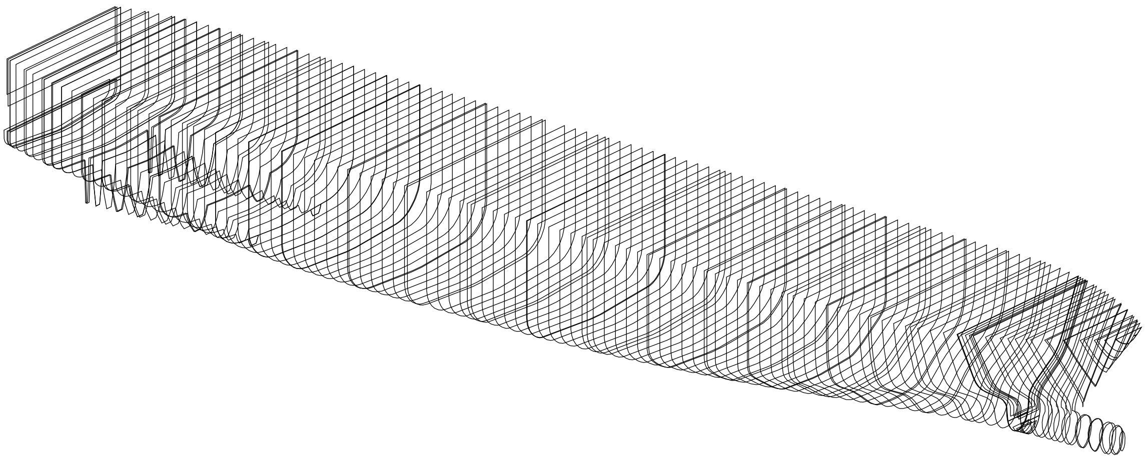

Figure 8: Stability Model Calculation Sections

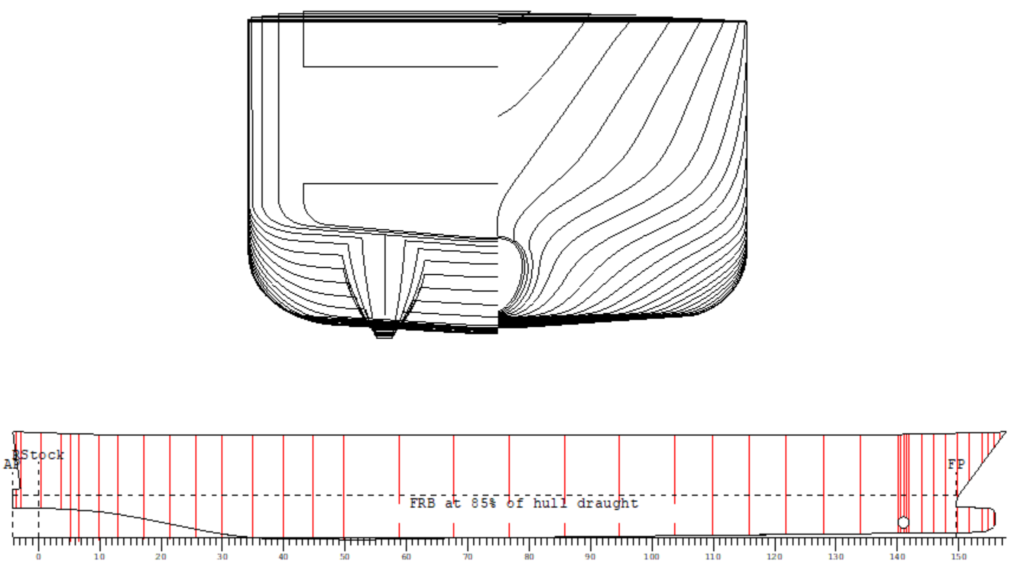

Figure 9: Stability Model Body Plan & Profile

Relevant Openings

When calculating the range of positive stability beyond the angle of equilibrium, the GZ curve has been truncated when an unprotected opening has been submerged. However, if an opening with a weathertight closing appliance has been temporarily submerged, it has had no effect on the range of positive stability. Instead, such openings are only accounted for if immersed in the final equilibrium floating position, resulting in s=0.

Subdivision Arrangement

In the calculation of the Attained Subdivision Index, the vessel subdivision has been discretised into 14 zones, Figure 11.

Permeabilities

The permeabilities used in the damage stability calculations are in accordance with the SOLAS 2020 prescribed values:

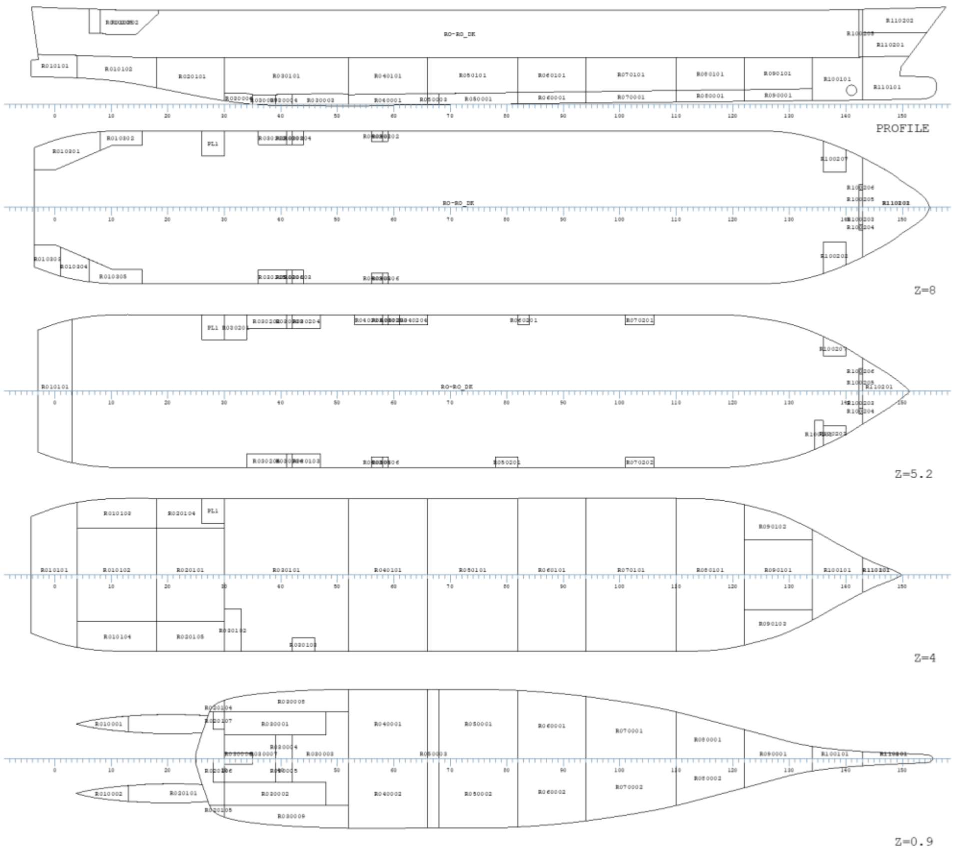

Figure 10: General Arrangement Plan

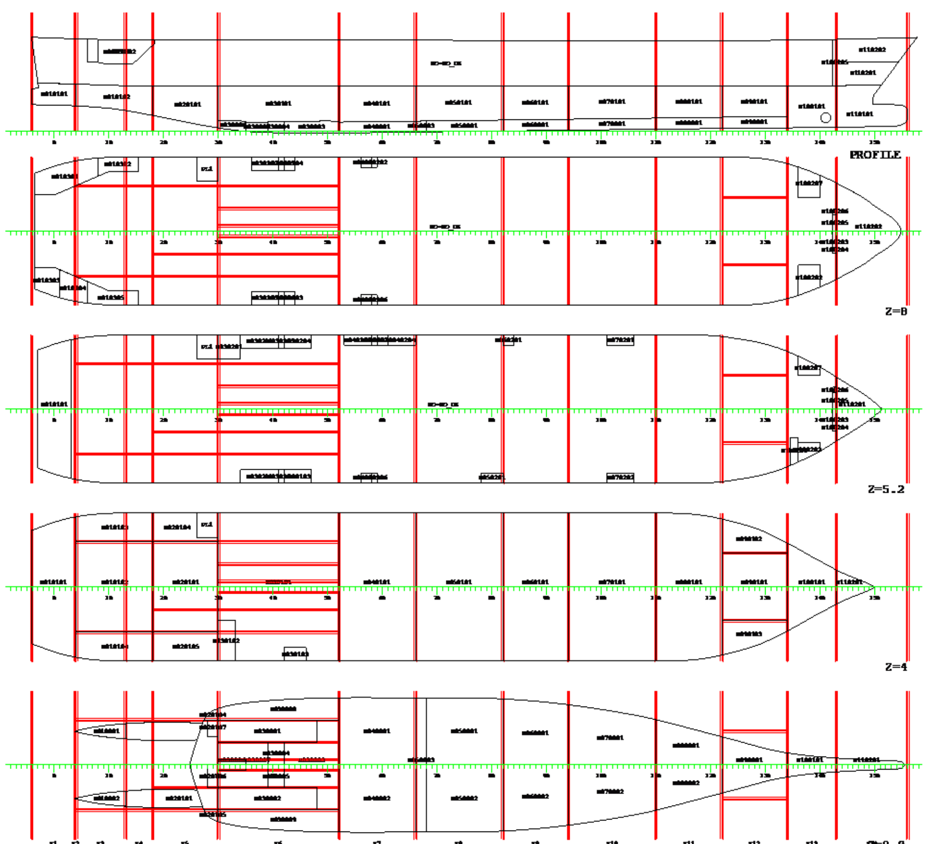

Figure 11: Subdivision Arrangement Plan

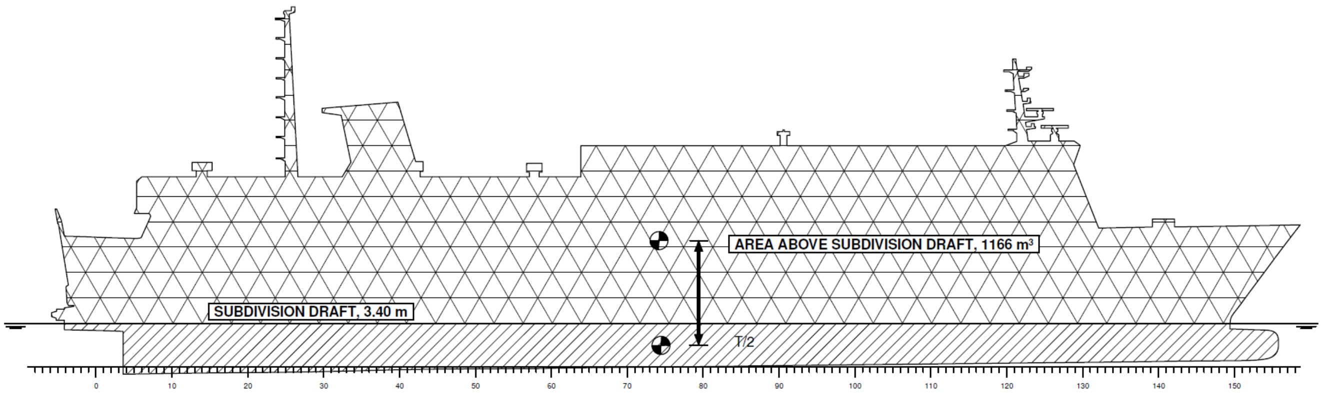

Figure 12: Wind Profile

Compartment Connections

As the vessel does not possess any A-class boundaries liable to inhibit floodwater equalisation, nor any cross-flooding arrangements, there are no damage cases flooded in stages.

Moments Due to Wind and Passenger Crowding

4.81 Wind-Induced Moment
The projected windage area of the vessel and corresponding moment lever are shown in Figure 12. The wind-induced heeling moment pertinent to damage stability calculations is estimated with the following formula:

$$\boldsymbol{M_{wind} = (P \cdot A \cdot Z)/9.806\ (tm)} \quad [8]$$

Where,
P = 120 (N/m^2)
A = Windage area (m^2), measured in accordance with the projected lateral area relating to each calculation draft.
Z = Distance from T/2 to the centroid of windage area (m)

Moment Resulting from Passenger Crowding

The moment resulting from passenger crowding has been calculated in accordance with the maximum number of persons onboard the vessel (738 persons). A conservative transverse lever of B/2 (8.15m) from the centreline has been assumed and the weight attributed to each passenger is 75 Kg.

Moment by crowding of passengers = 451.1 tm [9]

Initial Conditions

In accordance with Regulation 7, MSC.421(98), damage stability calculations shall be conducted with respect to three different drafts that define assumed upper and lower extremities of the vessel draft range, in addition to an intermediate condition. This includes the vessel deepest subdivision draft (3.41 m), the light service draft (2.89 m), and a partial subdivision draft determined by the following formula:

dp = dl+0.6(ds-dl) = 3.202* m [10]

The damage stability calculations are performed with a typical aft trim of -1.45 m for the light service draft and with zero trim (even keel) for the partial and deepest subdivision drafts. The draft, trim, intact GM and KG values applied in the calculations are summarised in Table 5. The assessment has been conducted under limiting GM conditions relating to Regulation 7 compliance, and hence the GM/KG values assigned to the calculation loading conditions, as detailed in Table 5, differ from those attributed to the statutory loading conditions of the vessel.

Table 4: Required Subdivision Index Acc. to MSC.421(98), Reg. 6

Persons on board	Required Index, R
N<400	R = 0.722
400 ≤ N ≤ 1,350	R = N/7,580 + 0.66923
1,350 < N ≤ 6,000	R = 0.0369 x Ln(N+89.048) + 0.579
N > 6,000	R = 1 – (852.5 + 0.03875 x N)/(N + 5,000)

Table 5: Attained Subdivision Index Calculation - Limiting GM

Initial Condition	T [m]	TR [m]	GM [m]	A/R	COEF	A*COEF
DL	2.890	-1.450	3.360	1.001	0.200	0.154
DP	3.202	0.000	3.195	1.021	0.400	0.313
DS	3.410	0.000	4.050	1.002	0.400	0.309
Attained Subdivision Index A						**0.775**
Required Subdivision Index R						**0.767**

Required Subdivision Index R

The vessel subdivision and damage stability performance are considered satisfactory when the Attained Subdivision Index A, as calculated in accordance with Regulation 7, is not less than the Required Subdivision Index, R. The details of this calculation are provided in Table 5, leading to a Required Index value of 0.767 for the vessel under assessment.

Attained Subdivision Index Calculation Under Limiting GM Conditions

Based on the assumptions outlined within the foregoing sections, the vessel Attained Subdivision Index has been calculated as summarised within
Table . Here, the Attained Index of the vessel has been optimised such that A=R for each of the calculation conditions, thus allowing limiting GM values to be derived.

Derivation of the Limiting GM Curve & GM Margins

Having optimised the Attained Subdivision Index in accordance with the requirements of SOLAS 2020, it has then been made possible to derive the limiting GM curve of the vessel. This represents the minimum required GM across the vessel draft range, such that statutory requirements are met. This is a significant design property as it dictates the boundary between safe and unsafe operation of the vessel. The results of this calculation are presented firstly within Figure 13. Here, plots of both the intact and damage stability limiting GM curves are shown relative to all statutory loading conditions, indicated as blue markers. Through examination of this diagram, a number of key observations can be made. Firstly, it is clear that the vessel limiting GM is dictated to a significant degree by the damage stability requirements according to SOLAS 2020. Secondly, by looking at the relative position of each loading condition to the limiting GM curve, it is clear that a number of conditions have notably low GM margins, with others failing to comply entirely (LD11 & LD9). This indicates that there is a requirement for improvements to be made in the vessel design in order to achieve compliance.

Vessel Risk Profile

A useful tool in identifying areas of heightened vulnerability within any vessel design, is to look upon the Risk Profile. This is a graph that maps collision risk across the vessel, allowing focus to be placed on those areas demonstrating the greatest vulnerability to flooding. Figure 14, shows the Risk Profile derived from the previously detailed calculations conducted under limiting GM conditions. Within the figure, collision risk is plotted along the vertical axis, and the damage centre is plotted along the horizontal axis. Differing damage lengths are distinguished by varying marker types, ranging up to four adjacent compartment damages.

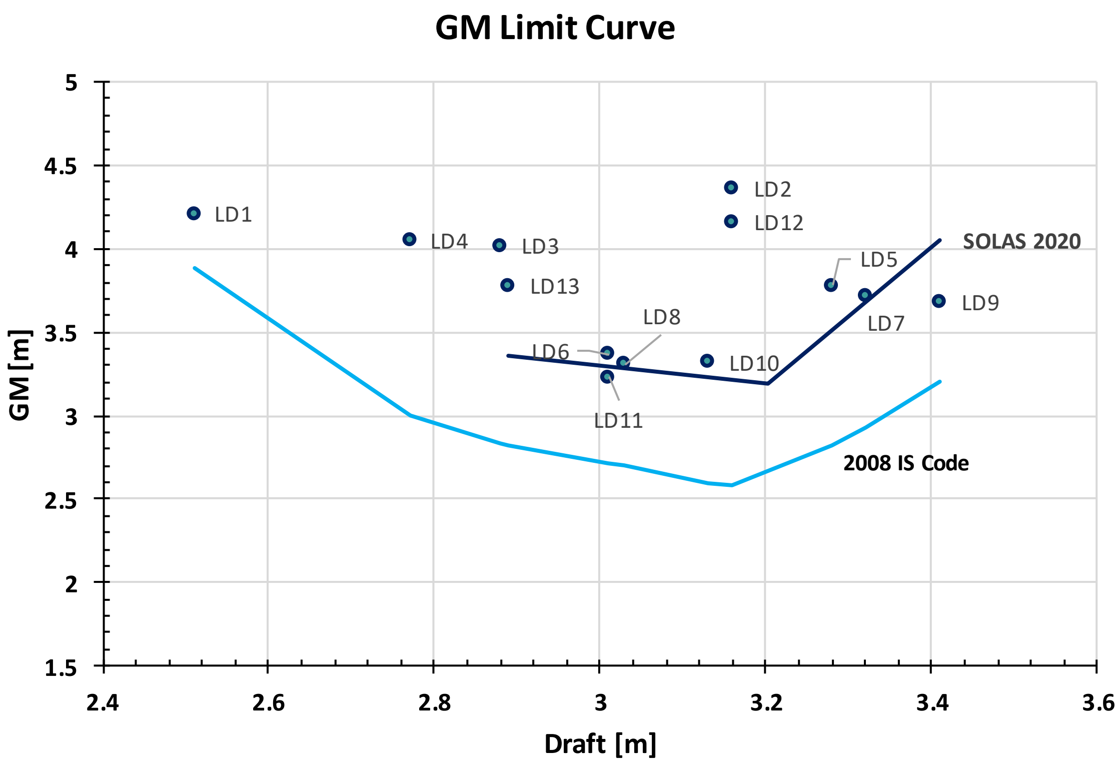

Figure 13: As-built Intact and Damage Limiting GM Curves

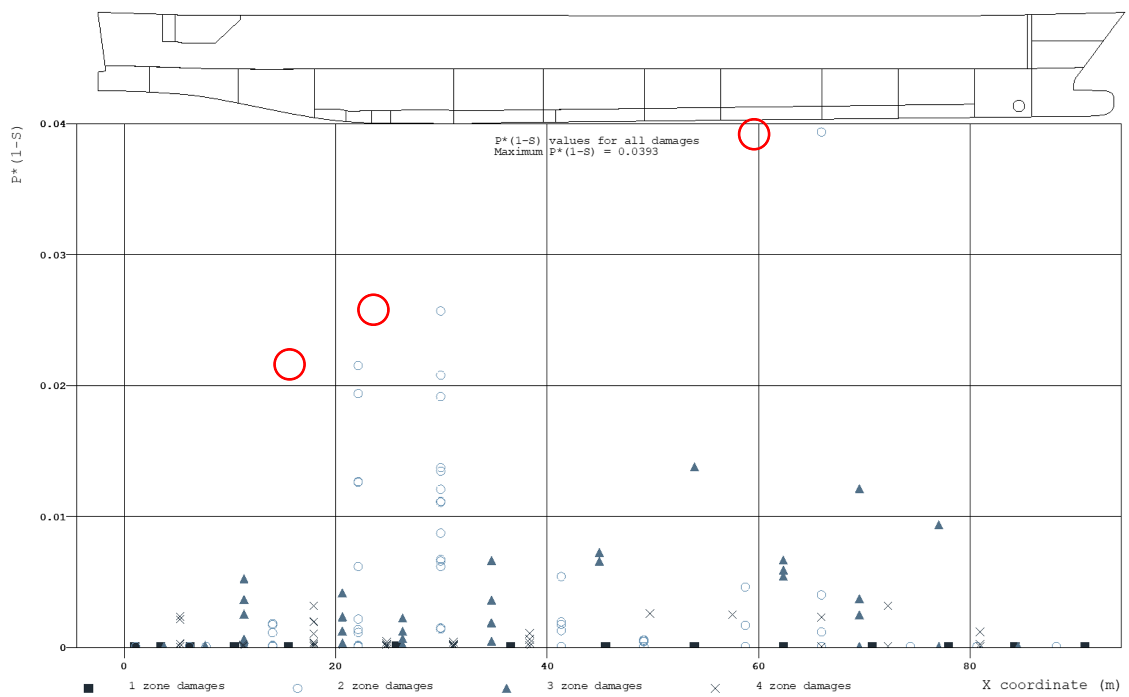

Figure 14: Vessel Risk Profile Under Limiting GM Conditions (High risk shown in red)

Observation of the Risk Profile indicates peak risk around the vessel fore shoulder, which is typical for RoPax vessels and, indeed, passenger ships in general. Heightened risk is also evident in damages affecting the two machinery spaces, located towards the aft shoulder of the vessel. In this location there is also a larger concentration of loss scenarios, meaning that the cumulative risk within this area will be significantly higher than that relating to any other part of the vessel. On the basis of these findings, the implementation of RCOs, as covered in the following sections, will target these areas. Through doing so, it can be ensured that the design receives help where it is needed most, whilst at the same time allowing risk to be reduced in the most efficient and thereby cost-effective manner.

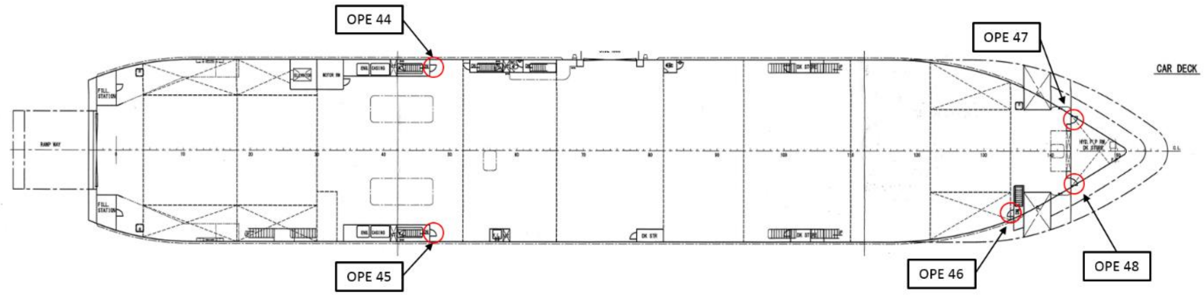

Figure 15: Critical Openings

Table 5: Attained Subdivision Index Calculation – As-Built Limiting GM Conditions + RCO 1

Initial Condition	T [m]	TR [m]	GM [m]	A/R	COEF	A*COEF
DL	2.890	-1.450	3.360	1.001	0.200	0.154
DP	3.202	0.000	3.195	1.033	0.400	0.317
DS	3.410	0.000	4.050	1.066	0.400	0.327
Attained Subdivision Index A						**0.797**
Required Subdivision Index R						**0.767**

RCO 1 – Critical Opening Protection

Description of RCO 1

On the basis of the results outlined within the foregoing, the first Risk Control Option explored has been to address critical openings identified within the vessel design. These are openings that have been found to adversely affect the magnitude of the Attained Subdivision Index, as a consequence of:

- Truncating the GZ curve, thus reducing GZ max,
- Truncating the GZ curve, thus reducing Range,
- Immersion in the final equilibrium condition, leading to a designation of $s_i = 0$

Details pertaining to each of those openings showing the highest risk can be seen in a plot of the openings in Figure 15 . Here, three of the openings (OPE 44, 45 & 46), represent non-watertight openings leading from the vessel ro-ro deck to spaces below the bulkhead deck. As such, this represents a particular downflooding risk in such cases where water accumulates on deck. Given that this is a significant hazard in the case of Ro-Pax vessels, this needs addressing. Furthermore, two openings leading to the fore hydraulic pump room have been identified as considerably impacting the vessel Attained Index.
The proposed solution to this problem is to uprate these doors to watertight status, using either hinged or sliding watertight doors. The impact of this design change has then been measured through re-calculating the vessel Attained Index, accounting for these modifications, the results of which are outlined in the following section.

Re-evaluation of Attained Subdivision Index

Table 5 outlines the results of the updated Attained Index calculations, conducted in light of uprating the watertight integrity of the openings described within the foregoing section. These calculations have been conducted with respect to the “as-built” limiting GM values of the vessel, as calculated previously, which provides a sound baseline from which to gauge improvement. The results demonstrate an impressive increase in the Attained Index from 0.775 to 0.797.

Re-evaluation of the Vessel Risk Profile

Once again, the vessel Risk Profile has been generated, this time accounting for the implementation of RCO 1. Here we can observe that the peak risk towards the vessel fore shoulder, having previously existed within the “as-built” condition, has now been eradicated. In addition, a number of high-risk cases towards the aft shoulder of the vessel have been mitigated. However, there still remain a number of high-risk scenarios situated around the vessel machinery spaces. This results from the fact that the majority of such cases are lost due to capsize and, as such, internal openings bear no significance on the outcome.

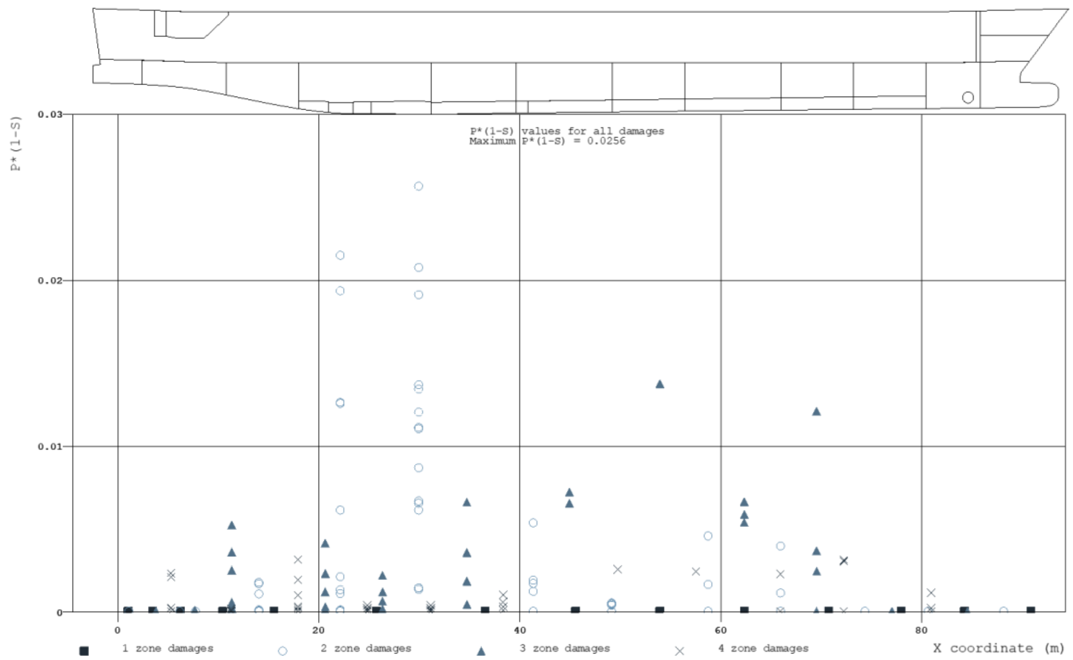

Figure 16: Vessel Risk Profile Under Limiting GM Conditions, with RCO 1 Applied

Table 6: Attained Subdivision Index Calculation - Limiting GM with RCO 1

Initial Condition	T [m]	TR [m]	GM [m]	A/R	COEF	A*COEF
DL	2.890	-1.450	3.355	1.000	0.200	0.153
DP	3.202	0.000	3.080	1.001	0.400	0.307
DS	3.410	0.000	3.440	1.002	0.400	0.307
Attained Subdivision Index A						**0.768**
Required Subdivision Index R						**0.767**

Derivation of the Limiting GM Curve & GM Margins

A further assessment has also been made in order to derive the updated limiting GM curve, thereby allowing the change in GM margins to be measured in light of the implemented RCO. The results of this process are provided in Table 6, including the limiting GM values.

Figure 17 contrasts the updated limiting GM curve to that of the existing vessel design. Here, it can be observed that a large improvement in limiting GM has been achieved, particularly towards the upper draft range. This is to be expected, as it is often deeper drafts having a tendency to suffer from lack of residual freeboard. As such, non-watertight openings pose a greater risk when the vessel is loaded to such conditions.

RCO 2 – Passive Foam Installations

Description of RCO 2

The second RCO considered has been the application of passive, high-expansion foam as a means of enhancing damage stability performance. This is achieved by strategically locating fixed-foam installations in vulnerable void spaces within the vessel design, resulting in a decrease in space permeability and leading to:

- A reduction in floodable volume, which preserves buoyancy, thus enhancing floatability, damaged freeboard, and reserve buoyancy.
- Enhanced stability in the form of increased damaged GM, as the foam installations increase waterplane area inertia and the metacentric radius.

The selected spaces for such applications are depicted in blue within Figure 18, and their location has been informed by the calculations pertaining to ship vulnerability.

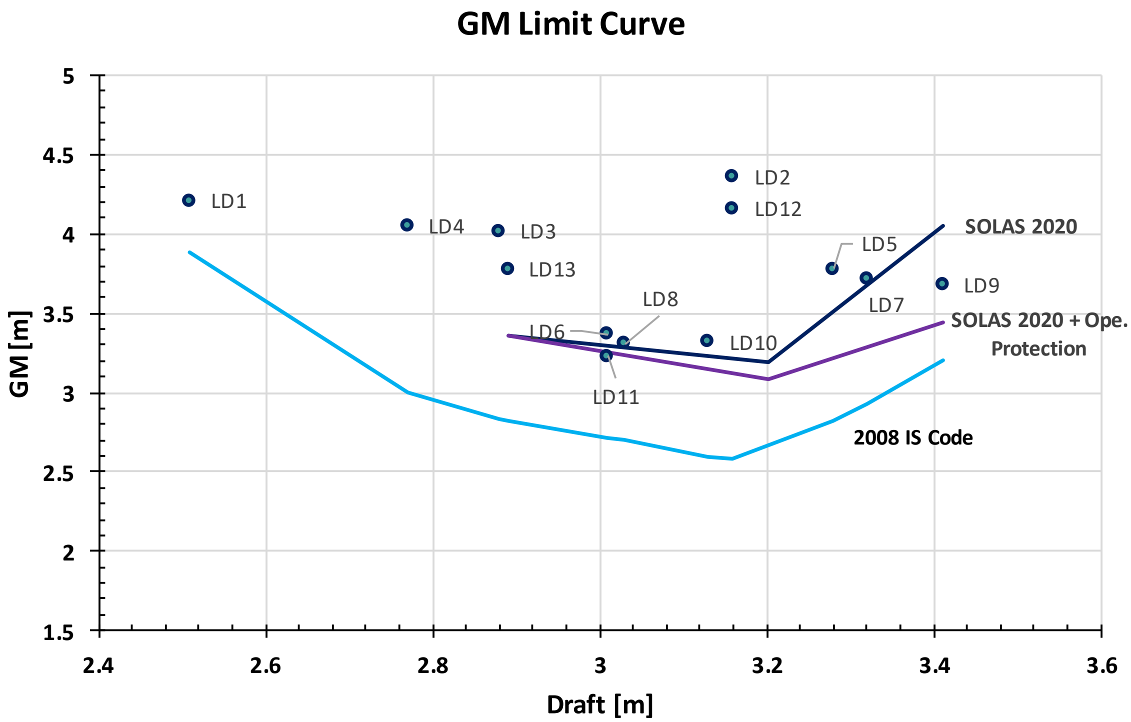

Figure 17: Intact and Damage Limiting GM curves comparison with RCO 1

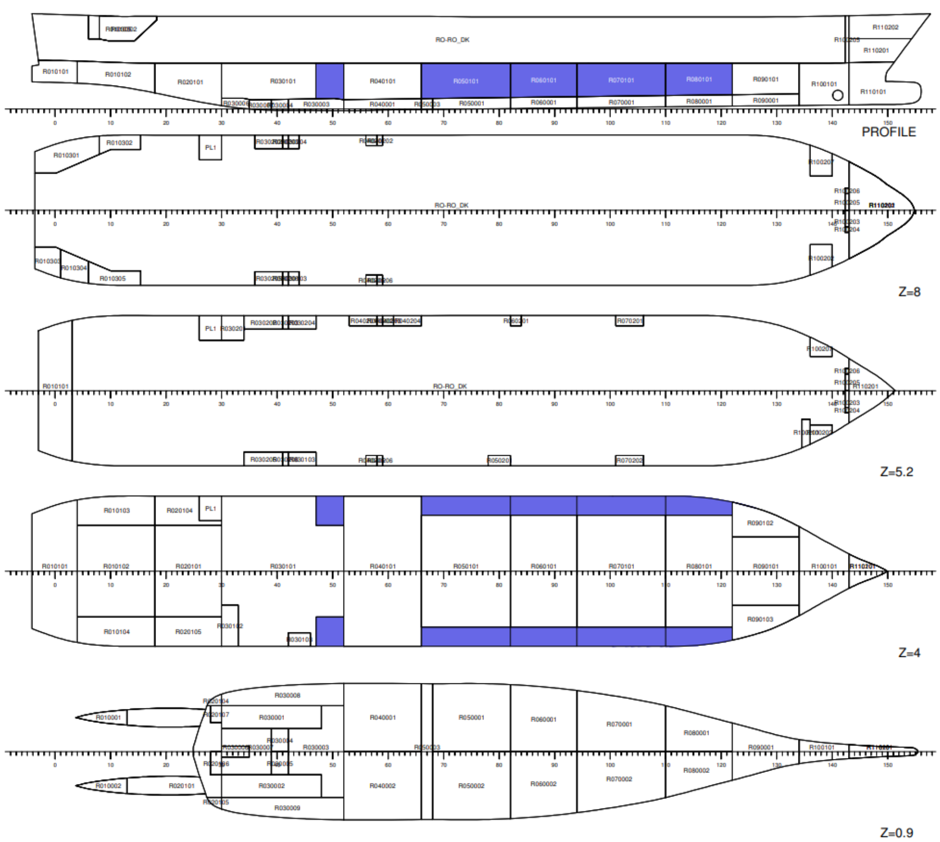

Figure 18: Spaces Subject to Foam Application (Shown in blue)

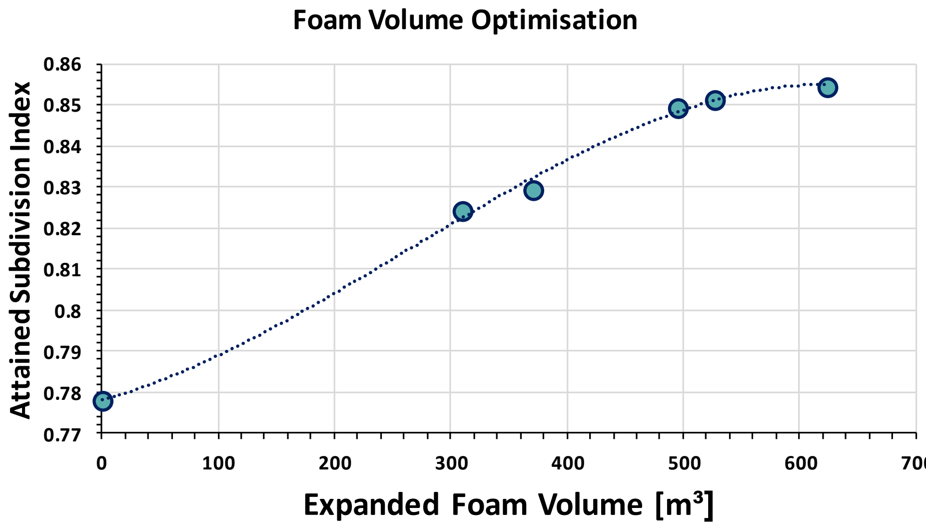

Figure 19: Foam Volume Sensitivity Analysis

Table 8: Foam Volume Vs. Attained Subdivision Index Value

A-Index	Foam Volume (m3)	Installation Weight (t)
0.8546	623.2	20.8
0.85142	**527.3**	**17.6**
0.84936	494.9	16.5
0.82934	370.8	12.4
0.82428	309.5	10.3
0.778 (As-built)	0.000	0.0

Table 9: Attained Subdivision Index Calculation with Passive Foam Installations (RCO 2)

Initial Condition	T [m]	TR [m]	GM [m]	A/R	COEF	A*COEF
DL	2.89	-1.45	3.36	1.064	0.2	0.1631
DP	3.202	0	3.195	1.087	0.4	0.3333
DS	3.41	0	4.05	1.083	0.4	0.8301
Attained Subdivision Index A						**0.829**
Required Subdivision Index R						**0.767**

Optimisation of Foam Volume

Having identified those spaces, which would be best served by passive foam protection, an optimisation process has been undertaken to determine the foam volume to be applied. This approach involves calculating the vessel Attained Subdivision Index for a series of incremental values of foam volume. This, in turn, allows the optimum foam volume to be determined as the point of diminishing returns in the relationship between the Attained Index and the volume of foam utilised.
The results of this process are outlined in Figure 19 in graphical form and within
Table in numerical form. Here, it can be observed that the optimal foam volume lies at approximately 500 m^3, leading to an installation weight of approximately 17 tonnes.

Re-evaluation of Attained Subdivision Index

Having identified the optimum foam volume solution, the damage stability performance of the vessel has been re-evaluated. Calculations have firstly been conducted with only the foam solution (RCO 2) in place, leading to the results presented within Table . Furthermore, an additional calculation has been conducted with consideration of opening protection (RCO 1) and foam protection (RCO 2) implemented simultaneously. Through doing so, it has been possible to measure the combined impact of both RCOs, as detailed within
Table . Quite remarkably, the results of this process show that with the foam solution in place the vessel has achieved an Attained Index of 0.829. Moreover, it has been possible to further raise the Attained Index to 0.850 when utilising both RCOs.

This indicates that the RCOs have been highly effective at reducing flooding risk, to the extent at which the damage stability performance of the vessel is now comparable with any modern RoPax operating today.

Table 10: Attained Subdivision Index Calculation with Opening Protection and Passive Foam Installations (RCOs 1 & 2)

Initial Condition	T [m]	TR [m]	GM [m]	A/R	COEF	A*COEF
DL	2.890	-1.450	3.360	1.102	0.200	0.169
DP	3.202	0.000	3.195	1.117	0.400	0.343
DS	3.410	0.000	4.050	1.100	0.400	0.337
Attained Subdivision Index A						**0.850**
Required Subdivision Index R						**0.767**

Table 11: Limiting GM Calculation - RCO 2

Initial Condition	T [m]	TR [m]	GM [m]	A/R	COEF	A*COEF
DL	2.89	-1.45	2.85	1.003	0.2	0.158
DP	3.202	0	2.56	1.001	0.4	0.307
DS	3.41	0	3.1	1.002	0.4	0.307
Attained Subdivision Index A						**0.768**
Required Subdivision Index R						**0.767**

Table 12: Limiting GM Calculation - RCOs 1 & 2

Initial Condition	T [m]	TR [m]	GM [m]	A/R	COEF	A*COEF
DL	2.89	-1.45	2.84	1.002	0.2	0.154
DP	3.202	0	2.56	1.001	0.4	0.307
DS	3.41	0	2.99	1.000	0.4	0.306
Attained Subdivision Index A						**0.767**

Derivation of the Limiting GM Curve & GM Margins

In this section, the impact of RCOs on the vessel GM limit curve and the scale of the GM margins has been explored. Firstly, the updated limiting GM values have been calculated for RCO 2 and then RCOs 1 & 2, as detailed within Table 11 and Table 12 .

Risk Analysis & Calculation of RCO Cost-Effectiveness

PLL Calculation

A good measure of Societal Risk is the Potential Loss of Life (PLL), which is defined as the expected value of the number of fatalities per year. PLL is a form of risk integral, being a summation of risk as expressed by the product of consequence and frequency. The integral is generally summed up over all potential undesired events that can occur, in this case limited to collision events. In the following, PLL values are calculated for the vessel in as-built condition, as well as having implemented each of the RCOs examined. Furthermore, the cost-effectiveness of each solution has been gauged by calculating the Net Present Value of each RCO and contrasting this value to a Gross Cost of Averting a Fatality (GCAF) limit, determined by the value of statistical life within the Philippines. The latter has been determined in accordance with estimates made by the Economy and Environment Program for Southeast Asia, where an estimation of $0.8 million per life within the Philippines is proposed.

In addressing cost, the following assumptions have been applied for each RCO:

- Watertight door - $20,000 per door installed.
- Passive Foam - $6/kg installed.

The results of the calculation are summarised in Table 13, where it can be observed that all RCOs are significantly cost-effective; each exceeding GCAF limits by at least a factor of two.

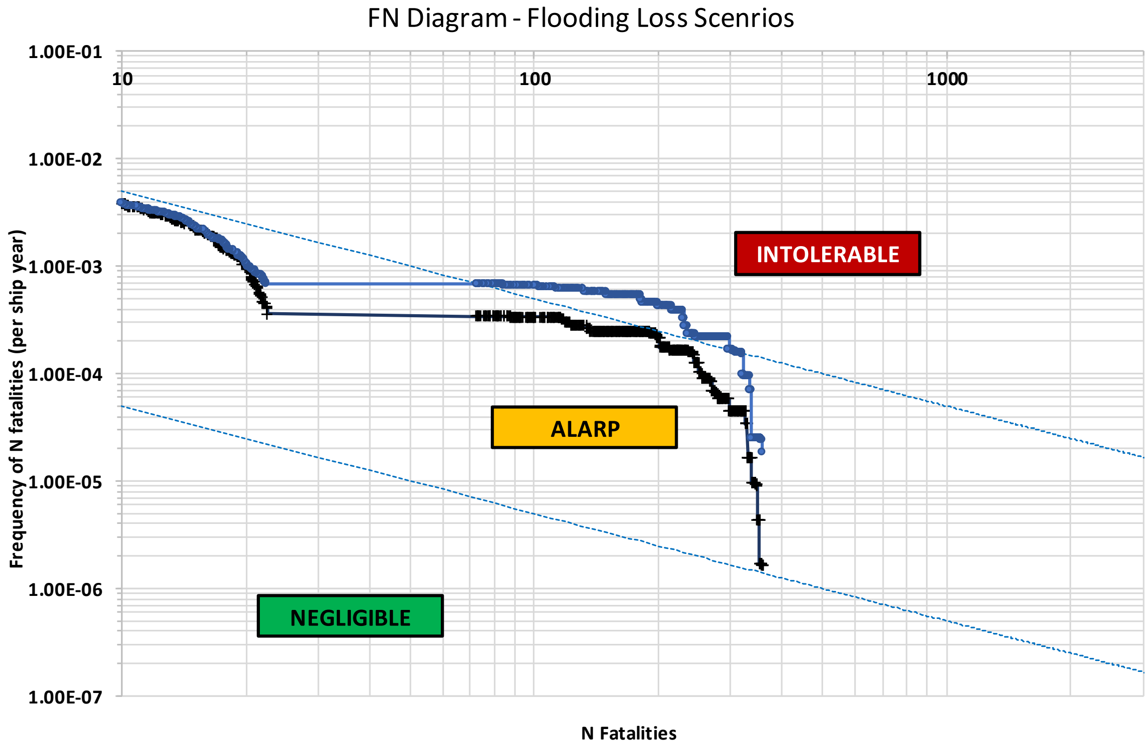

Figure 20: FN-Diagram Showing the Impact of RCOs

Table 13: Cost Effectiveness Calculation on the Basis of PLL, NPV & NCAF

Item	As-Built	RCO 1	RCO2	RCO1 & RCO 2
Attained Index	0.755	0.797	0.829	0.851
PLL	0.136	0.123	0.104	0.090
ΔPLL/ship-year	N/A	0.013	0.032	0.046
ΔPLL/ship-life	N/A	0.399	0.9624	1.387
Costs for financing, insurance etc ($)	N/A	8,000	7,127.6	15,128
CAPEX ($)	N/A	100,000	96,222.6	204,223
Net Present Value NPV ($)	N/A	118,800	105,844.86	224,645
GCAF Limit ($)	N/A	319,334.4	769,920	1,109,251
GCAF/NPV	N/A	2.69	7.27	4.94

Risk Acceptance Criteria – FN Diagram

Another useful approach to gauging the effectiveness of the RCOs, is by plotting what is known as an FN Diagram. This is a means of expressing societal risk, by illustrating the relationship between the frequency of an accident and the number of fatalities. Such diagrams are generally plotted against some form of risk-acceptance criteria, in this case taken as the IMO criteria expressed in MSC-MEPC.2/Circ.12/Rev.2. With consideration of the vessel in the as-built condition and also following the implementation of the combined RCO solution, an FN-diagram has been created as shown in Figure 20. Here, the blue curve represents the existing vessel design and the black curve the modified design with the RCOs implemented. The risk-acceptance criteria are plotted with light blue dashed lines, creating three regions within the chart, defined as follows:

- **Intolerable Region:** Risk cannot be justified and must be lowered.
- **ALARP Region:** Risk is tolerable if further risk reduction is impractical.
- **Negligible Region:** Risk is negligible.

If we observed the FN diagram, we could see that the existing vessel design falls within the intolerable region, indicating that action should be taken to bring the vessel into the ALARP region. In this respect, the application of the combined RCO solution has achieved this aim, with all events considered now lying within the ALARP region. This again is another indicator that the RCOs considered hold significant potential to reduce flooding risk in a meaningful way.

CONCLUSIONS

General Conclusions

- One way of ensuring that action is taken before a disaster occurred is by using a process known as Formal Safety Assessment (FSA, MSC-MEPC.2/Circ.12/Rev.2.). This has been described as "a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of options for reducing these risks." Such options have been extended to other stakeholders (Flags, Administrations, Class, Shipyards and Ship operators), aiming at identifying cost effective solutions to improve safety standards of existing ships and new buildings.
- As the nature of this undertaking is highly technical, the proposed solutions in the form of recommendations are communicated with decision makers in mind, to ensure that all stakeholders gain sufficient information at a level that is readily understood to support effective decision making. To this end, proposed changes are compared with existing standards, targeting life cycle implications (design, operation, emergencies) to enable a balance to be drawn between technical and operational issues, including the human element, by contrasting safety (Delta Risk) and cost (Delta cost) in the implementation of the proposed measures, targeting identified hazard categories individually whilst considering cross-hazards implications.
- The focus on design solutions in the project and in this paper, is on the highest risk contributor, as previously identified, namely inadequate damage stability and the risk to human life. This comprises nearly 90% of the risk for all categories of passenger ships, as manifested by accident statistics. Contributing factors for such loss comprises not only deficiencies in design but also in environmental, human, organisational, regulatory, and other unknown factors, which are also addressed by the FSA_P team. Therefore, collectively the team covers the whole spectrum of hazards and their ensuing consequences, leading to balanced recommendations, accounting for feasibility, practical implementation, time scales, and cost.
- To this end, representative ships from the Philippines fleet currently engaged in domestic voyages are selected for risk analysis and risk assessment, the latter by using cost-benefit assessment to aid decision making in the RCOs selection, implementation, and impact. Based on this process of using representative ship designs in the risk assessment, any conclusions reached and recommendations ensuing on the basis of this sample of ships would, in principle, apply to the whole fleet of the domestic passenger ships operating in the Philippines. The selected ships include: (a) a medium size RoPax vessel; (b) a small motor banca vessel; (c) a large old design RoPax. This paper addresses ship (a).

Specific Conclusions

- Deriving from the analysis performed on the selected ship design, detailed in the report, it has been possible to identify and rectify design vulnerabilities to flooding hazards, typical of the fleet of domestic passenger ships operating internationally. Specific remarks pertaining to the selected RoPax ship, which apply to the whole fleet, include the following:
- Certain features, which make the Philippines fleet more susceptible to flooding risk, include: (a) low index of subdivision, (b) low freeboard, leading to water reaching the car deck (c) low GM margins; hence susceptible to overloading or heavy weather, (d) unprotected openings, (e) inappropriate verification, thus further exacerbating the potential for catastrophic loss of life.

General Recommendations

- Considering the current state of enforcement and verification of damage stability standards for domestic passenger ships operating in the Philippines (lack of fit for purpose regulations; gaps in enforcement and verification – frequency and rigor), ships must be made more robust to withstand flooding hazards by adopting risk control measures that are extremely cost-effective to incentivise the operator to meet higher standards, which in turn will fuel a virtuous cycle for continuous safety enhancement.
- Working with this incentive in mind, the most effective and practicable solutions, applicable to new and existing ships, in any time scale, have been selected and applied to the sample ships, enabling all categories of ship size to reach damage stability standards applicable to passenger ships engaged in any domestic or international voyages, including the proposed modified designs of the motor bancas.
- This is unprecedented and exciting, enabling Philippines in the short to medium term to showcase the safety of their domestic fleet against the best in the world.
- Based on this work, a clear pathway is outlined for consideration by the safety stakeholders in the Philippines, to facilitate a safety transformation for all domestic ships operating in the Philippines.

Specific Recommendations

- Based on the results detailed within the foregoing, the following specific recommendations can be made:

- In order to correctly inform the process of evaluating the damage stability performance of vessels and subsequently implement effective RCOs, it is essential that accurate and up-to-date information is available on all regulated vessels.
- As the RCOs assessed have proven highly effective in reducing flooding risk across a range of ship types, sizes and ages, due consideration should be given to providing alternative routes to compliance on the basis of implementing such measures, particularly where novel forms of RCO are to be employed.
- Guidelines should be produced detailing the approach that should be adopted in order to effectively implement and judge the efficacy of approved RCOs, in line with the approach adopted within this report.

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CONTRIBUTION STATEMENT

D. Vassalos: Conceptualisation, Methodology, Writing Original-Draft, Writing Review/editing, **D. Paterson**: Calculations, Data curation, Writing Review/editing, **F. Mauro**: Data curation, Writing Review-Editing, **A. Salem**: Writing Review/editing.

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