Study of the specific damage stability parameters of Ro-Ro passenger vessels according to SOLAS 2009 including water on deck calculation

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Preface

This study has been performed by The Ship Stability Research Centre of the University of Strathclyde, National Technical University of Athens, Vienna Model Basin, Safety At Sea and Deltamarin.

The Ship Stability Research Centre of the University of Strathclyde was responsible for the overall coordination of the work, numerical simulations, analytical studies, risk assessment, derivation of recommendations and compiling of the main report.

The National Technical University of Athens performed studies on the sensitivity of ship stability and survivability to modelling assumptions.

Vienna Model Basin performed and reported all physical model testing.

Safety At Sea was responsible for the building of numerical models, all stability calculations, concept ship design and the plans and data needed for physical model testing.

Deltamarin was responsible for concept ship designs, the RoPax ships market analysis, and provided advice on the feasibility of design solutions.

Two concept ship designs were kindly provided independently by STX Europe.

Acknowledgements

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Special thanks to STX Europe for the provision of two ship designs for the purposes of the studies carried out in this project.

Executive Summary

This report summarises the study on the stability of RoRo passenger (RoPax) ships performed between 17 December 2009 and 15 June 2011.

The study constitutes Phase II of a project on the subject undertaken by EMSA, with Phase I (Study N° EMSA/OP/09/2008) commissioned by a Consortium led by the Hamburg Ship Model Basin in July 2009. The concluding report of Phase I expressed serious concerns regarding the safety level of RoPax ships as governed by current regulations, such as the following:

- "… the present investigation …. shows that in the framework of the new … rules (SOLAS 2009) … it is possible to create ship designs with significant **deficits** with regard to safety."
- "It is possible to design internal watertight subdivisions that may have a non-negligible risk of a **catastrophic failure** in case of side damage to the ship".

The key objective of Phase II of the project was to develop concept designs of five variations of RoPax ships compliant with SOLAS 2009 Chapter II rules, followed by a comprehensive survivability assessment based on appropriate physical experimentation, analytical reasoning and numerical simulations to examine sensitivity of stability to controllable design parameters.

Based on the findings of Phase II, specific proposals for amendments to SOLAS 2009 to accommodate the intent of the Stockholm Agreement and to address various identified shortcomings of SOLAS 2009 were presented, together with comprehensive disclosure of the reasoning process and detailed explanations founded in scientific methods.

A conclusion was reached to the effect that the level of safety implied by SOLAS 2009 and the Stockholm Agreement for the provision of ship stability is insufficient to prevent the occurrence of a flooding accident on a RoPax ship resulting in a major loss of life. This is the result of allowing "zero" stability, with expected rapid capsize in calm water, for a high proportion (typically 10%) of feasible flooding cases.

A further proportion (approx. 20%) of the flooding cases are allowed "some" degree of stability, albeit, insufficient to cope with the effects of waves of up to Hs=4m. In these situations, a capsize may occur within 30 minutes if the sea state encountered during the actual accident is higher than the "critical" sea state a ship is designed to withstand when flooded. 134 such capsizes out of 385 tests were observed during experiments performed in phase II of the project. Approximately 1-3 real-life flooding cases occur among the RoPax fleet annually.

SOLAS 2009 regulations can account for all physical phenomena underlying the loss of ship stability and can address all such deficiencies in a consistent and comprehensive manner by means of the Attained Subdivision Index A. Therefore, it is suggested that the level of ship safety may be effectively set by an appropriate level of A, such that A > R, where R is the Required Subdivision Index.

The level to which the Required Subdivision Index R is raised is proposed to be based on the goal of the recurrence interval for large accidents of at least 100 years, whereby the calculated expected frequency of their recurrence among the current RoPax fleet of 1,499 ships must not exceed 1 per 100 years.

The specific formulation for R adhering to such a goal, together with the suggestions for the various amendments are summarised in the table below. Further details are provided in the

section entitled "Comprehensive Summary", as well as in the main body of the report and its annexes.

Regulation	Purpose / Meaning	Suggested Amendment
s-factor MSC216 (82) Reg. 7-2.3 or Reg. 1.1 of Annex I of DIRECTIVE 2003/25/EC	Ship watertight architecture, loading, impact of waves, water accumulation	Modify formulation by setting GZ_{max} to 0.25m and Range to 25deg to account for longer survival times of 10 hours and inherent uncertainties of quantifying survivability, including effects of water accumulation on car deck. As a direct method of ensuring that the intent of the Stockholm Agreement is met under SOLAS 2009, it may be required that the provisions of Regulation II-1/B/8.2-3 shall be complied with by demonstration that s=1. However, the deterministic constraints on "freedom of design" and inconsistencies resulting from focusing on a small sample of flooding cases would still remain as a characteristic of the Stockholm Agreement.
K-factor MSC216 (82) Reg. 7-2.3 and MSC216 (82) Reg. 8-1.2	The process of abandonment by encouraging symmetry in flooding	Remove from current regulation to encourage building in of stability at higher angles of heel, and instead require relevant ship systems to operate in higher angles of heel of up to 25deg.
w-factor MSC216 (82) Reg. 6.1 and Reg. 7.1	The frequency of operation in given loading conditions	Remove from regulation, as the loading conditions should not be regarded as a random variable, but a well-defined range for which an adequate level of stability should be maintained at all times.
A-factor MSC216 (82) Reg. 7	Relates all parameters with one another	Interpret as the total probability (rather than an index) of ship surviving for appropriate time to allow abandonment, if needed, and consider the serious meaning of probability of 1-A.
R-factor MSC216 (82) Reg. 6.2.3	Sets the level of damage stability	Set R as follows: $R(N_{max}) \geq \begin{cases} 0.875 & for \quad N_{max} < 100 \\ 1 - \dfrac{1}{0.0845 \cdot N_{max} - 36.67 \cdot 10^{-6} \cdot N_{max}^2} & for \quad 100 \leq N_{max} < 375 \\ 1 - \dfrac{1}{0.0845 \cdot N_{max} \cdot \exp\left(\dfrac{-(N_{max} - 250)}{704}\right)} & for \quad 375 \leq N_{max} \leq 704 \\ 0.968 & for \quad N_{max} > 704 \end{cases}$ N is the number of persons onboard (crew and passengers).

It is recommended that the above amendments be considered for the worldwide fleet of RoPax ships, so as to reduce the risk to as low as reasonably practicable (ALARP).

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List of Abbreviations and Symbols

A	Attained index of subdivision according to MSC216 (82) Reg. 7. Probability of survival in waves
A_{DS}, A_{DP}, A_{DL}	Attained index of subdivision at specific draught DS, DP or DL, respectively
$A\|T_j$	Probability of survival at draught j
ALARP	As low as reasonably practicable, MSC/Circ.1023, MEPC/Circ.392
B	Ship breadth
$cdf_{N_{\max}}(N_{\max})$	Probability that a ship has the capacity of up to $N_{\max}$ persons (crew and passengers) in the fleet of given ship types
$d_{i,k}$	Flooding case number "i"
DS, DP, DL	Deepest subdivision draught, "partial" subdivision draught and light subdivision draught, according to MSC216 (82) Reg. 2
$E^{*}(N)$	Expected number of fatalities per ship in 30 years
$fr_{HZ}(hz_j)$	Frequency of occurrence of a scenario $HZ = hz_j$ per ship per year
fr_{coll}	Annual frequency of serious collision, the ship being the one that is the struck ship and with the consequence of flooding
$fr_N(N)$	Frequency of occurrence of exactly N number of fatalities per ship per year
$f_{Hs\|coll}(Hs)$	Probability density distribution for $Hs\|coll$
$F_{fleet}(N)$	Annual frequency of N or more fatalities in the fleet
$F_{Hs\|coll}(Hs)$	Cumulative probability distribution for $Hs\|coll$
$F_N(N)$, F_N	Cumulative distribution of frequency for occurrence of N or more number of fatalities per ship per year, known as an "F-N curve"
GM, GM_{DS}	Transverse metacentric height.
GT	Gross Tonnage
$GZ_{\max}$	Residual righting lever according to MSC216 (82) Reg. 7-2.1
KG	Vertical centre of gravity from the base plane
KG_{DS}	Vertical centre of gravity at specific draught DS
K	Factor K according to MSC216 (82) Reg. 8-1.2
Loa	Length over all
lm	Lane metres

LSA	Life saving appliance
BHD	Bulkhead
$\Omega_i = \{x_i, \lambda_i, b_i, h_k\}$	Hull breaches are characterised by location " x_i ", length " λ_i ", penetration " b_i " and height " h_k "
$F_{surv}(t \mid d_{i,k}, T_j, Hs)$	Probability of observing no capsizes within time t, given the ship is subject to flooding case $d_{i,k}$, draught T_j and sea state Hs
$F_D(t \mid x_i, \lambda_i, b_i, h_k, T_j, Hs)$	Probability of observing no capsizes within time t, given the ship is subject to hull breach case $\Omega_i = \{x_i, \lambda_i, b_i, h_k\}$, draught T_j and sea state Hs
FSA	Formal Safety Assessment, MSC/Circ.1023, MEPC/Circ.392
GCAF	Gross cost of averting fatality, MSC/Circ.1023, MEPC/Circ.392
$H_{crit,i}$	Significant wave height in which probability that a ship subjected to flooding scenario case d_i might capsize within $t = 30$ minute, is 50%
$f_\Omega(\sigma, T, \theta, GM)$	Joint probability density distribution for random variable set σ, T, θ, GM (draught T, trim θ , metacentric height GM and permeability σ)
H	Vertical extent of flooding
$N_{\max}$	Number of persons considered onboard a ship (e.g. number of crew, or number of passengers, or both)
NPV	Net present value
n_{ships}	Number of ships
p_f	Probability of observing a capsize within typical testing time of 30min
$PLL \equiv E(N)$	"Potential loss of life", expected number of fatalities per ship per year
$p_{N \mid HZ}(N \mid hz_j)$	Probability of occurrence of exactly N fatalities, given loss scenario hz_j occurred
$Range$	Range of residual righting lever according to MSC216 (82) Reg. 7-2.1
R, R(N)	Required index of subdivision according to MSC216 (82) Reg. 6.2.3. Required level of probability of survival after collision and flooding
RoRo	Roll-on, Roll-off
RoPax	RoRo passenger
RCO	Risk control option
SOLAS 2009	IMO Convention Safety Of Life At Sea, latest amendments MSC216 (82)
Stockholm Agreement	Directive 2003/25/EC and 2005/12/EC

$s_{i,j}$	Factor s, index s, given by MSC216 (82) Reg. 7-2.3. Probability that a ship at draught T_j survives a flooding case d_i (or "worst" vertical flooding case in zone "i")
$s_{final,i}$	Probability s_i for final stages of flooding (for either of draughts)
$s_{i,j,k}$	Probability that a ship at draught T_j survives a flooding case $d_{i,k}$, $s_{i,j,k} \equiv (s_i \vert T_j \& h_k)$, specific vertical extent k
T_{mri}	Mean recurrence interval (period)
$\frac{1}{s \cdot y}$	One per ship year
T_j	Draught number "j"
t	Time
t_0	Time of 30 minutes
w_j	Factor w according to MSC216 (82) Reg. 6.1 and Reg. 7.1. Probability mass that ship operates at loading condition "j"
v_k	Probability of flooding extending reaching up to horizontal subdivision number k, and referred to as "reduction factor v"
WoD	Water on deck

Comprehensive Summary

The results of the project's research endeavours can be summarised as follows:

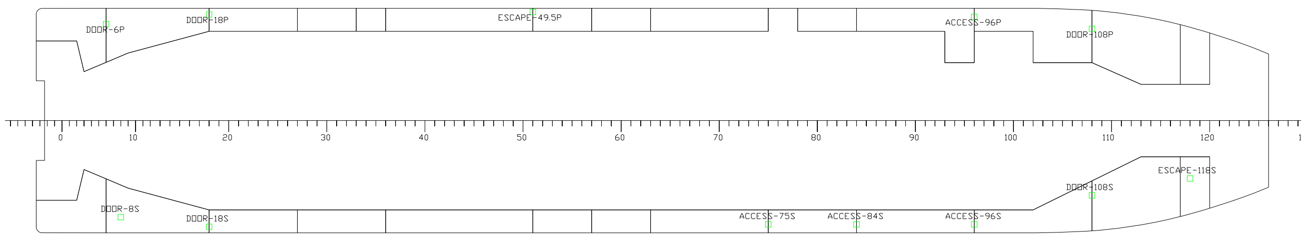
The design process

Five RoPax ship designs were developed according to SOLAS 2009 standards, as summarised hereunder:

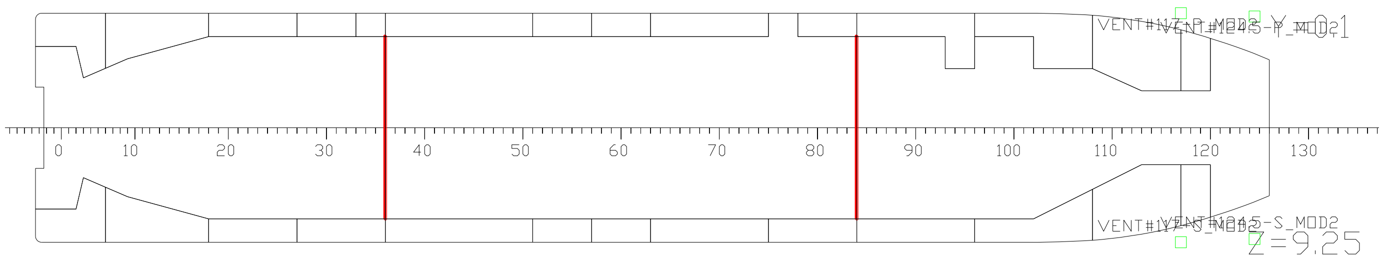
Ship 1 (STX design) is a small day ferry with large public spaces for passengers on two decks in the superstructure.

Ship 1 modified (STX design), a modification proposed by Safety At Sea, as shown in the figures below, involved the installation of two retractable bulkheads, raising of floodable openings and an increase of the transverse metacentric height (GM) by 21.5cm at the deepest subdivision draught.

Ship 1, KG_{DS} = 8.892m (GM_{DS} = 1.385m), A_{DS} = 0.75941[1]



Ship 1, modified design, KG_{DS} = 8.676m (GM_{DS}=1.600m), A_{DS} = 0.95249



The overall additional life time (30 years) cost is estimated to be of the order of \$2.4 million to \$6.6 million (see Table 13) compared to the original design solution. This estimate derives from the approximate cost range extrapolated from data published at MSC 85/INF.3, see reference [34].

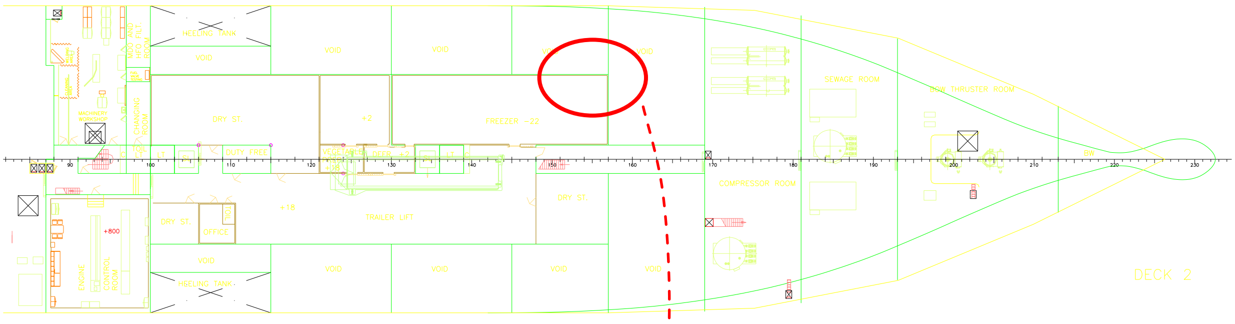
Ship 2 (DELTAMARIN design) is a small day ferry with small public areas. This type of ferry is designed to be a "workhorse" with the most important aspect being the RoRo cargo capacity. A diesel-electric propulsion system allows the lower hold to be used for cargo.

[1] Note that values of probability A quoted were assigned based on the alternative formulation for probability s, as developed in this project (GZ_{max} = 0.25m, Range = 25deg, K = 1). The partial index for deepest subdivision draught is used as a reference, since the level of stability in this draught is usually at the lowest level.

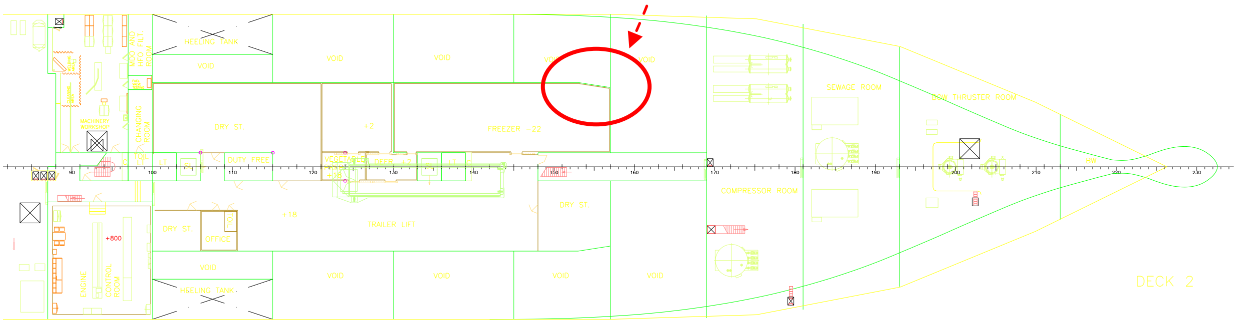
Ship 3 (STX design) is a large day ferry with cabin capacity for 600 passengers (lower berths) and a total capacity of 1,900 persons.

Ship 3 modified (STX design) is a modification proposed by Safety At Sea in frames #153 to #157 to "optimise" the watertight architecture for demonstration of "easy" compliance with the Stockholm Agreement. The modification shown in the figure below ensures that the lower hold is contained within B/5 boundary. Note that the probability A_{DS} is lower after the modification for attaining compliance with the Stockholm Agreement, indicating inconsistency of the Stockholm Agreement framework.

Ship 3, KG_{DS} = 15.352m (GM_{DS} = 2.3m), A_{DS} = 0.71175, non-compliant with the Stockholm Agreement.



Ship 3, modified design, KG_{DS} = 15.352m (GM_{DS}=2.3m), A_{DS} = 0.71170, compliant with the Stockholm Agreement.



Ship 4 (DELTAMARIN design) is a large day / night ferry with cabin capacity for minimum 1,100 passengers (lower berths) up to a capacity of 1,560 passengers, since some of the cabins will have three or four beds.

Ship 4 modified (DELTAMARIN design) comprises modifications to the open trailer deck cargo area (with two pillar lines), which is divided with two longitudinal watertight bulkheads (in lieu of two pillar lines) and with 10 watertight doors into 9 watertight cargo compartments. The design solution has the following consequences:

- The effective cargo capacity on the trailer deck will be about 20% lower due to the watertight doors (length of trucks assumed to be 17 metres).
- During loading and unloading, there may be a need for a trim control system, as the bow must be loaded first (not lane by lane).

- The watertight compartments on the trailer deck require more space for ventilation trunks and more fans. This may further decrease the cargo area.

- Escape routes from the watertight compartments on the trailer deck require more space, which may further decrease the cargo area.

- Hoistable decks are no longer possible on the trailer deck.

- The lightweight will be increased by an estimated 1-2%.

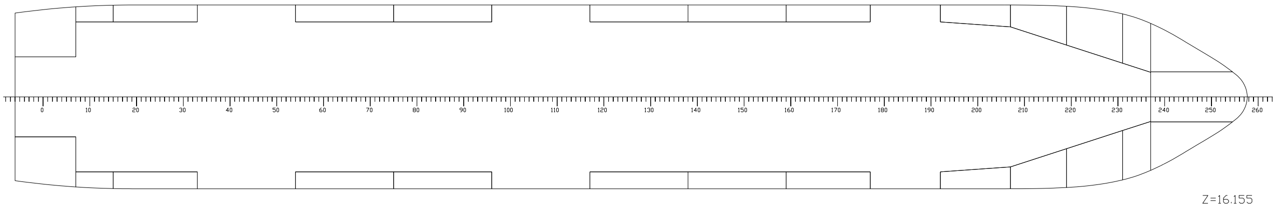
- The price of the vessel will be increased by an estimated 3-5%.

- The total trailer capacity will be decreased by about 8%.

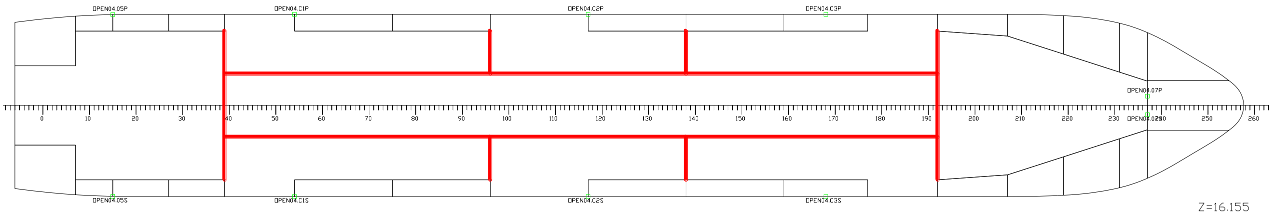
- The loading and unloading time will be increased. This may be a problem on short routes. For example, on the Helsinki-Tallinn route the increased speed to cover an additional 10 minutes of harbour time may result in about 30% higher fuel consumption.

The overall lifetime (30 years) cost is estimated to be of the order of $1.6 million to $4.5 million (see Table 13) with respect to the original design solution. This estimate derives from the approximate cost range extrapolated from data published at MSC 85/INF.3, see [34].

Ship 4, KG_{DS} = 14.187m (GM_{DS} = 2.95m), A_{DS} = 0.80624



Ship 4, modified design, KG_{DS} = 13.387m (GM_{DS} = 3.75m), A_{DS} = 0.9833



Ship 5 (Safety At Sea design) is a large night ferry with cabin capacity for minimum of 1,420 passengers (lower berths) up to a capacity of 2,000 passengers, since some of the cabins will have three or four beds.

Research observations

Based on the five concept designs and their modified versions (ships 1, 3 and 4), it was possible to examine the sensitivity of the assessed level of ship survivability (including the effects of water accumulation on the vehicle deck) to both the formulations involving stability parameters, as well as the design solutions themselves.

The main tool of the study proved to be the detailed analysis of the meaning of the various terms of the regulations. This has allowed the identification of common denominating factors between SOLAS 2009 and the Stockholm Agreement for addressing survivability.

The key conclusions and observations can be summarised as follows:

	Analyses, key conclusions and observations
Factor s	• The commonly referred to factor or index s is a mathematical construct, which conforms to axioms of probability. Therefore, in this report it will be regarded and referred to as probability s. • The analysis suggests that the currently used process for assigning probability s is a compromise between various modelling assumptions, resulting in apparent conservatism built into the concepts implemented. The three key concepts are as follows: ○ Approximation of survivability function F_{surv} for a flooding case as resulting from many hull damages (regardless of extent) by a survivability function for only one representative hull breach scenario (i.e. the "SOLAS" hull damage). ○ Further approximation of survivability function F_{surv} for a given sea state by a "jump" function (i.e. either 100% or 0% survival with no transition). ○ Approximation of the distribution of probability for sea states encountered in collision incidents with another function, redistributing probability weight mostly towards higher sea states. These three concepts are reasonably conservative and thus result in assigning a marginally lower probability s, than otherwise assigned through an exact solution (i.e. a solution for every hull breach, with a more realistic F_{surv} function and based on the actual observed statistics of sea states rather than assumed ones). These concepts were accepted in this project on the grounds of the apparent net conservatism mentioned above. • The robustness of assigning probability s then relies on the robustness of the relationship between two ship stability parameters (GZ_{max} and Range) and the sea state capable of causing capsize. The critical sea state is established through physical model experiments, which thus account for the process of accumulation of water on deck. This relationship is subject to considerable uncertainty leading to an unacceptable spread between predictions and measurements. All critical sea states established for cases selected for model experiments in this study proved to be higher than the calculated values. However, since no explanation can be put forward at present on the reasons for observed spread among all the data, these experimental results must be viewed together with all existing data. Therefore, a conservative engineering approximation is proposed in this project to ascertain that the predicted critical sea state is at least as high as that measured during experiments and for which records are available. • The conservatism applied in assigning probability s allows for a proposal to use it as an alternative measure of survivability to that proposed by the Stockholm Agreement, for pertinent flooding cases as implied by the Stockholm Agreement. Therefore, the level of stability intended by the Stockholm Agreement for such flooding cases may be accommodated conveniently by means of calculations according to SOLAS 2009 Regulation 7-

	2.5 (after the latter is modified according to recommendations made in this project). Note, however, that the deterministic constraints on "freedom of design" and inconsistencies resulting from focusing on a small sample of flooding cases would still remain as a characteristic of the Stockholm Agreement, and that the many cases resulting in "zero" stability would not be addressed at all.
Factor K	• Factor K encourages designs with as little asymmetric flooding as possible to enable orderly evacuation in case of flooding. However, a typical design that complies with current regulations could result in some 12% of cases being completely unsurvivable due to zero residual stability with rapid capsize in calm water (see Figure 2 and Figure 4), preventing any possible evacuation. • Overall, more than 30% of cases may be permitted under SOLAS 2009 to be unsurvivable (on some designs) either in calm seas or in seas up to Hs=4 (see Figure 6). Therefore, the intent of factor K is effectively irrelevant to all of these cases. • Factor K only applies to a small percentage of cases, e.g. ~14% for the sample design shown in Figure 2, reducing probability A by between 0% and 4%. As a result, factor K tends to contribute to marginally more stability built in for compliance with the requirement of $A \geq R$ in the <u>current</u> regulations. • Factor K effectively discredits any residual stability for flooding cases with angles of heel greater than seven degrees. Even if substantial residual stability exists, a flooding case will be assigned probability s=0 if an angle of heel of 15 degrees or more is experienced. This, in practice, discourages solutions such as side casings, which are effective in preventing capsize, even though allowing larger angles of heel. Therefore, factor K might discourage the construction of life-saving stability mechanisms onboard ships by artificially ("on paper") preventing demonstration of attainment of high survivability (high probability A), which can be based for instance on side casings. • Whilst factor K plays a positive role in current regulations, it would prove a major obstacle in encouraging ships with substantially higher survivability, compliant with proposed raised stability requirements by disallowing demonstration of their actual survivability. • Ship design solutions for very high survivability with no angles of heel seem difficult to achieve, but it seems that a reasonable design goal could be to maximise the survival rate of persons in as many cases as possible, even if the ship experiences high angles of heel. There is considerable expectation that many, or all, persons onboard could survive even in very severe flooding accidents, so long as the vessel does not capsize. • The results for a design case of high survivability (A>0.98) are shown in Figure 3 and indicate that it would attain A~0.94 if factor K remains as it is today. On this basis, it might have been argued that attainment of high survivability was not possible at all, or it was not cost effective. This might upset any possibility of reaching engineering consensus on raising stability standards adequately. • Whilst reaching A~0.94 might imply actual survivability in ~98% of flooding

	cases for Ship 4 design, it might be exactly 94% for other designs, where factor K does not play a significant role. Therefore, factor K could lead to probability s and, therefore A, be assigned inconsistently between ships. • To reiterate, factor K may result in an incorrect notion that attainment of high survivability, i.e. high values of probability A (R~0.98 for ships of 1,000 persons onboard or more) is difficult or impossible. Therefore, assuming that steps are taken to raise probability R (see Figure 2, Figure 4 and Figure 6), it is advisable that factor K be removed from current regulations. Its intent should be re-stated in another regulation to ensure equipment functionality.
Factor w	• The introduction of probability w derives from the assumption that the ship loading condition is a random variable at a design stage. This is contrary to many decades' practice of monitoring loading limits (limiting metacentric height GM) for a range of draughts for each of which the GM limits used to be set to attain a constant level of stability. • The draught has typically been assumed to be within a known range at every instant during the ship life cycle, whilst it is a known parameter at every instant of ship operation, and thus draught is never a random variable in real life. • Other limiting criteria on the GM, such as those related to intact stability, have never assumed draughts as a random variable, but as a known range. • The current formulation involving w for a ship's "flooding" state only is inconsistent with other regulations, as well as with operational practice. • The result of use of probability w allows for compensation of "lesser" stability (0.9R) in one draught, with better stability in another draught. Such compensation would typically lead to an overall probability A that is lower than anticipated, if the actual frequency of operating at the deepest draught is actually more than the assumed 40% (w_{DS} = 0.4). • It is proposed that probability w be removed from current regulations. This would result in (a) increased survivability at deepest draughts, as typically intended by the Stockholm Agreement and (b) consistent monitoring of the accepted level of survivability at any instant of ship operation.
Factor A	• The mathematical basis of the construct A allows it to be considered as a probability of surviving a collision flooding accident in a seaway, rather than an undefined "index" or a "factor". Deriving from Bayes' theorem on total probability, A signifies the proportion of cases that can survive a flooding accident, irrespective of likelihood of all other random variables relevant to survivability. Probability A considers the probability of a flooding taking place in any part of the ship, its feasible, longitudinal, vertical and transversal extents, and flooding incident taking place at any recorded sea condition. It is assumed that loading conditions should no longer be assumed as random, as discussed above. Moreover, through various assumptions related to probability s, it appears that probability A may be considered a probability of ship survival for some 10 hours after the flooding incident, even though it is attained implicitly by a set of mutually cancelling approximations. • Such comprehensive meaning of probability A may be contrasted with the

	previous practice to focus on only a small subset of feasible flooding cases, namely the 2-compartment flooding cases, and little or no explicit consideration of relevance to any of the other mentioned parameters. • Given the capacity of the probability A to consistently accommodate for all such parameters, it is suggested that the historical tradition of any deterministic focus on a "kind/type/subset of flooding cases" also prevailing in the Stockholm Agreement, be phased out. Instead, probability A could be regarded as an effective measure of ship stability. • Serious consideration must be given to the fact that probability A attains values of some 70-90% for typical designs compliant with current regulations (see Figure 6). This proportion of cases is expected to be "survivable", whereby orderly evacuation, waiting for assistance or return to port may physically be possible. • This implies that a proportion of 10-30% of the cases may result in rapid loss of stability with expected extensive loss of life. • For the various flooded conditions considered among three vessels tested in model basin, each of which having some degree of residual stability (GZmax>0), 134 capsizes in less than 30 minutes in seas of Hs<4m were recorded among 385 tests. All tests were performed in conditions that were feasible according to agreed statistical data (SOLAS 2009). • For many other cases, where no residual stability is attained after flooding, (GZ_{max} = 0m), a capsize is expected in less than 5 minutes. It is reasonable to expect no orderly evacuation, and therefore near complete loss of all persons onboard. • Figure 2 demonstrates that for a Ship 4 design with A_{DS} = 0.8062, some 12% of cases have no residual stability at this draught, implying that the ship would capsize rapidly in calm seas. The remaining ~8% would capsize in seas less than Hs = 4m. Therefore, approximately (1-A) x 100% of flooding cases would be unsurvivable under SOLAS 2009 (the Stockholm Agreement requirements would be expected to affect this proportion only marginally). • According to historical data, flooding accidents happen several times per year. It is estimated that outcome involving substantial loss of life may occur on average every 17 years. It appears reasonable to infer that the observed extensive loss of life in such accidents results from the lack of stability, which may be regarded as the last measure of mitigation for the initiating factors that would have led to the occurrence of flooding. Such lack of stability to prevent escalation of flooding events into catastrophic outcomes may thus be regarded as the root cause for the observed and calculable catastrophic nature of stability impairment accidents. Therefore, the current level of attained value of A of 70-90% for typical designs today is recommended to be raised substantially and expediently. • The following rationale on the appropriate level for the required probability R is proposed.
Factor R	• Elements of the Formal Safety Assessment (FSA) principles have been followed to systematically disclose and assess the contributions to risk to life from flooding events.

	• The current level of risk appears high and, when expressed as a typical expected number of fatalities in a ship's lifecycle (30 years), it is between 0.9 to 3.7 fatalities, between the five concept designs. Considering some 1,449 relevant RoPax ships are in active operation today, this implies 1,350 to 5,546 persons expected to lose their lives over the next 30 years in passenger ship flooding accidents. It is calculated as 0.9 x 1,449 and 3.7 x 1,449, respectively. This may result from limited number but large accidents. It should be noted that some 4,231 people lost their lives in the past 30 years as a result of lost stability by RoPax ships (Fairplay database, all accidents inclusive) in a small number of accidents. For example, MV Estonia (852 fatalities out of 984 persons onboard, 87%), Herald of Free Enterprise (193 out of 539, 36%), Jan Heweliusz (55 out of 64, 86%) and Al Salam Boccaccio 98 (988 out of 1376, 72%) combined resulted in 2088 fatalities. • Ship flooding accidents tend to be characterised by large loss of life, with survivors often saved after disorderly abandonment. These results from the rapid nature of ship capsize when loss of stability occurs. Under the current SOLAS 2009 regulations, a considerably high proportion of feasible flooding cases are allowed to have zero stability (GZ_{max} = 0). For instance, 12% of feasible flooding cases on Ship 4 result in zero stability (see Figure 2). • It is assumed that such a high proportion of flooding cases with no stability should not be regarded as a "tolerable risk", or in other words, As Low As Reasonably Practical (ALARP). • The frequency of such accidents is estimated to recur every 17 years, with historical events (large fatality rate e.g. 852 lost out of 984 = 87%) recurring every 10 years due to all casual events. This supports the assumption that such risk level appears to be intolerable. • The recommended mitigation measure for such risk is raising the required level of stability, which can be attained by raising the required value of the "index" R. • It is suggested that the level to which the required "index" R is raised is based on the goal of the recurrence interval of at least 100 years, whereby the calculated expected frequency of catastrophic accidents, and where catastrophic is specified as 1,000 fatalities or more for this purpose, among the pertinent fleet of 1,499 RoPax ships must not exceed 1 per 100 years. • The proposed level of R is shown in Figure 7, with an example for Ship 4 modified to this standard shown in Figure 3 and Figure 5. • The probability that a large scale accident would occur among the fleet in the 100 years after full implementation of the standard would still be considerable 63%. This supports the suggestion that the 100 years recurrence interval be considered as the minimum goal, with possibly even more stringent targets to be considered in the future. • Adopting the above standard for all existing and new ships would result in a reduction of risk by an estimated 0.8 to 3.4 averted fatalities per ship over 30 years. This appears to be achievable at an estimated cost of 1 to 7 million USD per fatality averted (Table 13). • It is recommended that this amendment is considered for the worldwide fleet of RoPax ships, so to reduce the risk to as low as reasonably practicable

<table>
<tr><td></td><td>(ALARP).</td></tr>
<tr><td>Stockholm Agreement</td><td>• The principle of the Stockholm Agreement is different from that of SOLAS 2009 in two respects, as follows:
o Firstly, the Stockholm Agreement criteria only apply to a small set among all of the feasible flooding cases (2-compartment, B/5).
o Secondly, the technique for demonstrating a level of survivability in a given flooding case (including accumulation of water on deck) at a given sea state is based on a different formulation between both standards. The Stockholm Agreement uses a SOLAS 90 criterion with an artificial wedge of water on a vehicle deck (or direct physical experiment), whereas SOLAS 2009 uses direct regression between critical seas and ship stability parameters. Both addresses the phenomenon of water accumulation, simply the technique is different.
• As a result of the first principle it is possible for designers to “optimise” the watertight arrangement to “fit” into the requirements, assumingly to meet commercial objectives. The “fitting” signifies the arranging of watertight architecture in a manner which ensures that as many as possible of the critical flooding cases are outside the range of characteristics to be subjected to the Stockholm Agreement stability check, such as B/5 bulkhead arrangements.
• It can be shown, for instance, based on the Ship 3 design, that a very insignificant physical modification to the arrangement, that would enable it to comply with the Stockholm Agreement requirements, results in a dramatically reduced probability A that would otherwise be required for compliance with the Stockholm Agreement without modifications (see Figure 6, results labelled as “STOCKHOLM by calculations (new GM)”, and shown for design cases of “Ship 3” and also for “Ship 3 Mod Z17/Z18”).
• When such “optimisation” is not carried out, as was the case with all of the five ship designs (other than the Ship 3 Mod Z17/Z18), compliance with the Stockholm Agreement may only be obtained by significantly raised GM values, with resultant high probability A. This level of A, however, may be construed as the “level” of stability that would be implied by the Stockholm Agreement for these specific geometrical arrangements, which is noticeably higher than the level required by SOLAS 2009.
• It is to be noted that introducing the very small modification at Z17/Z18 for attaining compliance with the Stockholm Agreement results in marginal reduction in the probability A, if all parameters remain unchanged (i.e. only the impact of watertight arrangement is considered). Therefore, it can be concluded that the requirements of the Stockholm Agreement are not consistent, since two ships that are both compliant with the Stockholm Agreement could have different levels of survivability (as measured by probability A). The key reason for this derives from the limited number of flooding cases required to be addressed by the Stockholm Agreement. The instrument A of SOLAS 2009 eradicates this deficiency, as it addresses all of the feasible flooding cases.
• Raising of standard R, as demonstrated below (see Figure 7), would assure that the intent of the Stockholm Agreement is fulfilled at all times (see Figure</td></tr>
</table>

	6). • As regards the second of the above-mentioned principles of the Stockholm Agreement, it is suggested that its provisions may be substituted effectively by use of the formulation for probability s as the required level of stability for each of the Stockholm Agreement cases (see also the above discussion on the s). It is proposed that the Stockholm Agreement is catered for by the s of SOLAS 2009, given that the amendments proposed are implemented, and keeping in mind that Stockholm Agreement focus on only small proportion of the feasible damage cases, the “freedom of design” would still be compromised. Also, the many cases resulting in “zero” stability would not be addressed by the Stockholm Agreement alone, and therefore, raising the level of R is recommended to be considered.

Recommended regulatory amendments

The following key instruments of SOLAS Chapter II Regulations 6, 7 and 8 (MSC 82/24/Add.1, Resolution MSC 216 (82), adopted on 8th December 2006) shall suffice to develop the best way forward in consistently addressing the level of stability a ship should possess in order to deal with hazards such as serious breach of hull integrity, with subsequent flooding of all spaces.

Revise MSC216 (82) Reg. 7-2.3

It is proposed that Regulation 7-2.3 be revised by replacing $GZ_{\max}$ with a suitable value of approximately 0.25m for passenger ships, that the $Range$ be taken as no more than 25deg, and that the coefficient K be taken as 1.

This amendment would consistently accommodate the data on survivability of Ro-Ro passenger ship types, as derived in the HARDER project (currently underlying the SOLAS 2009 rules). The revision would lead to a reduction in the value of index A to the order of 0.2% - 6%. However, removing of the factor K from current Regulation 7-2.3 would encourage the building in of stability at higher angles of heel. Instead of factor K intent, it may be required that relevant ship systems operate at higher angles of heel of up to 25deg.

Revise MSC216 (82) Reg. 6.1 and Reg. 7.1

It is proposed that Regulations 6.1 and 7.1 are revised to assure that the Attained Index of Subdivision A is equal to or higher than the Required Index of Subdivision R for every loading condition during ship operational life, rather than be “weighted” according to the assumed probability of occurrence of various loading conditions. None of the loading conditions should be regarded as a random variable, but as a well-defined range for which an adequate level of stability should be maintained at all times.

Revise MSC216 (82) Reg. 6.2.3

Set R as follows:

$$R(N_{\max}) \geq \begin{cases} 0.875 & \textit{for} \quad N_{\max} < 100 \\ 1 - \dfrac{1}{0.0845 \cdot N_{\max} - 36.67 \cdot 10^{-6} \cdot N_{\max}^2} & \textit{for} \quad 100 \leq N_{\max} < 375 \\ 1 - \dfrac{1}{0.0845 \cdot N_{\max} \cdot \exp\left(\dfrac{-(N_{\max} - 250)}{704}\right)} & \textit{for} \quad 375 \leq N_{\max} \leq 704 \\ 0.968 & \textit{for} \quad N_{\max} > 704 \end{cases}$$

This recommendation aims to ensure that catastrophic accidents do not occur more often than once per 100 years on average. N is the number of persons onboard (crew and passengers).

Revise MSC216 (82) Reg. 8-1.2

It is proposed to consider the intent of the factor K in Regulation 7-2.3 to be accommodated by the following text of Regulation 8-1.2:

> "Availability of essential systems in case of flooding damage"
>
> "A passenger ship shall be designed so that the systems specified in regulation II-2/21.4 remain operational and sustain heel angles of up to 25 degrees when the ship is subject to flooding."

This recommendation aims to ensure that all adequate systems needed for facilitating orderly evacuation are available for all feasible flooding cases.

Revise Reg. 1.1 of Annex I of Directive 2003/25/EC

As a possible alternative to all of the above proposed amendments, a direct method of ensuring the intent of the Stockholm Agreement is met under SOLAS 2009, it may be required that Regulation II-1/B/8.2-3 shall be complied with by demonstrating that s=1.

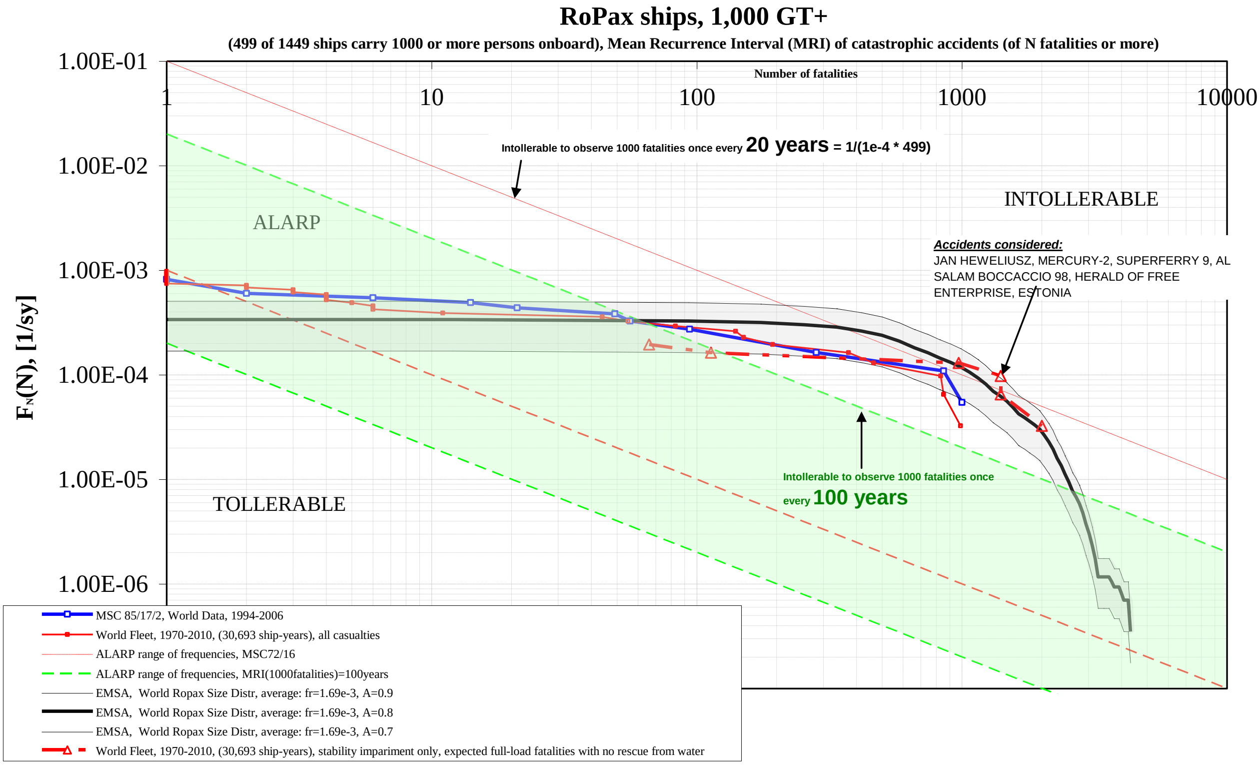


Figure 1 - F_N curves for the worldwide fleet of RoPax ships

In Figure 1, a range of probability A=0.7 to 0.9 is assumed. Two sets of risk tolerability criteria are shown, the MSC72/16 and proposed 100-year principle. Historical data reproduced from reference [33] is also shown. It is noted that no uncertainty has been given for historical data assessment of [33].

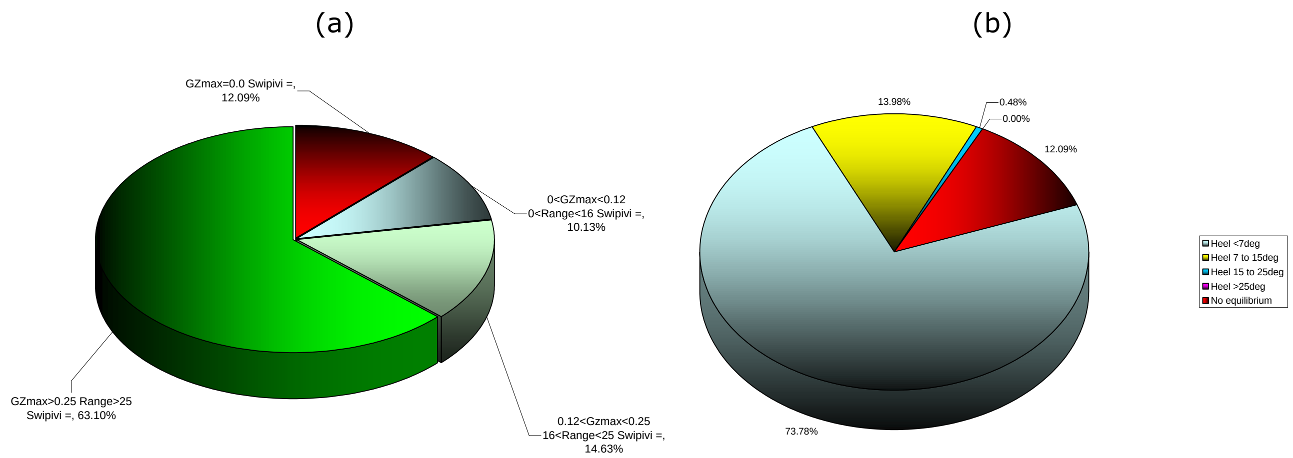


Figure 2 - Distribution of probability (SHIP 4 original design)

Figure 2 shows the distribution of probability for (a) occurrence of flooding cases with given range of parameter of residual stability, and for (b) heel angles (SHIP 4, original design to SOLAS 2009, A_{DS} = 0.80624).

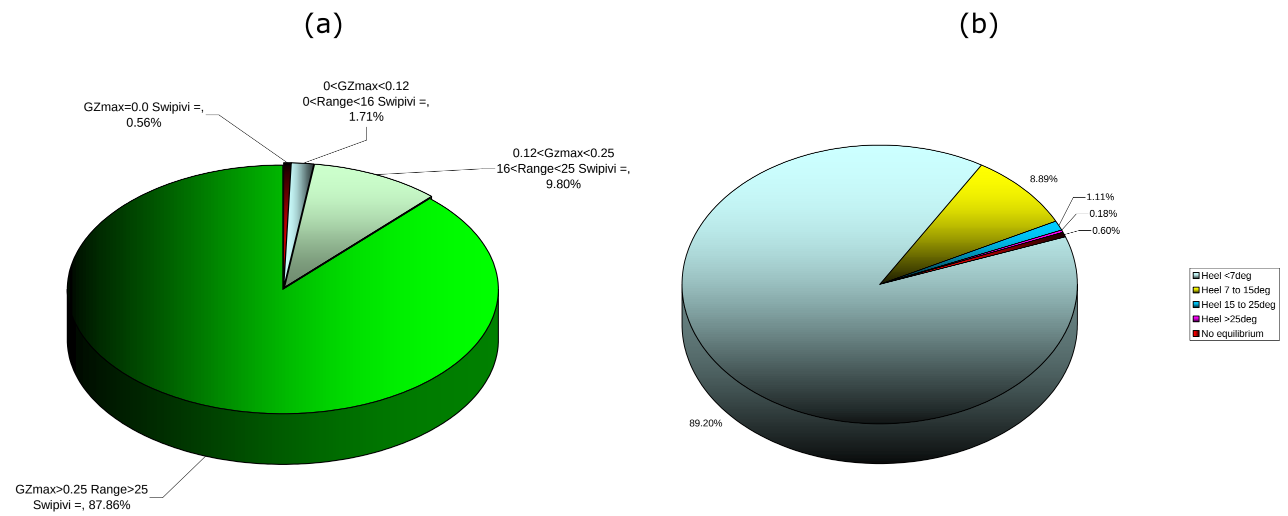


Figure 3 - Distribution of probability (SHIP 4 modified design)

Figure 3 shows the distribution of probability for (a) occurrence of flooding cases with given range of parameter of residual stability and (b) for heel angles (SHIP 4, modified design to minimum "100 years principle", A_{DS} = 0.98328).

Ship4, A=0.87820, All draughts, 025 25 K=1

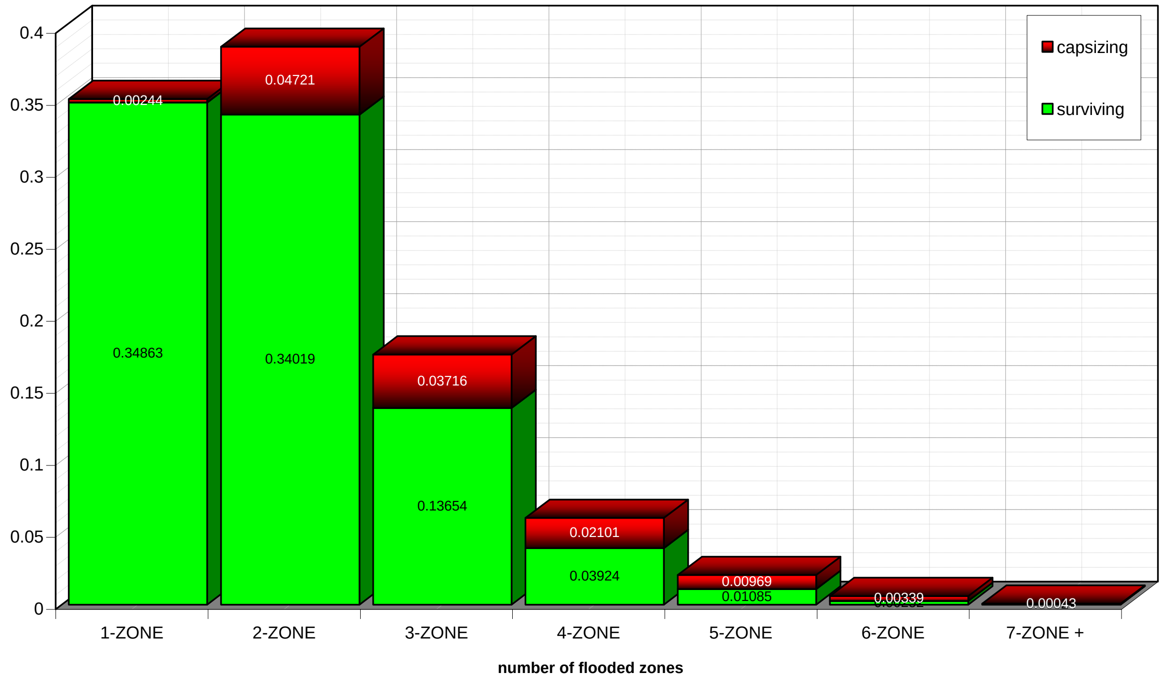


Figure 4 - Distribution of probability for surviving and capsizing, SHIP 4

Ship4, A=0.98813, All draughts, 025 25 K=1

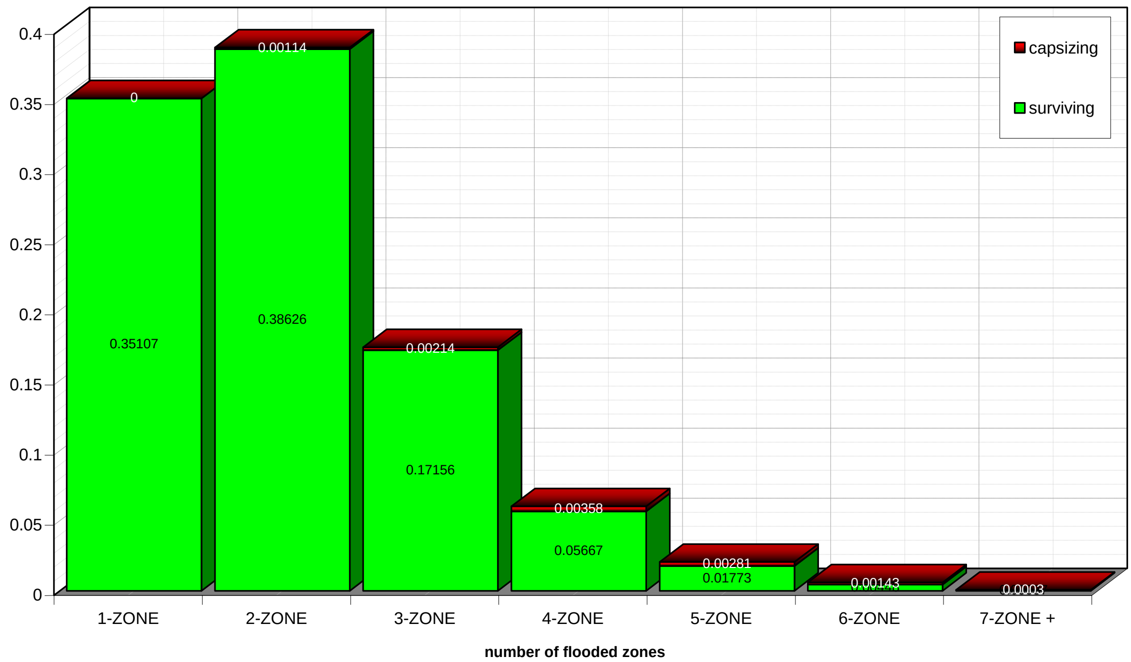


Figure 5 - Distribution of probability for surviving and capsizing, SHIP 4 modified

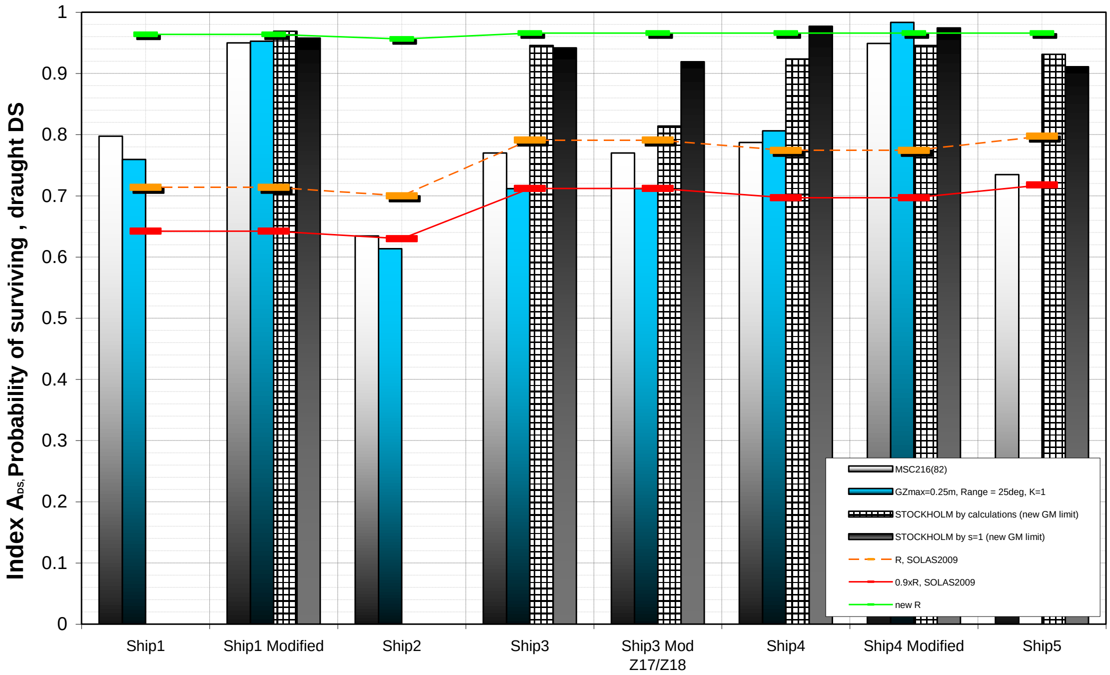


Figure 6 - Summary of assessed survivability in terms of probability A

Figure 6 presents a summary of the assessed survivability in terms of probability A at deepest subdivision draught. A comparison between the various standards and assumptions on stability parameters is made (e.g. GM).

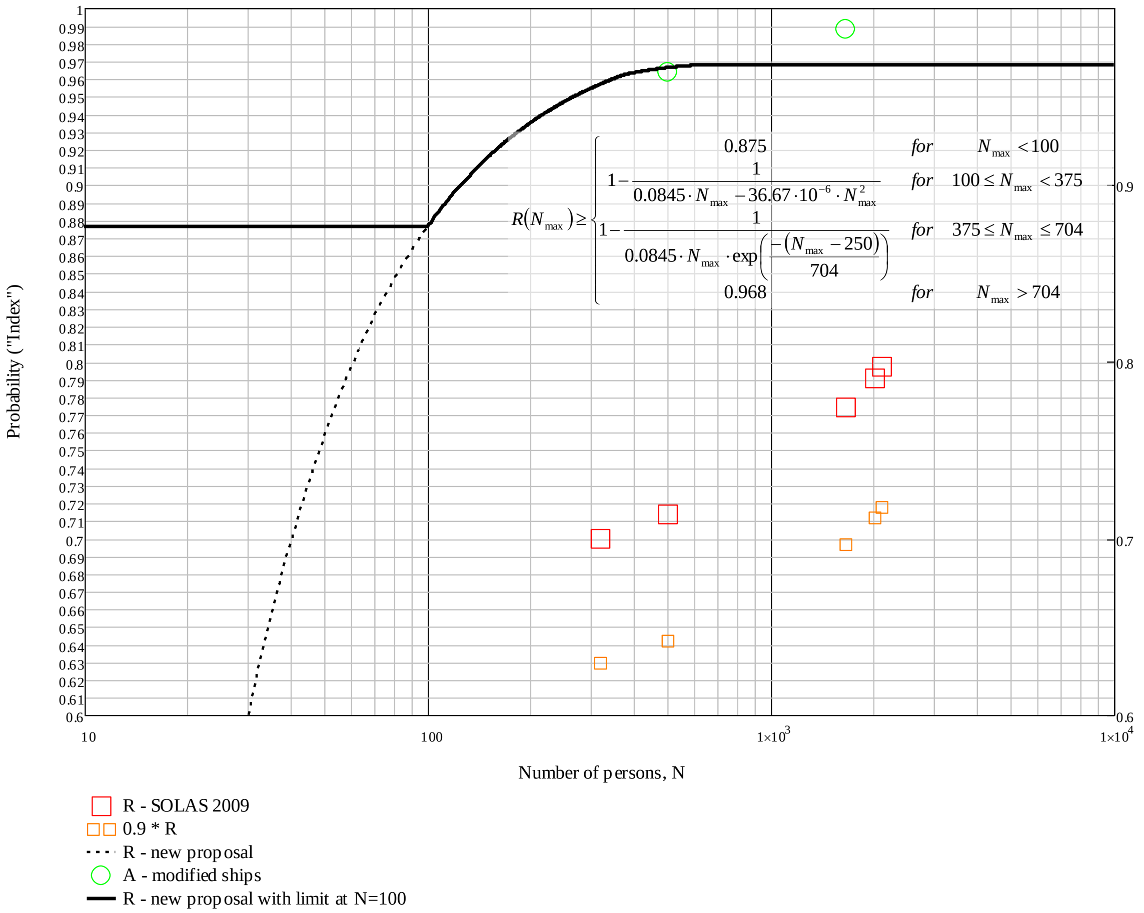


Figure 7 - Proposed index R for ships carrying N persons onboard

Figure 7 presents the proposed index R for ships carrying N persons onboard. It is proposed that A≥R for any draught conditions.

1. Introduction

In 2004, more than 1.3 billion passengers, 188 million cars, 856,000 buses and 28.7 million trailers were carried on 5.9 million RoPax[2] ship crossings globally.

According to the Fairplay database, in June 2011 there were 1,449 RoPax ships larger than 1,000 GT worldwide.

Due to a number of catastrophic accidents, serious concerns have arisen about the level of safety of the passenger ship industry.

Following the 1994 accident of the MV Estonia, regional EU Directives 98/18/EC and the subsequent Directive 2003/25/EC have been introduced to address stability issues inherent to the RoPax ship concept.

In order to address the perceived discrepancy between methods for accommodating effects of accumulation of water on deck implied by these directives and SOLAS 2009 Chapter II-1 rules, a study N° EMSA/OP/09/2008 was commissioned on 19th June 2008 by the European Maritime Safety Agency (EMSA). The study was performed by an HSVA Consortium, and reported in July 2009.

Based on physical scaled-model experiments, advanced numerical simulations, traditional naval architecture analyses, and statistical simulations, an opinion was put forward by the HSVA Consortium regarding the observed level of safety of passenger RoPax ships, which can be summarised by the following excerpts from the report [15]:

- "… safety level presented by the SOLAS 2009 Reg. B-1 rules clearly drops down to a significantly lower level than that presented by SOLAS 90 Reg. II-1/8 standard together with the Stockholm Agreement."
- "The hydrostatic calculations show that the smaller ship suffers from a general lack of stability, but the designed subdivision is reasonable (sic. from the viewpoint of stability standards)."
- "The larger ship has a sufficient level of stability (sic. to comply with stability standards), but the ship would capsize or sink rapidly also in calm water, if the lower hold got damaged."
- "… the present investigation …. shows that in the framework of the new … rules (SOLAS 2009) … it is possible to create ship designs with significant deficits with regard to safety."
- "… the ship stability required by the SOLAS 2009 rules is not likely to be sufficient in all cases."

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[2] The roll-on/roll-off ship, defined in the November 1995 amendments to Chapter II-1 of the International Convention for the Safety of Life at Sea (SOLAS), 1974 as being "a passenger ship with ro-ro cargo spaces or special category spaces...", is one of the most successful types operating today due to its flexibility, ability to integrate with other transport systems and speed of operation. The total number of ferries worldwide on 1 January 2006 (excluding ferries less than 1,000 gross tonnage) was 1,162, with a combined capacity of 1.15 million passengers and 226,210 cars or 769,210 lane-meters of commercial vehicles. Combined gross tonnage was 12.8 million and the average age of the fleet was 21 years. *http://www.imo.org/ourwork/safety/regulations/pages/ro-roferries.aspx*

- "It is possible to design internal watertight subdivisions that may have a non-negligible risk of a catastrophic failure (sic.) in case of side damage to the ship".

- "Corrective action should be taken to amend the SOLAS 2009 rules."

- "In some … damage cases … ship is expected to capsize in much lower waves, also when there is no water on the vehicle deck."

- "The basic reason behind all the problems related to the survivability in damaged condition is that this ship suffers from an insufficient level of stability in general."

Amongst the various suggestions, the study [15] stated that "a water on deck requirement (equivalent to the Stockholm Agreement) shall be worked into the stability regulations to ensure that this condition is represented correctly." However, no detailed proposals have been forwarded, given the limited scope of the project. Therefore, a second phase study was commissioned by EMSA, N° EMSA/OP/08/2009, on 20 August 2010, aimed at establishing corrective measures to amend the SOLAS 2009 stability rules so to address the issue of accumulation of water on a vehicle deck, as well as any other damaged ship stability problems.

2. Objectives

This study aims to propose corrective amendments that could be considered for revision of SOLAS 2009 damage stability rules to ensure that the problem of water on the vehicle deck of RoPax type vessels is addressed.

The following specific objectives were set:

- To design five RoPax ships to SOLAS 2009 standards.
- To perform a comprehensive and advanced survivability assessment of all possible parameters or configurations of such parameters (e.g. long lower hold configuration) affecting stability of such ships and which are controlled by the design process.
- To derive scientifically backed proposals for criteria amendments to address the accumulation of water on the vehicle deck or other damage stability problems, as well as design guidelines as appropriate.
- To experimentally test and demonstrate the derived criteria and/or specific design solutions for enhanced stability.

3. Programme of Work

The programme of work involved the concurrent tasking addressing the proposed objectives.

A series of analytical studies and numerical simulations were supported by further evidence of ship survivability in waves acquired through model experiments.

The study was conducted to gain an in-depth understanding of the intents and assumptions underlying the mathematical instruments of both the Stockholm Agreement and SOLAS 2009 to support recommendations made. An attempt was made to disclose all key conceptualising and engineering modelling adopted for both standards.

The reasoning has been extended for the risk assessment, following formal guidelines, to substantiate key recommendations on raising the level of ship stability.

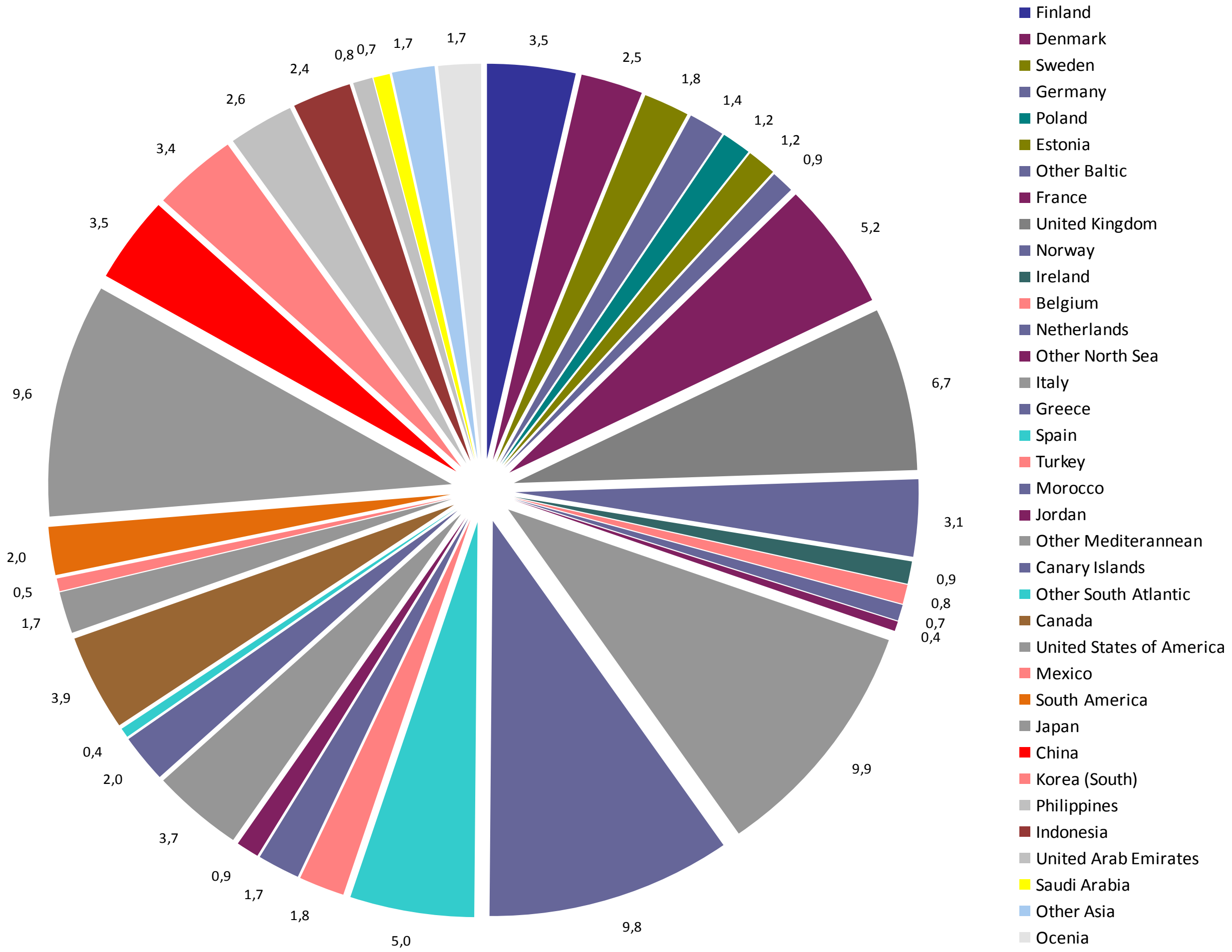
The following chapters describe in more detail all work performed.

4. Ship Designs

Five RoPax ship designs were developed to SOLAS 2009 rules (two designs were developed by Deltamarin, one by Safety at Sea and two by STX Europe), (see Table 1, Table 2, Figure 19 and Figure 20).

The following market summary was the background information for design development.

Figure 8 shows the very fragmented RoPax market that has many local operators. When all 5,000 to 40,000 GT ships built after 1970 are considered it can be found that Italy, Greece, Japan and UK are the main ferry operators[3].

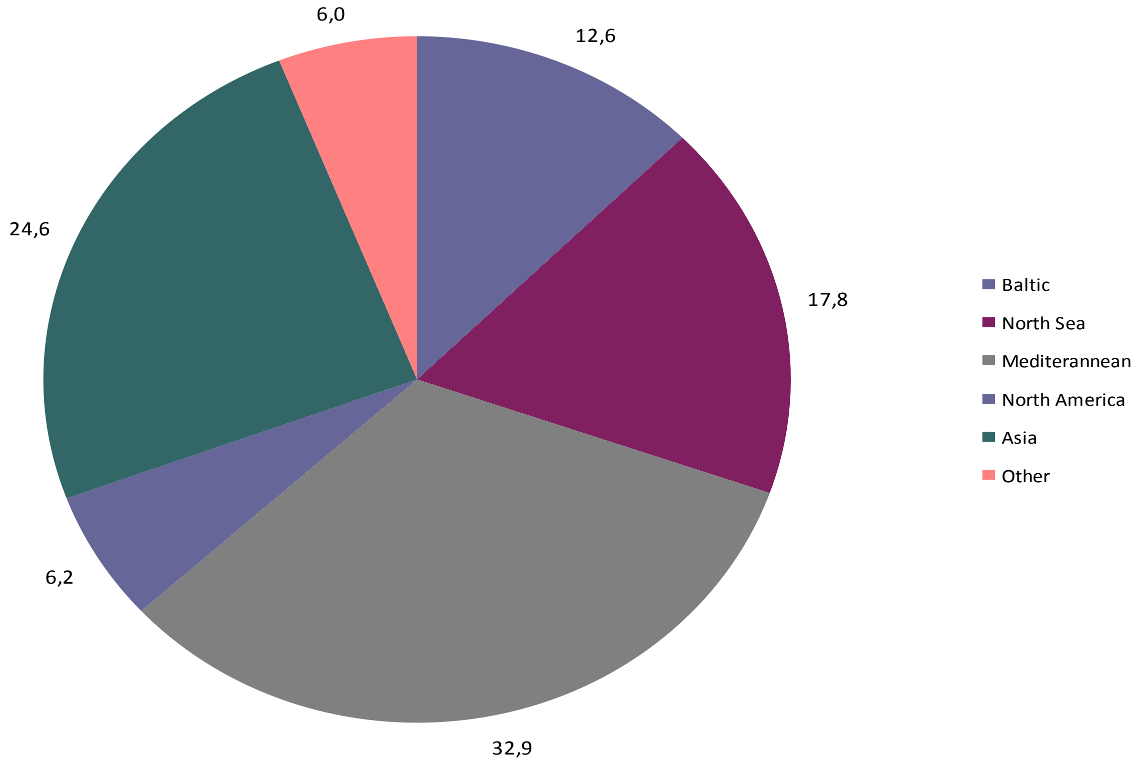


Source: Fairplay database and Shipax statistics

Figure 8 - Worldwide distribution of countries for RoPax operations

[3] *Fairplay database and Shipax statistics, © Deltamarin.*

Figure 9 shows that about one third of RoPax ships operate in the Mediterranean area, one third in North Europe and a quarter in Asia.



Source: Fairplay database and Shipax statistics

Figure 9 - Worldwide distribution of wider regions for ferry operations

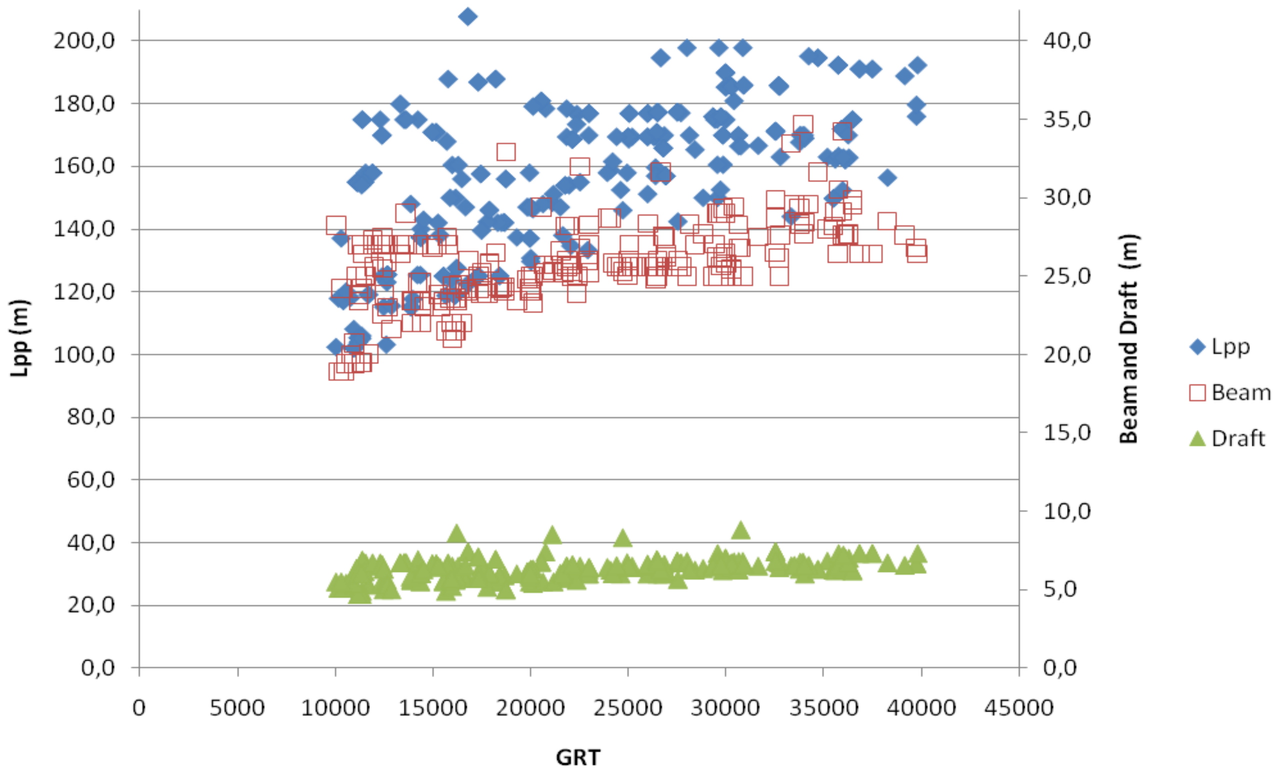


Figure 10 - Distribution of RoPax ship parameters

RoPax ships can be divided into two main types:

- Day ferry (no or only few passenger cabins);
- Night ferry (large number of passenger cabins).

The average size of a day ferries is about 23,000 GT and the average size of a night ferry is about 25,000 GT.

About 70% of car ferries are traditional two shaft line ferries. Azimuth propulsion is used on smaller short-distance ferries.

Typical propulsion machinery is diesel-mechanical but a small number of ferries use a diesel-electric propulsion arrangement either with two shaft lines or with azimuthing thrusters. Diesel-electric propulsion provides more freedom for machinery arrangement and for the watertight compartment arrangement.

Small ferry designs

Ship 1 (STX design) is a small day ferry with large public spaces for passengers on two decks in the superstructure. This kind of ferry is designed to accommodate tourist passengers and the selling of food, drinks and other merchandise onboard.

A diesel-mechanical propulsion system does not allow the utilisation of the spaces below bulkhead deck for cargo. The vessel is designed to have minimum distance between the design waterline and the bulkhead deck. The side casings are considered to improve the damage stability performance.

This design could be used in shorter routes, for example, in the Baltic Sea or Mediterranean.

Ship 2 (DELTAMARIN design) is a small day ferry with small public areas. This type of ferry is designed to be a “work horse”, with the most important aspect being the RoRo cargo capacity.

The propulsion system is diesel-electric, which allows the lower hold to be used for cargo.

Azimuth thrusters are needed for challenging harbour operations. Typically, sea voyages are short and may include intermediate stops.

The bulkhead deck has no continuous side casing, but since the diesel generators are located in side compartments, the engine casings could provide some additional buoyancy above the bulkhead deck.

This design could be used in shorter voyages, for example, in coastal traffic or for traffic to or between islands.

Table 1 - Summary of design specifications - two small RoPax ships

1 STX design	2 DELTAMARIN design
Loa=112m, B = 18,6 m	Loa=100m, B = 18,8 m
465 passengers	**300 passengers**
35 crew	**18 crew**
16 passenger cabins	16 passenger cabins
300 lm trailers	583 lm trailers (lower hold)
“more passenger orientated”	“more cargo orientated”
1200 dwt	1650 dwt
Diesel -mechanical propulsion	Diesel-electric propulsion
BHD-design draught = 1,9 m	BHD-design draught = 2,5 m

Large ferry designs

Ship 3 (STX design) is a large day ferry with passenger cabin capacity for only 600 persons (lower berths) and a total of 1,900 passengers. This ferry has two decks for trailer cargo and one dedicated car deck.

The propulsion system is diesel-mechanical with two shaft lines.

The ship has a centre casing and no lower hold for cargo.

This design could be used in routes where the sea voyage time is only a couple of hours and the harbour time is short.

Ship 4 (DELTAMARIN design) is a large day / night ferry with passenger cabin capacity for minimum 1,100 persons (lower berths) up to a total capacity of 1,560 passengers, since some of the cabins will have 3 or 4 beds.

This ferry has two full length decks and a lower hold for trailer cargo.

The propulsion system is diesel-electric with engines installed in the side compartments, which allows for maximisation of the lower hold length.

Side casings extend along the full length of the bulkhead deck.

This design could be used in routes where one or two crossings a day are made and the harbour time is long enough to enable loading and unloading of the lower hold cargo.

Ship 5 (Safety At Sea design) is a large night ferry with passenger cabin capacity for minimum of 1,420 persons (lower berths), and up to a total capacity of 2,000 passengers, since some of the cabins will have 3 or 4 beds.

The ferry has two full length decks for trailer cargo and both decks are loaded and unloaded either from stern or stem (drive trough) for fast harbour turnaround.

The propulsion system is diesel-mechanical with two shaft lines.

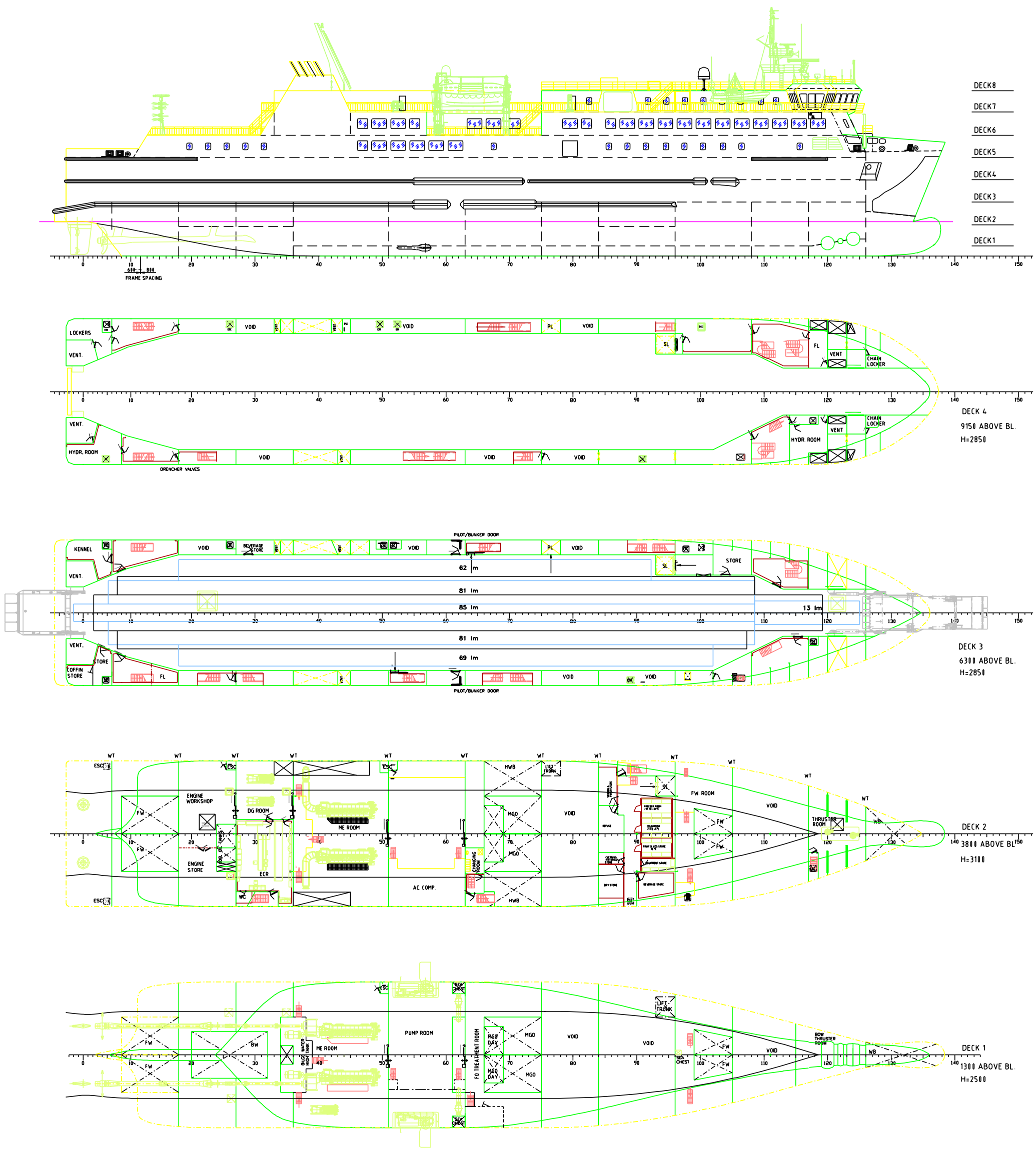
Side casings extend along the full length of the bulkhead deck.

This design could be used in long routes with limited harbour time for loading and unloading of cargo.

Table 2 - Summary of design specifications - three large RoPax ships

3 STX design	4 DELTAMARIN design	5 SaS design
Loa=195m, B = 30,4 m	Loa=199,9m, B = 29,4 m	Loa=216 m, B = 30.0 m
1900 passengers	**1560 passengers**	**2000 passengers**
100 crew	**85 crew**	**100 crew**
300 passenger cabins	520 passenger cabins	720 passenger cabins
2629 lm trailers	2711 lm trailers	2400 lm trailers
lower hold, NO	lower hold - YES	lower hold NO
"day ferry"	**"day/night ferry"**	**"night ferry"**
Diesel -mechanical propulsion	Diesel electric propulsion	Diesel -mechanical propulsion
BHD-design draught = 2,9 m	BHD-design draught = 3,7 m	BHD-design draught = 2,7 m

SHIP No 1 (code EMRP01-SV_NH_SC) - designed by STX Europe



MAIN DIMENSIONS:

LENGTH OA	abt. 112.0	m
LENGTH LPP	104.4	m
BREADTH	18.6	m
DRAUGHT DESIGN	4.4	m
DRAUGHT SCANTLING	4.5	m
DEPTH (DECK3)	6.3	m
DEPTH (DECK5)	12.0	m

MAIN DATA

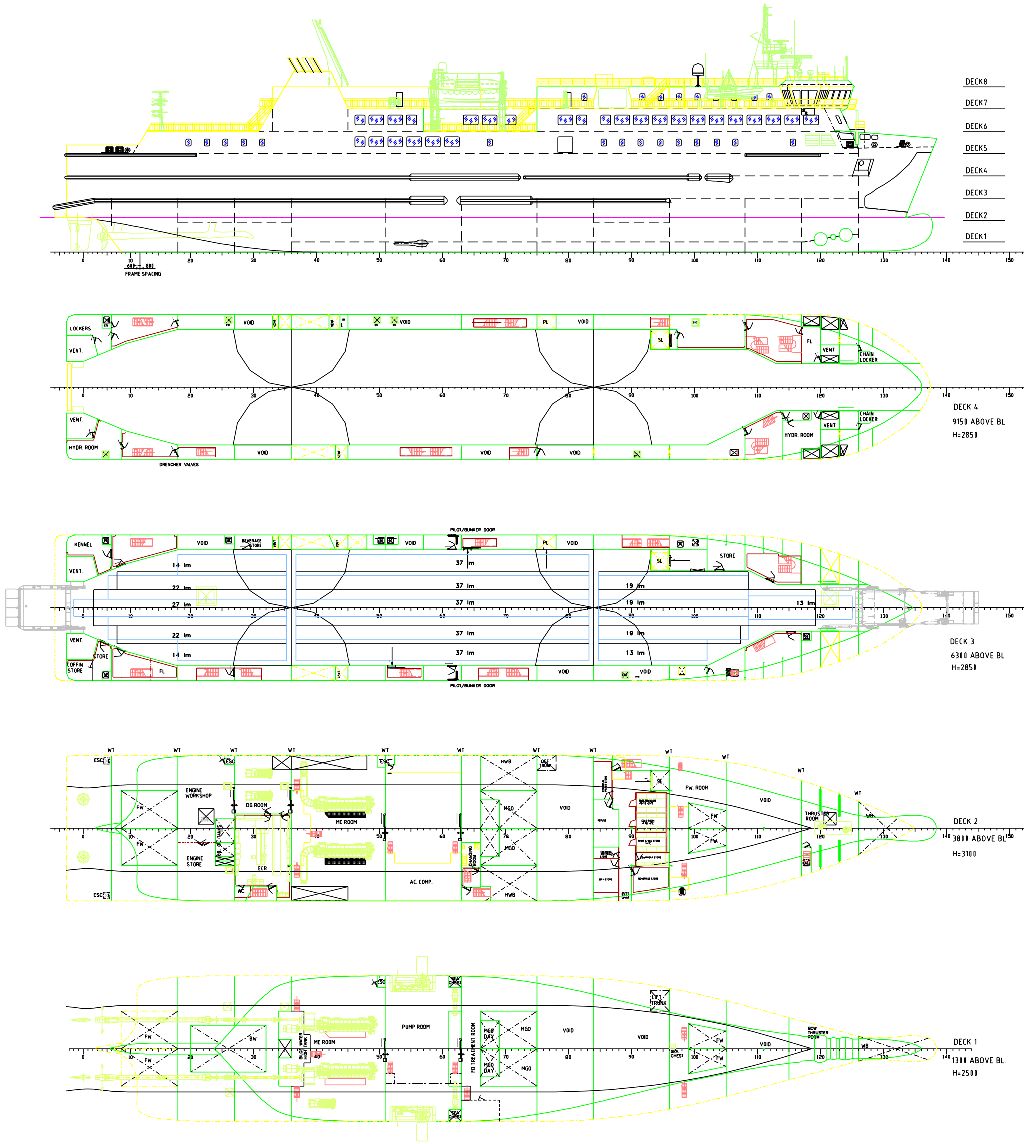
Passengers/cabins	465/16
Crew/cabins	35/35
Main Engines	2x4320 kW
Diesel Generators	3x545 ekW
Service Speed	18 kn
Lifesaving equipment	Short Int. 500 persons
Deadweight	1200 t
GT	8780

RORO CARGO CAPACITY

TRAILER LANES	300 LM
CAR LANES	80 LM

Figure 11 – SHIP No 1 – designed by STX Europe

SHIP No 1 (code EMRP01-SV_NH_SC) - Modified Design



MAIN DIMENSIONS:

LENGTH OA	abt. 112.0	m
LENGTH LPP	104.4	m
BREADTH	18.6	m
DRAUGHT DESIGN	4.4	m
DRAUGHT SCANTLING	4.5	m
DEPTH (DECK3)	6.3	m
DEPTH (DECK5)	12.0	m

MAIN DATA

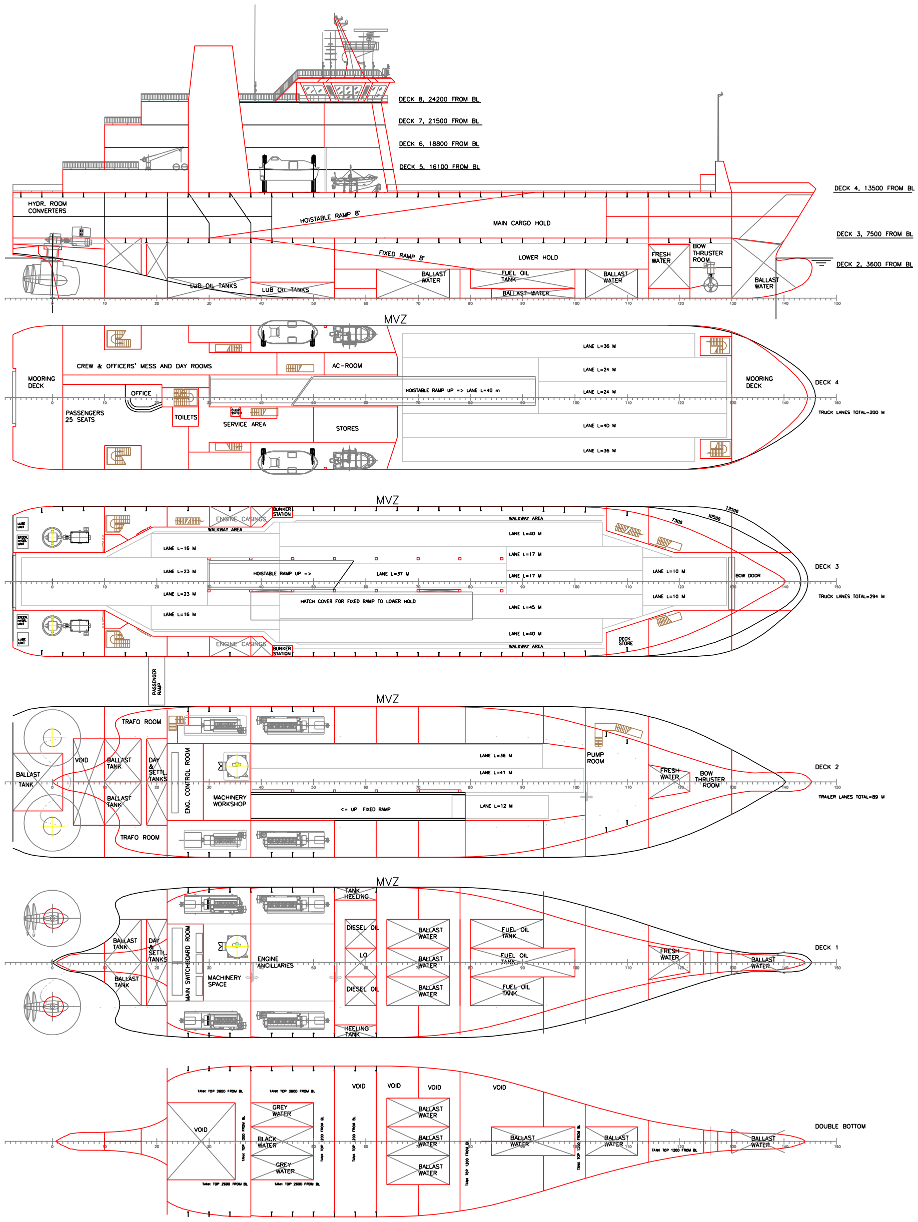
Passengers/cabins	465/16
Crew/cabins	35/35
Main Engines	2x4320 kW
Diesel Generators	3x545 ekW
Service Speed	18 kn
Lifesaving equipment	Short Int. 500 persons
Deadweight	1200 t
GT	8780

RORO CARGO CAPACITY

TRAILER LANES	284 LM
CAR LANES	83 LM

Figure 12 – SHIP No 1 (code EMRP01-SV_NH_SC) – Modified Design

SHIP No 2 (code EMRP01-SV_LH_SC) - designed by DELTAMARIN

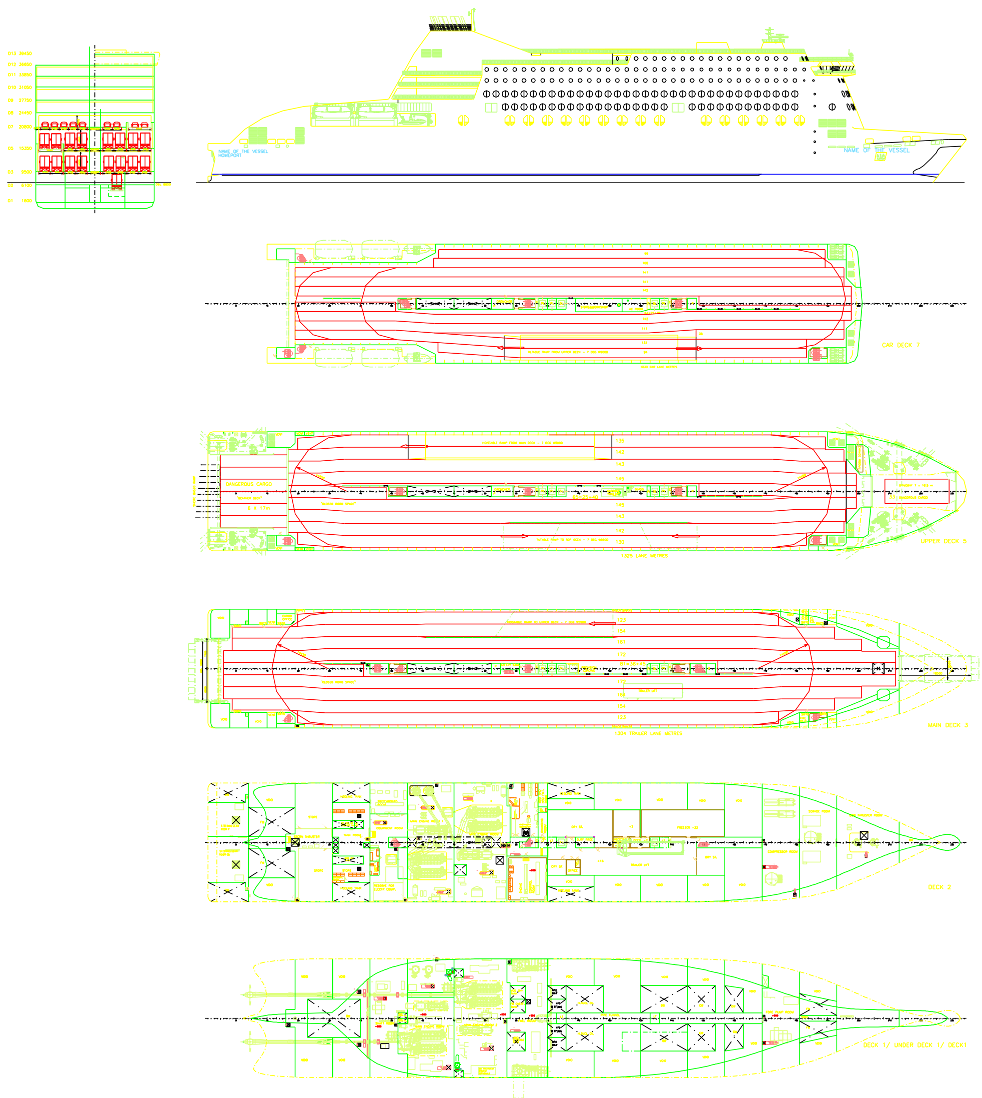


MAIN DIMENSIONS:	
LENGTH OA	100.0 m
LENGTH LPP	90.0 m
BREADTH (moulded)	18.8 m
DEPTH (main deck)	7.5 m
DRAUGHT dwl	5.0 m

MAIN DATA	
Passengers/cabins	300/16
Crew	18
Main Engines	2x2700 kW
	2x2000 kW
Service Speed	18 kn
Lifeboats	2*50 person
Deadweight	1650 t
GT	7500

Figure 13 – SHIP No 2 (code EMRP01-SV_LH_SC) – Designed by DELTAMARIN

SHIP No 3 (code EMRP02-LV_NH_CC) - designed by STX Europe



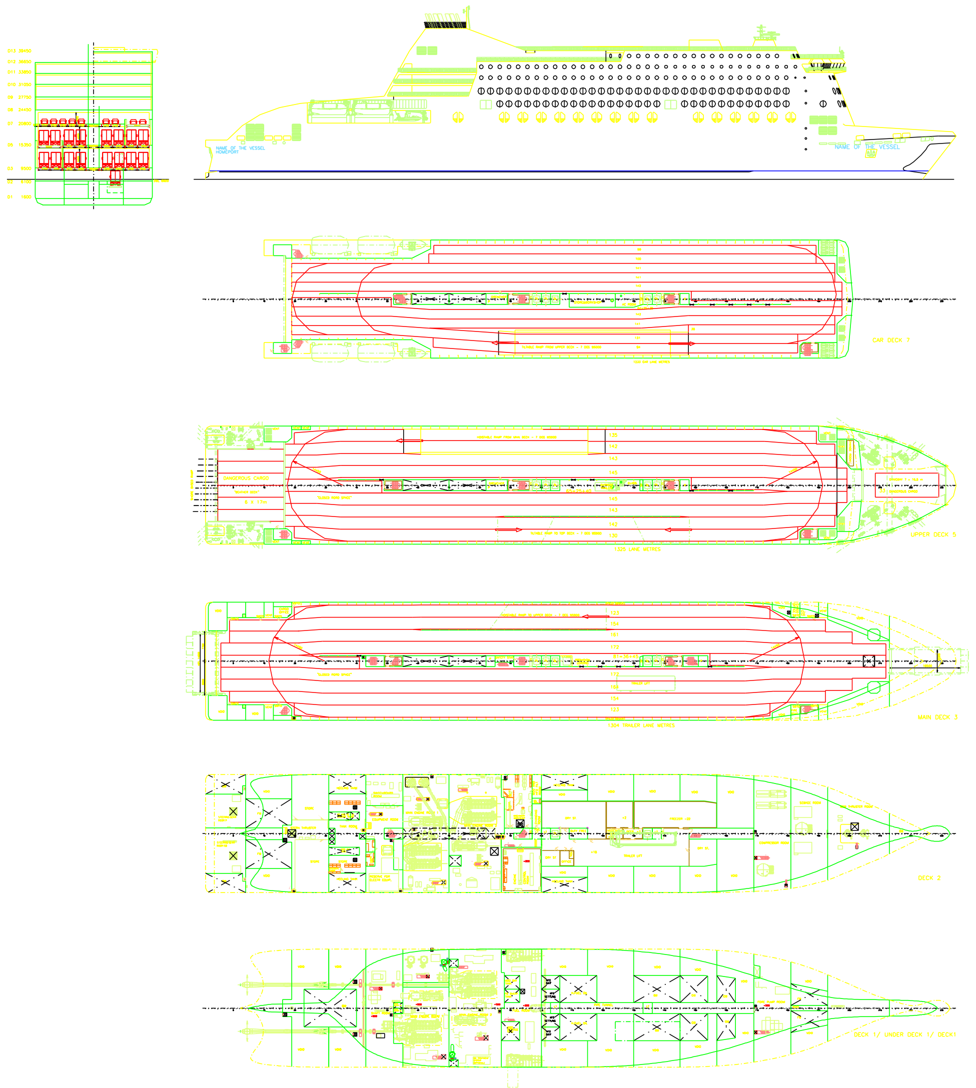
MAIN DIMENSIONS:	
LENGTH OA	195.0 m
LENGTH LPP	179.0 m
BREADTH (moulded)	30.4 m
H Main Deck	9.5 m
H Upper Deck	15.35 m
H Top Deck	20.80 m
DRAUGHT DESIGN	6.60 m
DRAUGHT SCANTLING	6.70 m

MAIN DATA	
Passengers/cabins	1900/300
Crew/cabins	100/100
Main Engines	4x7200 kW
Diesel Generators	4x1500 kW
Service Speed	22 kn
Lifesaving equipment	Short Int. 2000 persons
Deadweight	7200 t
GT	45000

TRAILER LANE METRES	
UPPER DECK 5	1325 LM
MAIN DECK 3	1304 LM
TOTAL	2629 LM

Figure 14 – SHIP No 3 (code EMRP02-LV_NH_CC) – Designed by STX Europe

SHIP No 3 (code EMRP02-LV_NH_CC) - Modified Design



MAIN DIMENSIONS:

LENGTH OA	195.0 m
LENGTH LPP	179.0 m
BREADTH (moulded)	30.4 m
H Main Deck	9.5 m
H Upper Deck	15.35 m
H Top Deck	20.80 m
DRAUGHT DESIGN	6.60 m
DRAUGHT SCANTLING	6.70 m

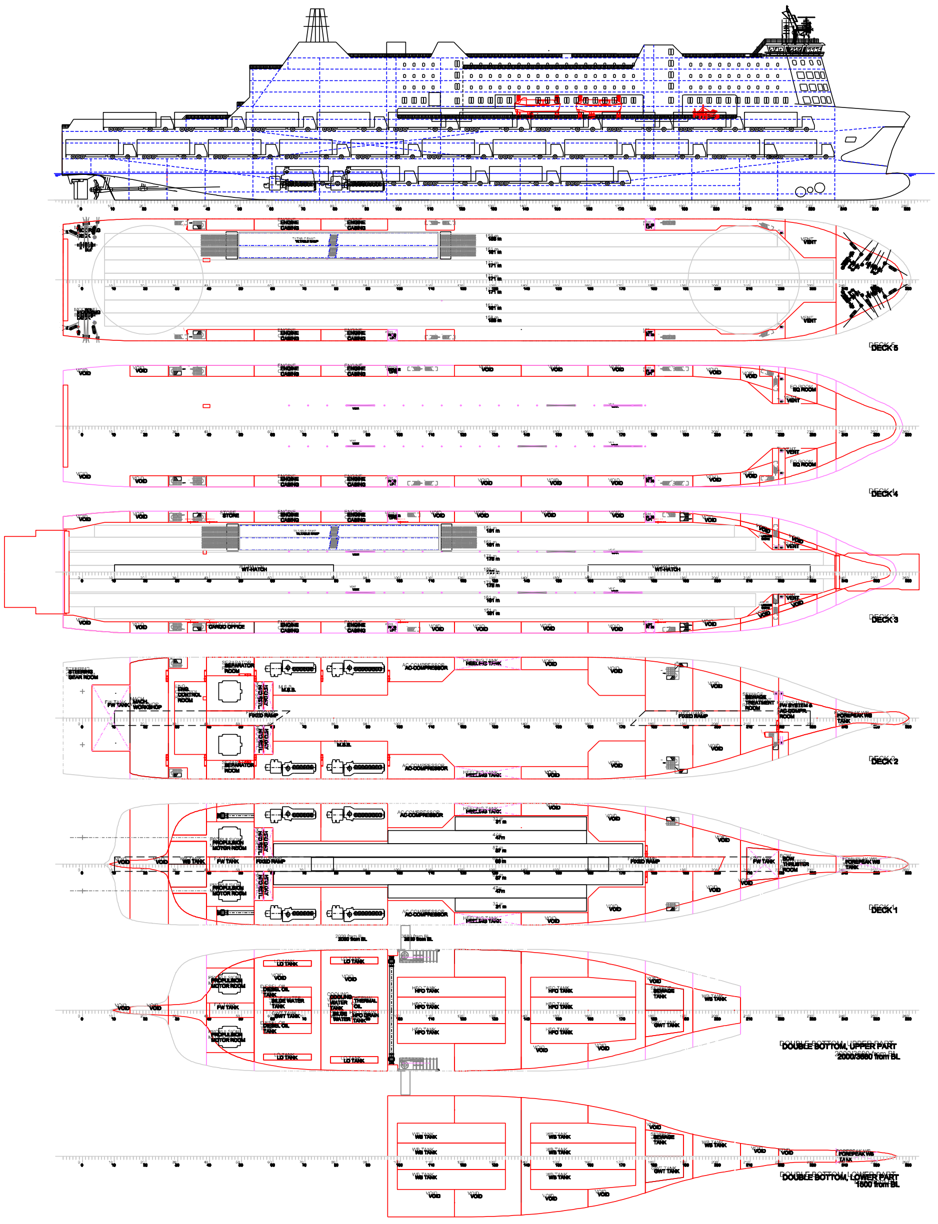
MAIN DATA

Passengers/cabins	1900/300
Crew/cabins	100/100
Main Engines	4x7200 kW
Diesel Generators	4x1500 kW
Service Speed	22 kn
Lifesaving equipment	Short Int. 2000 persons
Deadweight	7200 t
GT	45000

TRAILER LANE METRES	
UPPER DECK 5	1325 LM
MAIN DECK 3	1304 LM
TOTAL	2629 LM

Figure 15 – SHIP No 3 (code EMRP02-LV_NH_SC) – Modified Design

SHIP No 4 (code EMRP02-LV_LH_SC) - designed by DELTAMARIN

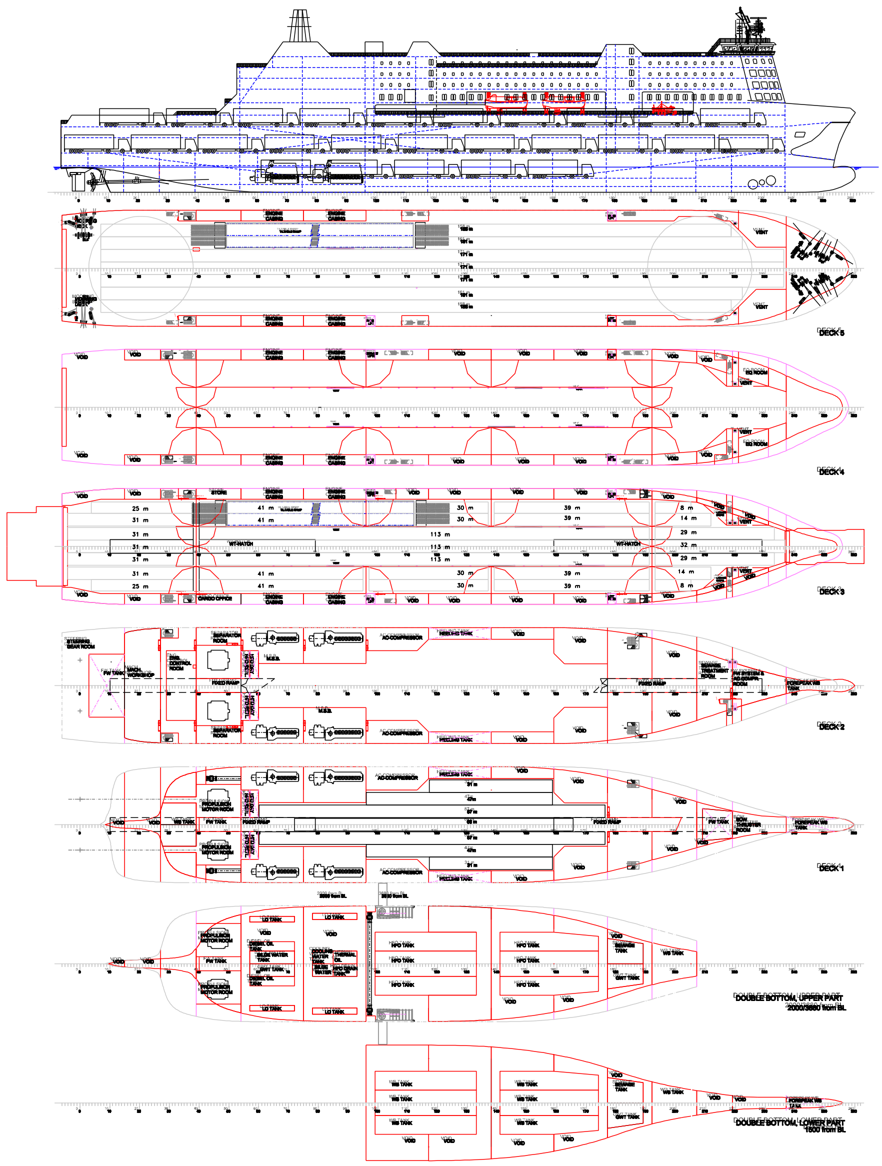


MAIN DIMENSIONS:		
LENGTH OA	199.96	m
LENGTH LPP	190.00	m
BREADTH (moulded)	29.40	m
DEPTH (Deck 3)	10.00	m
DEPTH (Deck 5)	16.65	m
DRAUGHT dwl	6.30	m

MAIN DATA	
Passengers/cabins	1560/520
Crew	85
Main Engines	2x8800 kW 2x6600 kW
Service Speed	21.5 kn
Lifeboats	4*150 person
Deadweight	7100 t
GT	45500

Figure 16 – SHIP No 4 (code EMRP02-LV_LH_SC) – Designed by DELTAMARIN

SHIP No 4 (code EMRP02-LV_LH_SC) - Modified Design



MAIN DIMENSIONS:

LENGTH OA	199.96	m
LENGTH LPP	190.00	m
BREADTH (moulded)	29.40	m
DEPTH (Deck 3)	10.00	m
DEPTH (Deck 5)	16.65	m
DRAUGHT dwl	6.30	m

MAIN DATA

Passengers/cabins	1560/520
Crew	85
Main Engines	2x8800 kW 2x6600 kW
Service Speed	21.5 kn
Lifeboats	4*150 person
Deadweight	7100 t
GT	45500

Figure 17 – SHIP No 4 (code EMRP02-LV_LH_SC) – Modified Design

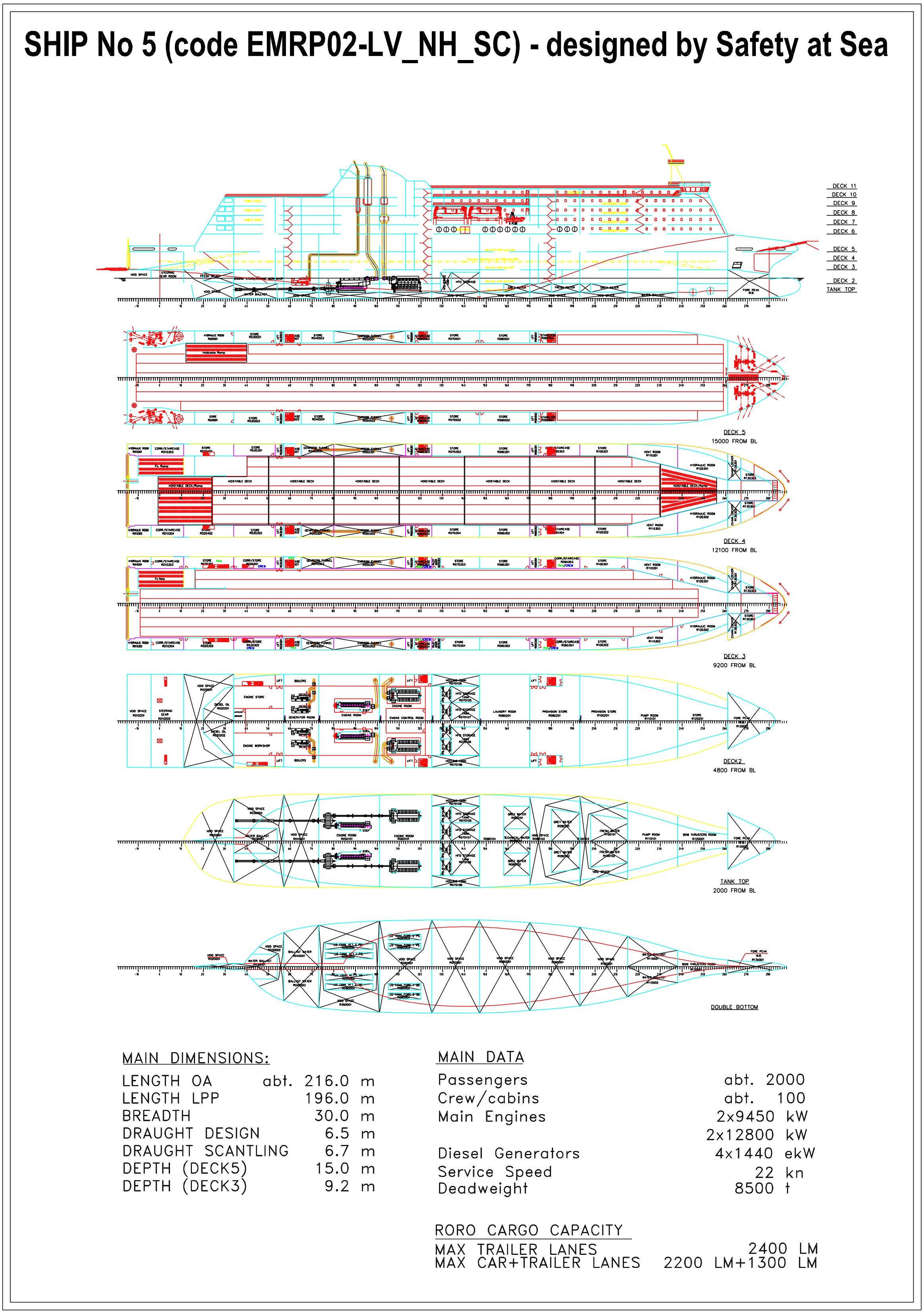


Figure 18 – SHIP No 5 (code EMRP02-LV_NH_SC) – Designed by Safety at Sea

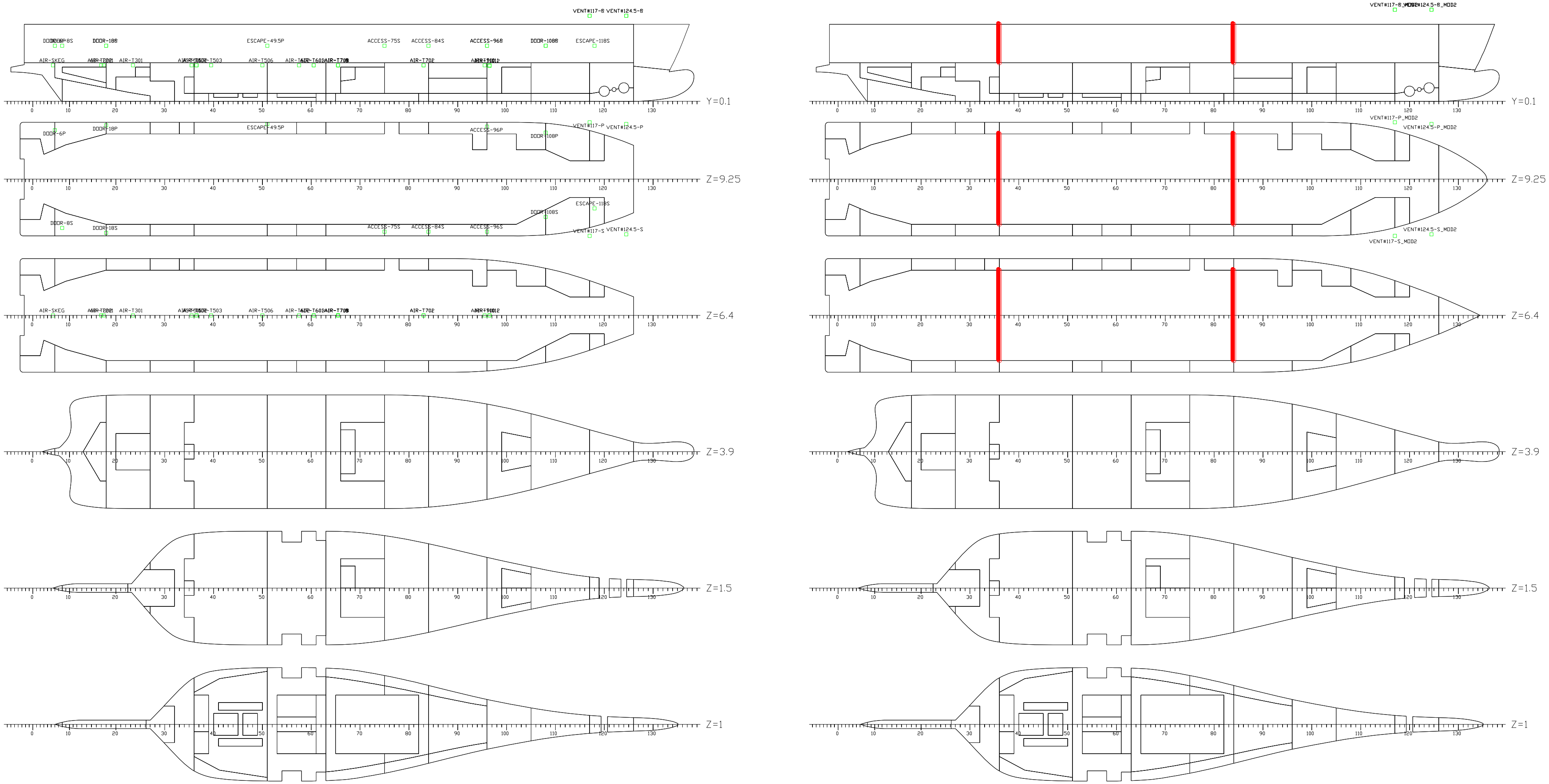


Figure 19 - SHIP 1, Original and Modified Design

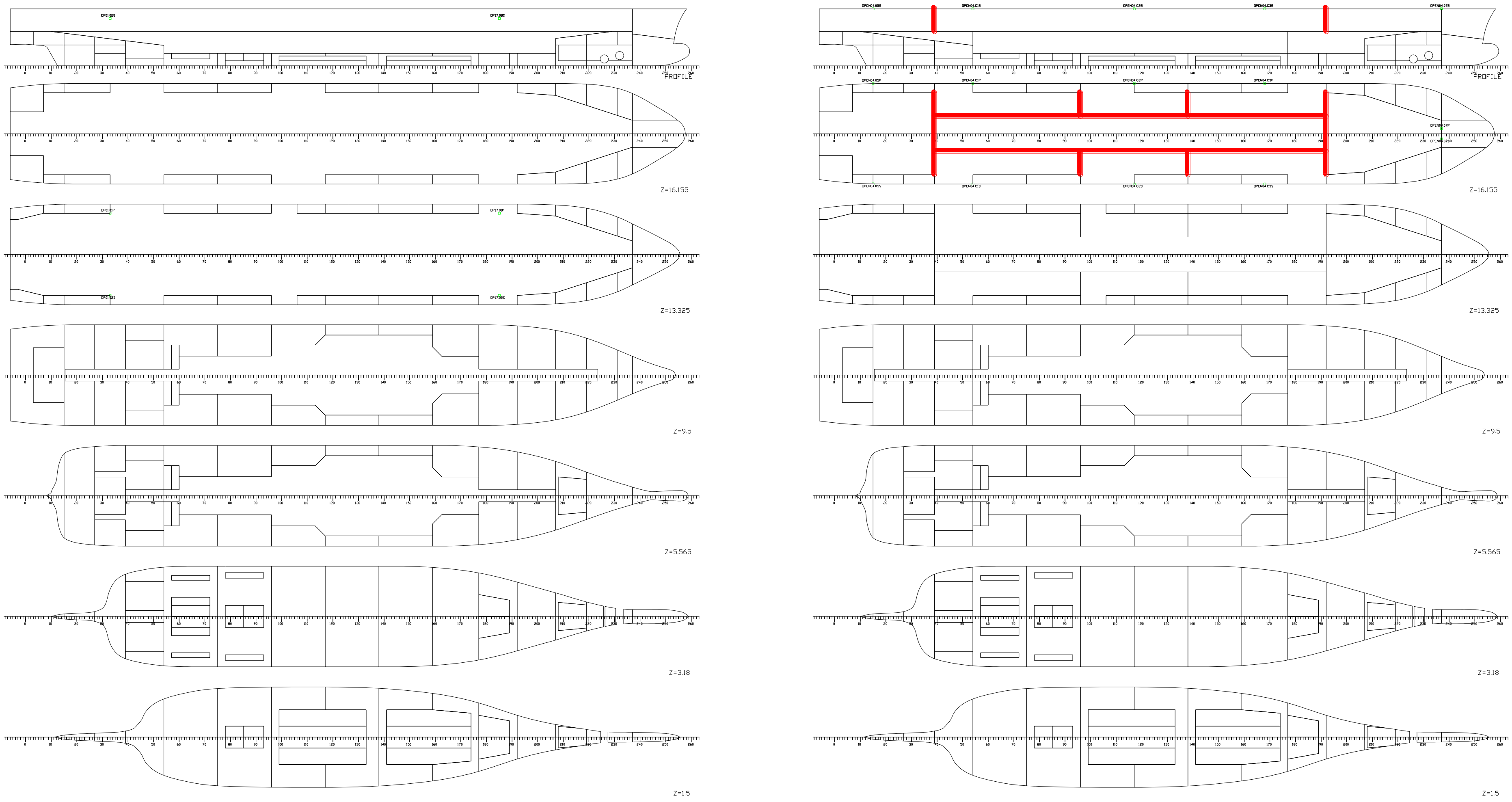


Figure 20 - SHIP 4, Original and Modified Design

5. Report of the Study and Recommendations

The study of the specific damage stability parameters of RoPax ships according to SOLAS 2009 including water on deck calculation undertaken in this project was performed in view of the latest standard on stability, as described in MSC 216 (82), [4].

The "water on deck" (WoD) issue was considered as the main problem for the RoPax stability in the previous regulations of the Stockholm Agreement. The approach of the Stockholm Agreement assumes a specific water wedge on the deck depending on the height of the freeboard.

The SOLAS 2009 standard includes the WoD effect in an implicit manner by means of regression-based relationship between ship parameters and critical sea state observed in experiments.

However the present study demonstrates that WoD is only an element of ship stability after flooding, specifically affecting flooding cases which otherwise would have some residual stability. A much bigger issue is presented by many flooding cases which results in zero stability after flooding with rapid capsize in calm seas.

The SOLAS 2009 method has a wider scope; it can address the problem of ship stability after flooding, including cases of zero stability. Therefore, the following parameters of the SOLAS 2009 are considered as the key for addressing the objectives of this research study:

- Factor s (accommodates for ship architecture, waves, water accumulation);
- Factor K (accommodates for abandonment);
- Factor w (accommodates for loading conditions);
- Factor A (relates all parameters with one another);
- Factor R (sets level of stability).

All theoretical details deemed relevant for explaining the relationship between the Stockholm Agreement and SOLAS 2009, as well as highlighting overall issues of choosing adequate regulations on stability, sensitivity studies and ensuing observations or conclusions are presented in this chapter, followed by clear recommendations on possible amendments to regulations aiming for rationalisation of goals of any ship stability standard.

5.1. Ship Stability Parameters

The study comprised techniques available for addressing the problem of stability, including physical model experiments and numerical time-domain simulations to supplement with further evidence on the observable physics affecting ship stability.

The observed physical behaviour was then compared with various simplified mathematical formulas that use ship design parameters, and ultimately form basis for judgement of adequacy of ship stability.

5.1.1. Factor s

The most recent factor s was derived during project HARDER No: GRD1-1999-10721.

As reported in [21], the "factor s represents a measure of the probability of survival of a damaged vessel accounting for the dynamic effects of waves and ensuring accumulation of water on deck …".

The formulae is given below as (1).

$s_{\text{final},i} = K \cdot \left[\frac{GZ_{\max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}}$ $GZ_{\max}$ is not to be taken as more than 0.12 m;	*Regulation 7-2.3 of IMO MSC.216(82)*	(1)

Note that the construct s has been referred to most often as a "factor" or "index", supposedly for ease of communication among the engineering community. However, it would be more appropriate to relate to s exclusively as probability, since the process of engineering derivation and mathematical operations, as reported in [21] and [19] and summarised as (2), are consistent with this meaning.

For RoRo Ships: $H_S = 6.7h - 0.8f - 0.9$ For Non-RoRo Ship: $H_S = 4 * (GZmax/TGZmax)*(Range/TRange)$ Where, TGZmax = 0.12m and GZmax not to exceed TGZmax TRange = 16 degrees and Range not to exceed TRange For all types: $S = 0$, if GZmax < 0.05 or Range < 7degrees $S = \exp(-\exp(0.16-1.2*H_S))$	(2)

The marginalisation process

Furthermore, for the purpose of explanation of the significance of physical experiments, numerical tests, and expert analyses and observations made in this project, it is important to highlight what the meaning intended for s was in the statement mentioned above that "*factor s represents a measure of the probability of survival of a damaged vessel in waves …*", and which meaning has subsequently been executed, without detailed explanation, in the latter part of the process (2).

To state that s is intended to assign a probability that a ship at draught T_j survives a flooding case "$d_{i,k}$" in "waves" (including effects of accumulation of water on deck), whereby "waves" was assumed to represent <u>a range of sea conditions</u> that may be encountered whilst suffering a <u>collision incident</u>, i.e. $Hs \equiv Hs|coll$, is equivalent to construct a model (3), representing what can be termed an expectation integral, or the Bayes' theorem on total probability:

$s_{i,j,k} = \int_0^\infty dHs \cdot f_{Hs\|coll}(Hs) \cdot F_{surv}(t_0 \| d_{i,k}, T_j, Hs)$	(3)

Where $f_{Hs|coll}(Hs)$ is probability density distribution for sea states expected to be encountered during a collision incident, see Table 3 and Figure 21, resulting in flooding extent $d_{i,k}$ (flooding case "*i*" involving spaces up to horizontal subdivision "*k*") whilst the ship operated at draught T_j. Note that (3) could also be denoted as $s_{i,j,k} \equiv (s_i | T_j \,\&\, h_k)$. Note that relevant statistics for sea states encountered during collisions were derived in an European Commission funded project HARDER, [31], which summarised the process of derivation as follows: "*From the original 3000 damage records, the sample has been reduced to 502 cases for which two conditions are fulfilled; the weather is reported, and the ship is a "struck ship". The sample is further reduced to 389 by disregarding incidents at rivers and channels, to make the requirements valid for pure ocean going ships."*

Table 3 - Wave height distribution recorded during collisions

Hs		No. of cases	Cumulative	
			Numbers	%
0		112	112	0.288
0 -	0.5	100	212	0.545
0.5 -	1	70	282	0.725
1 -	1.5	50	332	0.853
1.5 -	2	4	336	0.864
2 -	2.5	30	366	0.941
2.5 -	3	0	366	0.941
3 -	3.5	13	379	0.974
3.5 -	4	1	380	0.977
4 -	4.5	3	383	0.985
4.5 -	5	0	383	0.985
5 -	5.5	0	383	0.985
5.5 -	6	3	386	0.992
6 -	6.5	0	386	0.992
6.5 -	7	0	386	0.992
7 -	7.5	0	386	0.992
7.5 -	8	0	386	0.992
8 -	8.5	0	386	0.992
8.5 -	9	0	386	0.992
9 -	9.5	2	388	0.997
9.5 -	10	0	388	0.997
10 -	10.5	0	388	0.997
10.5 -	11	0	388	0.997
11 -	11.5	0	388	0.997
11.5 -	12	0	388	0.997
12 -	12.5	0	388	0.997
12.5 -	13	0	388	0.997
13 -	13.5	0	388	0.997
13.5 -	14	0	388	0.997
14 -	14.5	1	389	1.000

Source: HARDER [31]

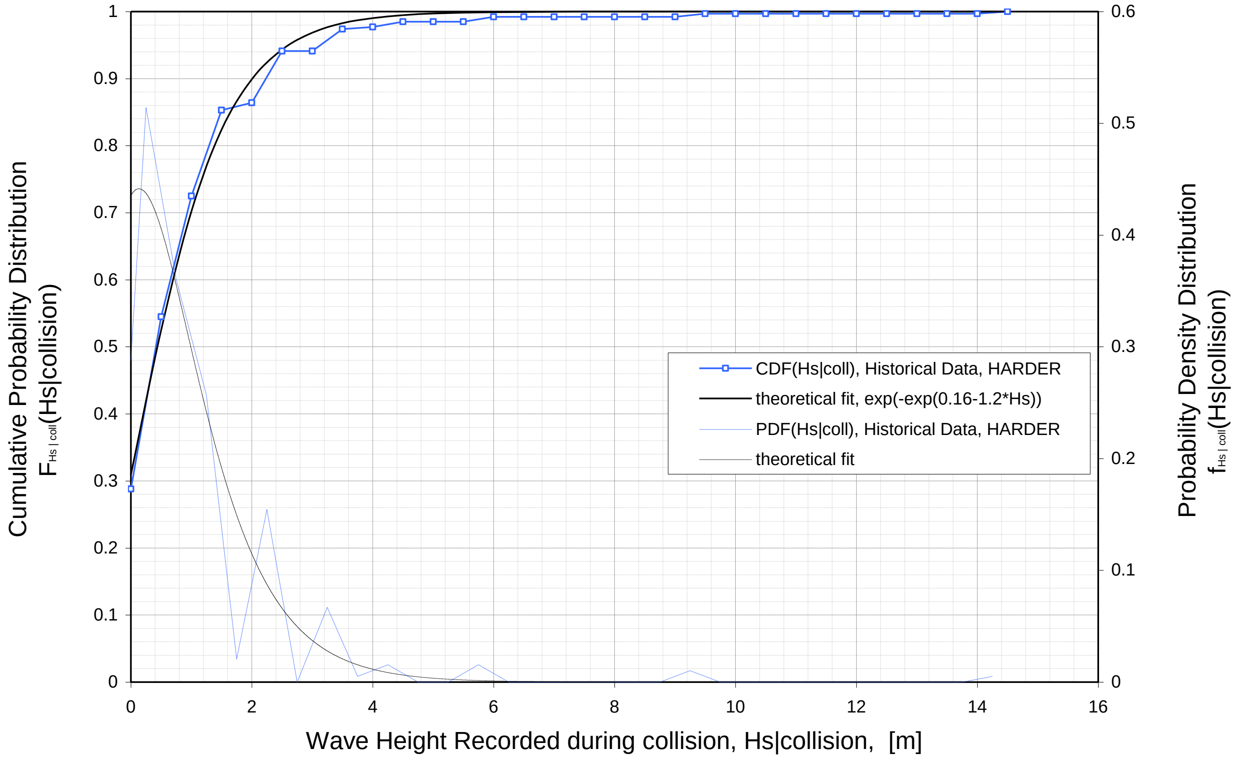


Figure 21 - Probability distributions for wave height recorded during collisions, Data from Table 3. Fit model given in [19]

The cumulative probability distribution for sea state Hs|coll to be encountered during a collision event $F_{Hs|coll}(Hs)$ can be approximated by equation (4), as shown in Figure 21:

$F_{Hs\|coll}(Hs) = e^{-e^{0.16-1.2\cdot Hs}}$	(4)

With $f_{Hs|coll}(Hs)$ derivable as follows:

$f_{Hs\|coll}(Hs) = \frac{dF_{Hs\|coll}}{dHs}$	(5)

A "collision incident" at sea state Hs, mentioned above, is assumed to lead the vessel at draught T_j to a specific flooding extent $D = d_{i,k}$ and resulting from a set of all possible hull breaches, denoted as Ω_i henceforth, that can bring about exactly that flooding extent $D = d_{i,k}$. Note again that the hull breaches are characterised by location " x_i ", length " λ_i ", penetration " b_i " and height " h_k ", that is the set $\Omega_i = \{x_i, \lambda_i, b_i, h_k\}$. Therefore, the $F_{surv}(t_0 | d_{i,k}, T_j, Hs)$ in equation (3) is the probability that the vessel operating at draught T_j will survive for a period of t_0 minutes in specific sea state Hs when exposed to such specific flooding case $D = d_{i,k}$ resulting from any of hull breaches $\Omega_i = \{x_i, \lambda_i, b_i, h_k\}$, and resulting, among others, to flooding of car deck spaces.

Since there are many possible hull breaches that can lead to such specific flooding extent, whereby there is a range of x positions that can cause the flooding extent "*i*", range of λ, etc, the $F_{surv}\left(t_0 \middle| d_{i,k}, T_j, Hs\right)$ is, furthermore, a marginalised case of survivability $F_D\left(t_0 \middle| x_i, \lambda_i, b_i, h_k, T_j, Hs\right)$ for every such hull breach case, characterised by its location "x", length "λ", penetration "b" and height "h", and all of which can cause flooding extent $D = d_{i,k}$. This can be written as (6) as follows:

$$F_{surv}\left(t_0 \middle| d_{i,k}, T_j, Hs\right) = \int_{\Omega_i} d\Omega_i \cdot f_{\Omega_i}\left(x_i, \lambda_i, b_i, h_k\right) \cdot F_D\left(t_0 \middle| x_i, \lambda_i, b_i, h_k, T_j, Hs\right)$$	(6)

The provisions of [1] and [2] assume that (6) can be approximated with (7) as follows:

$$F_{surv}\left(t_0 \middle| d_{i,k}, T_j, Hs\right) \approx F_D\left(t_0 \middle| x^*, \lambda^*, b^*, h^*, T_j, Hs\right)$$	(7)

Where the damage characteristics x^*, λ^*, b^*, h^* are specified in [2] as (8):

1. trapezoidal profile with side at 15° slope to the vertical and the width at the design waterline defined according to SOLAS regulation II-1/8.4.1; 2. isosceles triangular profile in the horizontal plane with the height equal to B/5 according to SOLAS regulation II-1/8.4.2. If side casings are fitted within B/5, the damaged length in way of the side casings should not be less than 25 mm;	(8)

The specifications (8) can be expressed as (9):

$x^* = bulkhead\_position$ $\lambda^* = 0.03 \cdot Lpp + 3$ $b^* = B/5$ $h^* = \infty$	(9)

In other words, it is assumed that probability of survival of the vessel for a period of t_0 minutes in given sea state Hs when subject to given flooding extent $D = d_{i,k}$ and resulting from all feasible hull breaches, as shown in Figure 22 and Figure 23, can be represented by probability of such survival tested for only one specific set of hull breach characteristics as given by (9) and shown in Figure 24, Figure 25, Figure 26 and Figure 27. Note also the indication of damage characteristics shown in Figure 23.

The assumption (7) is made in a similar fashion for both the Stockholm Agreement and the SOLAS 2009 stability standards for a flooding extent spanning typical two-compartment damages.

Its use for either two, three or more flooded zones cases does not seem to have been thoroughly substantiated.

A numerical simulation based on Monte Carlo (MC) sampling, as shown in Figure 22 and Figure 23, has been used to solve equation (6) and so thus to test assumption (7).

As shown in Figure 28, the assumption seems to be conservative for this particular design configuration, whereby simulations for a single hull breach seem to lead to the ship capsizing at lower seas than for simulations carried out for all feasible hull breaches leading to flooding within zone DS/6-7.

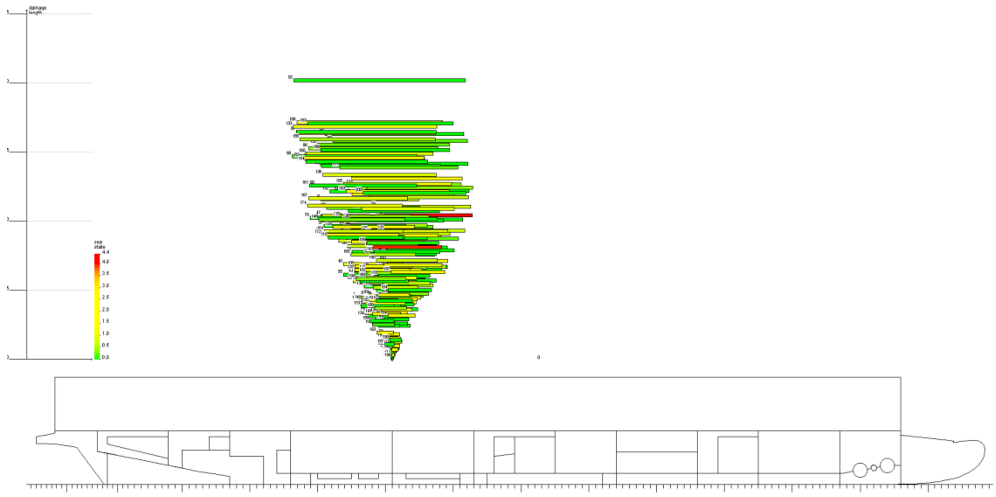
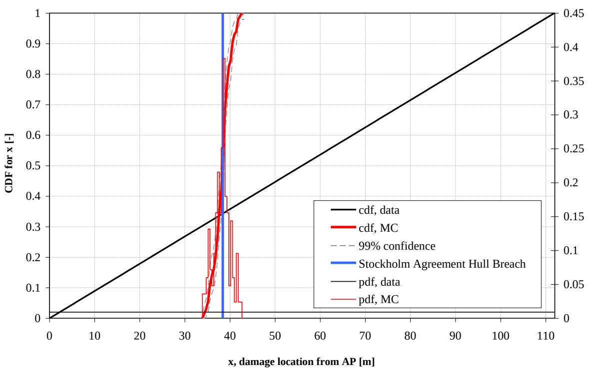
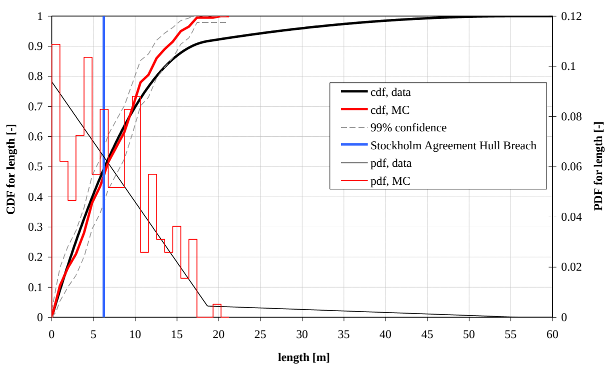


Figure 22 - Set of 200 hull breaches leading to flooding extent DS_REG7_P6-7.4.0 on SHIP 1

Figure 22 shows a set of 200 hull breaches leading to flooding extent DS_REG7_P6-7.4.0 on SHIP 1. The bars represent location and length of hull breach. The coloured bars represent the sea state (green signifies Hs = 0m and red Hs = 4m). Numerical Monte Carlo (MC) solution to (6).





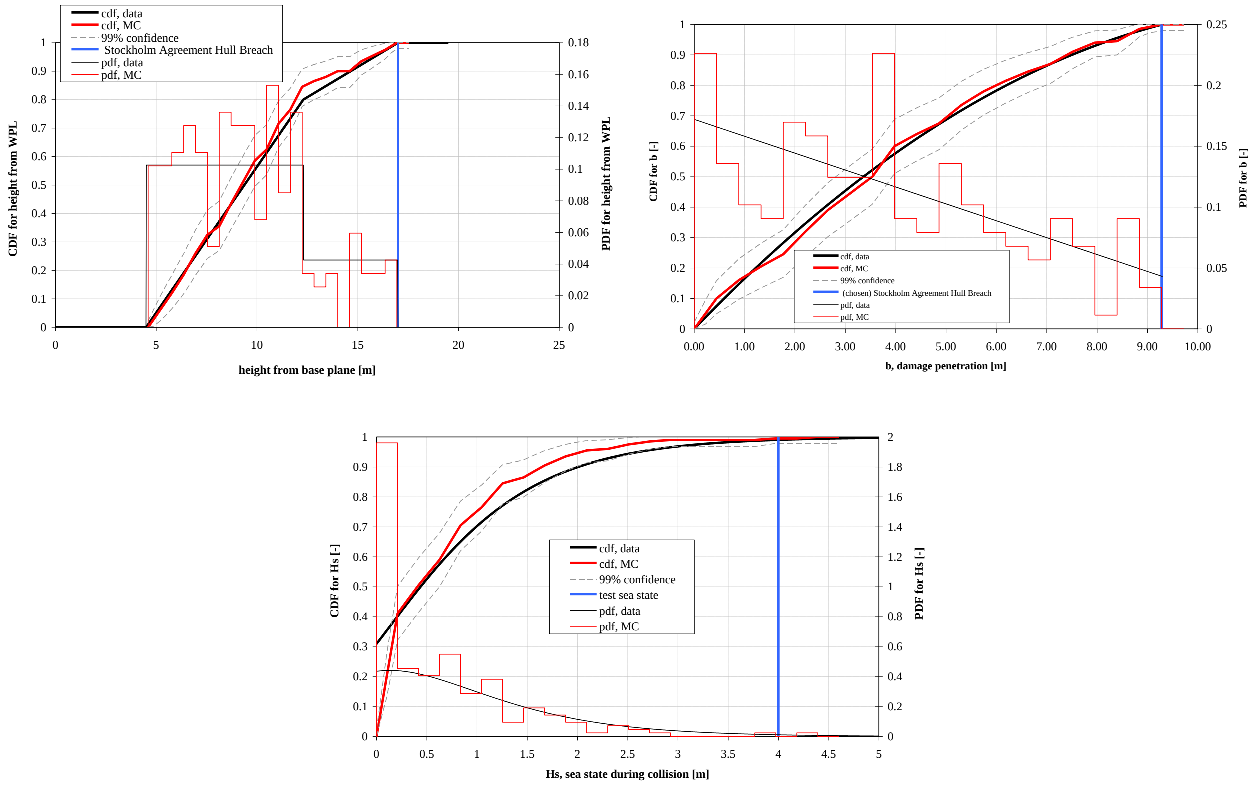


Figure 23 - Distributions of probability for damage characteristics and sea states during collision shown in Figure 22

In Figure 23, the specifics of hull breach (9) are marked by the blue lines.

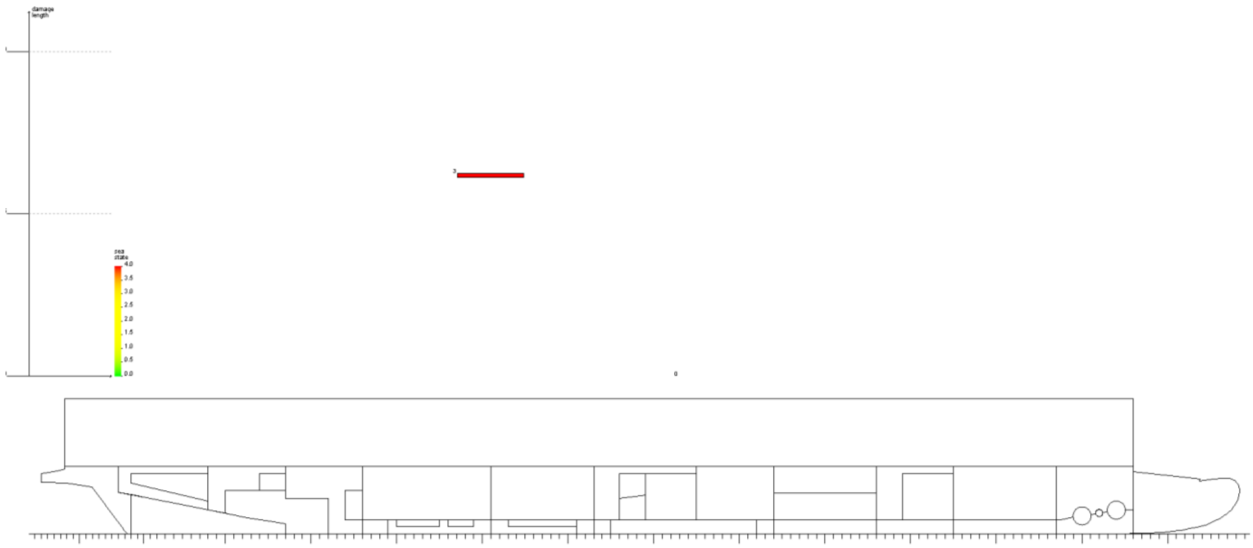


Figure 24 - Single hull breach leading to flooding extent DS_REG7_P6-7.4.0 on SHIP 1

Figure 24 shows a single hull breach leading to flooding extent DS_REG7_P6-7.4.0 on SHIP 1. The single bar represents the location and length of the hull breach as given by (8) and (9).

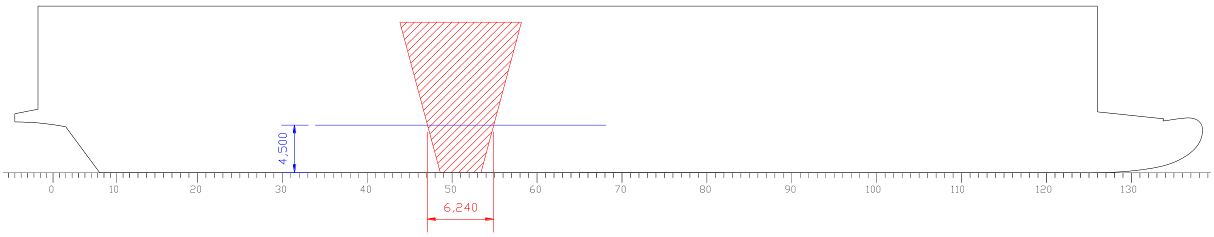


Figure 25 - A hull breach according to (8) and (9), SHIP 1

Model No. 2446B

Figure 26 - Hull breach according to (8) and (9), SHIP 1, physical model test, case R7_P6-7.4.0

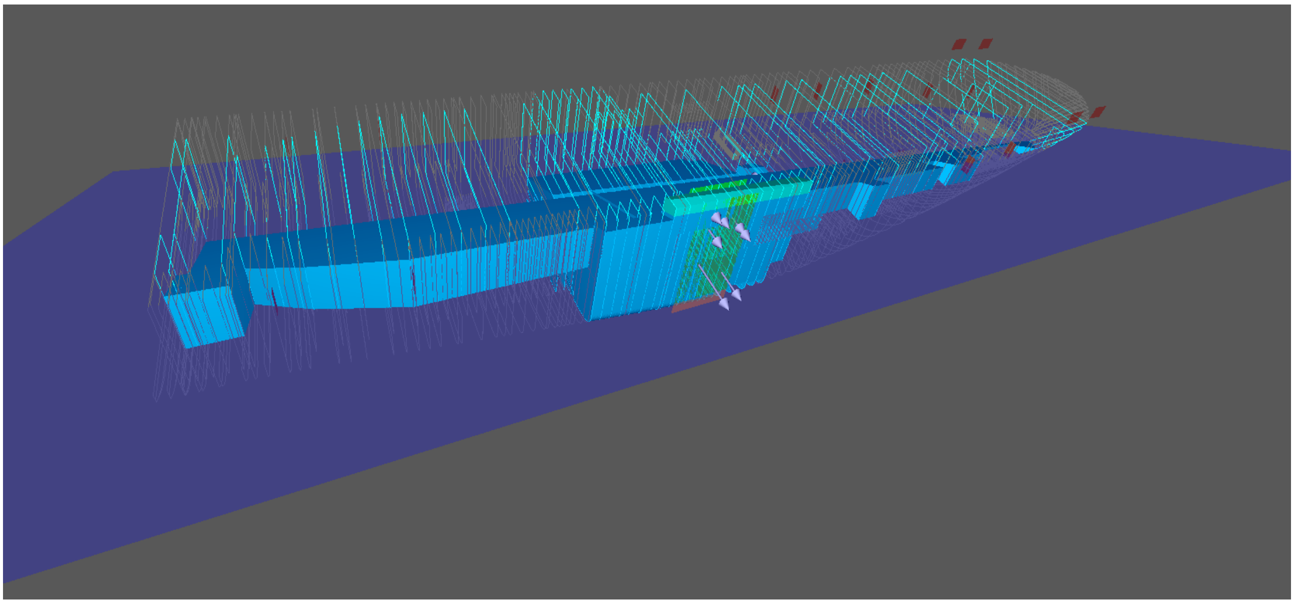


Figure 27 - Hull breach according to (8) and (9), SHIP 1, numerical simulation, case R7_P6-7.4.0

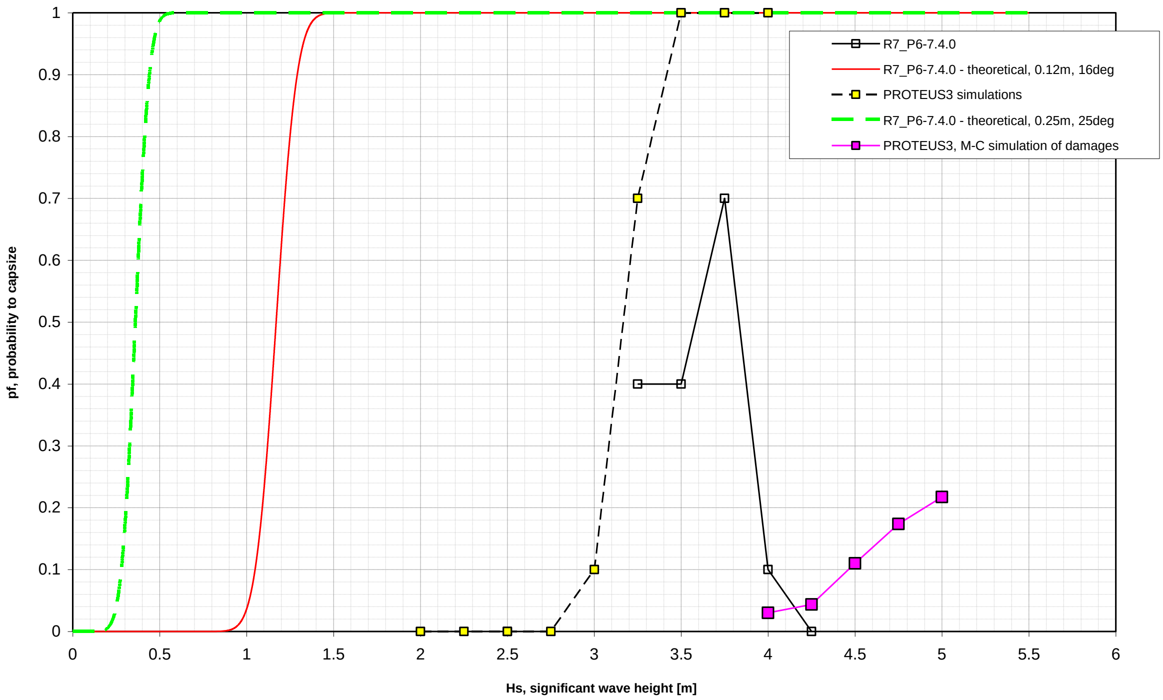


Figure 28 - Hull breach according to (8) and (9), SHIP 1, summary of results

Based on this one sample study case, it could be inferred that the probability of not losing stability can adequately be assessed as $F_{surv}(t_0|d_{i,k},T_j,Hs)$ for a specific flooding extent $d_{i,k}$, and assuming it results from what appears to be an onerous hull breach (9), and which can thus be systematically derived from physical model tests. Note that testing for a series of damages as performed numerically (see Figure 22) is simply impractical.

The nature of function (6) or (7) can be observed in Figure 28 (note that function $F_{surv}(t_0|d_{i,k},T_j,Hs)$ is a complement of the function p_f, that is $F_{surv}(t_0|d_{i,k},T_j,Hs)=1-p_f$. It has been known and observed in experiments of the HARDER project, that for some flooding cases and loading conditions, the vessel will not capsize at low sea states, i.e. $F_{surv}(t_0|d_{i,k},T_j,Hs)=1$ (i.e. pf=0), whereas it would capsize in all 30 minute tests for higher sea states, i.e. $F_{surv}(t_0|d_{i,k},T_j,Hs)=0$, (pf=1), with some transition $0<F_{surv}(t_0|d_{i,k},T_j,Hs)<1$ taking place for a range of sea states somewhere in between these extremes.

Note that the mentioned phenomenon of capsizing was a result, among others, of the process of water accumulation on the vehicle deck for RoPax ships, and that, therefore, $F_{surv}(t|d_{i,k},T_j,Hs)$ reflects this process.

The transition in $F_{surv}(t_0|d_{i,k},T_j,Hs)$ from 1 to 0 was observed and reported earlier in documents [5] to [9], and has eventually been approximated with model (10):

$F_{surv}\left(t \middle| d_{i,k}, T_j, Hs\right) = \left[1 - \Phi\left(\frac{Hs - H_{crit,i,j,k}}{0.039 \cdot H_{crit,i,j,k} + 0.049}\right)\right]^{\frac{t}{t_0}}$	(10)

Where $\Phi(z)$ is the cumulative standard normal probability distribution function.

$H_{crit,i}$ is the 50[th] percentile significant wave height in which a ship subjected to flooding scenario case d_i might capsize within $t = 30$ minutes, approximated according to (11).

$t_0 = 30\,\text{min}$ is the benchmark physical testing time.

$H_{crit,i,j,k} = 4 \cdot \left(\frac{GZ_{\max,i,j,k}}{0.12} \cdot \frac{Rnage_{i,j,k}}{16}\right)$	(11)

Adopting (10) as a sufficient model allows resolving the formulae (3) for consistent assignment of probability that a ship, suffering specific flooding extent $D = d_{i,k}$, will survive for 30 minutes in among any of the random sea states that might be encountered during collision leading to this flooding extent (a set of all pertinent hull breaches). Note that this is a viable rational methodology for dealing with the fact that nobody knows which sea state a ship might encounter during a collision.

Model (10) was not available during development of "factor s" and a simplification was adopted in (2) implying that the survivability for 30 minutes in specific sea conditions and subject to flooding and including progressive accumulation of water on deck for RoPax-type ships, $F_{surv}\left(t_0 \middle| d_{i,k}, T_j, Hs\right)$, could be represented with jump function (12) instead:

$F_{surv}\left(t_0 \middle| d_{i,k}, T_j, Hs\right) = \begin{cases} 1 & \Leftrightarrow \quad Hs \le H_{crit,i,j,k} \\ 0 & \Leftrightarrow \quad Hs > H_{crit,i,j,k} \end{cases}$	(12)

This assumption allows the integral (3) to be solved as follows:

$s_{i,j,k} = \int_0^{H_{crit,i,j,k}} dHs \cdot f_{Hs\|coll}(Hs)$	(13)

Following from the above, the probability $s_{i,j,k}$ can be assigned as (14), which is the model proposed in statement (2) of the HARDER project:

$s_{i,j,k} = F_{Hs\|coll}\left(H_{crit,i,j,k}\right)$	(14)

It appears that the significance of these assumptions have never been discussed or disclosed, but they bear relevance if decisions on improvements are to be considered. Namely, the following questions need to be addressed:

- Is the approximation (12) to the observable survivability (10) adequate?

- Is the survivability for 30 minutes appropriate for an instrument for judgement on ship safety?

- Does probability $s_{i,j,k}$ account for accumulation of water on deck?

To examine all these queries, in the first instance the equation (3) for assigning probability $s_{i,j,k}$ has been assessed for three hypothetical flooding cases resulting to an assumed $Hcrit_{50\%}$ = 1, 2 and 3m, and for approximation to F_{surv} as given:

- by model (10) for t=30min;

- by model (12) for Hcrit assumed to be median (50%) survival sea state;

- by model (10) for t=10hours.

The results are presented in Figure 30 to Figure 38 for each of the flooding cases (H_{crit}=1,2, and 3m) and for the different approximations to F_{surv}, respectively. A comparative summary for the calculated probability s is given in Figure 29.

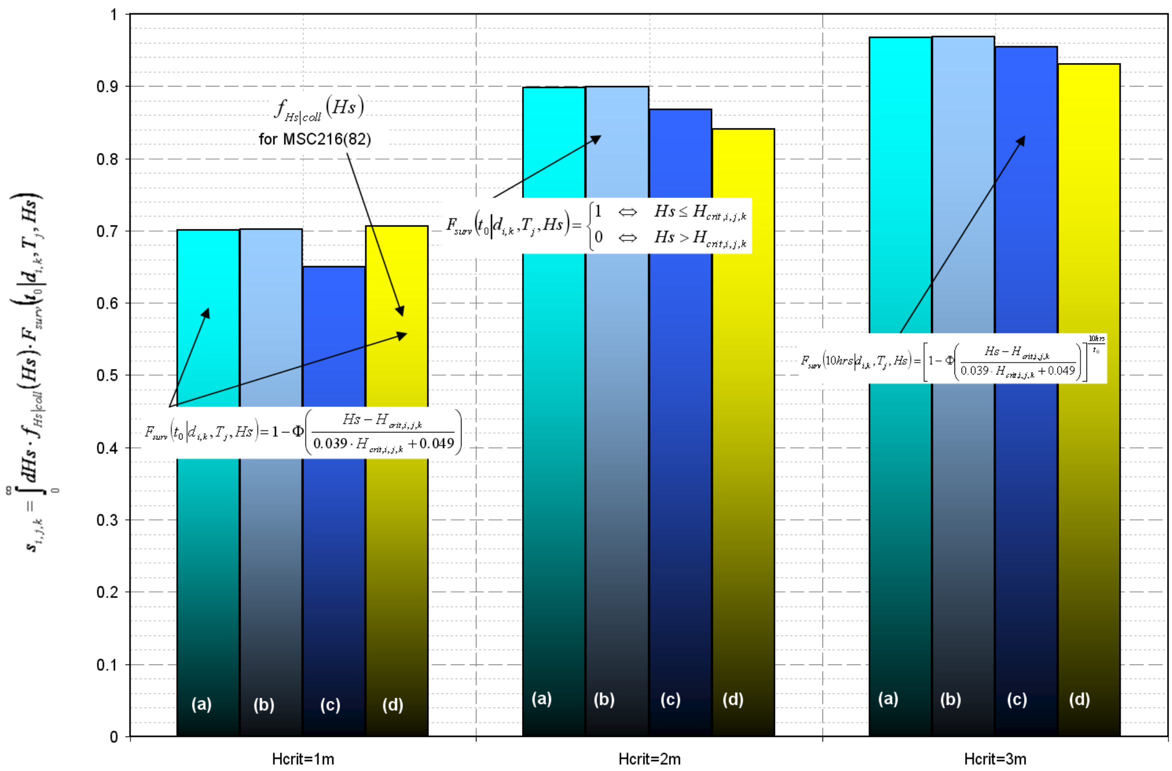


Figure 29 - Probability s for three flooding cases as per different approximate solutions to model (3)

Figure 29 shows a summary of the probability s for the three flooding cases (Hcrit = 1, 2 and 3m) and for the different approximate solutions to model (3), namely, assuming F_{surv}, given (a) by model (10) for t = 30min, (b) by model (12) for Hcrit assumed to be median (50%) survival sea state, (c) by model (10) for t = 10hours. The yellow bars correspond to solution (a) but with (4) replaced by (14) in equation (3).

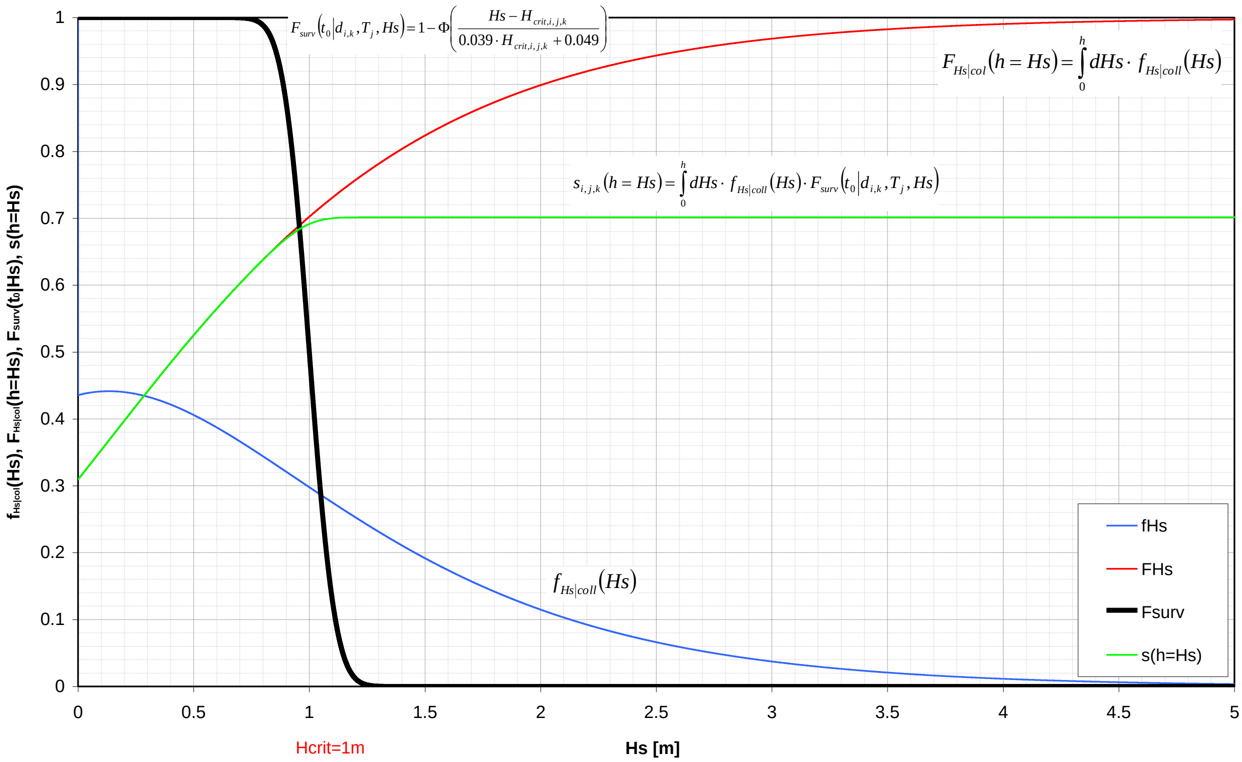


Figure 30 - Probability s as an averaging of survivability (1)

Figure 30 shows the process of assigning the probability s as an averaging (marginalisation) of survivability for a flooding case resulting in $Hcrit_{50\%}$ = 1m, based on (10) for t = 30min.

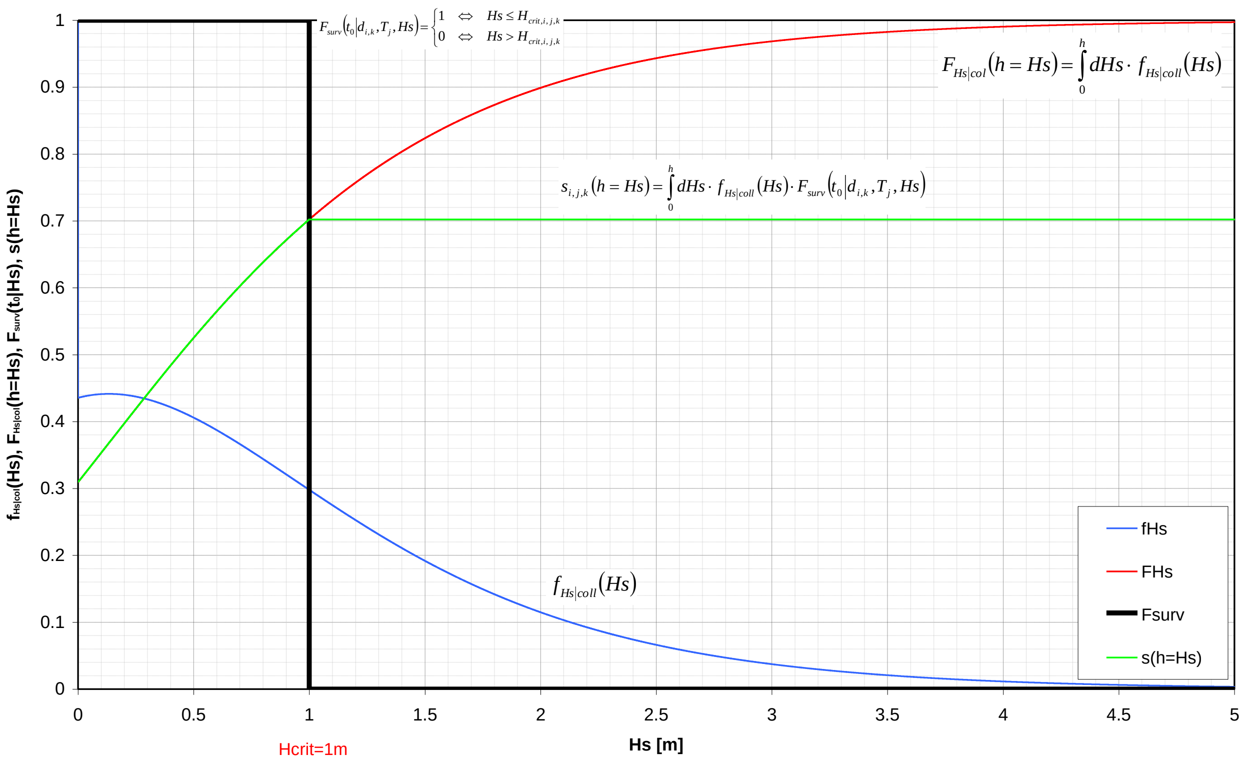


Figure 31 - Probability s as an averaging of survivability (2)

Figure 31 shows the process of assigning the probability s as an averaging (marginalisation) of survivability for a flooding case resulting in $Hcrit_{50\%}$ = 1m, based on (12) for Hcrit assumed to be median (50%) survival sea state.

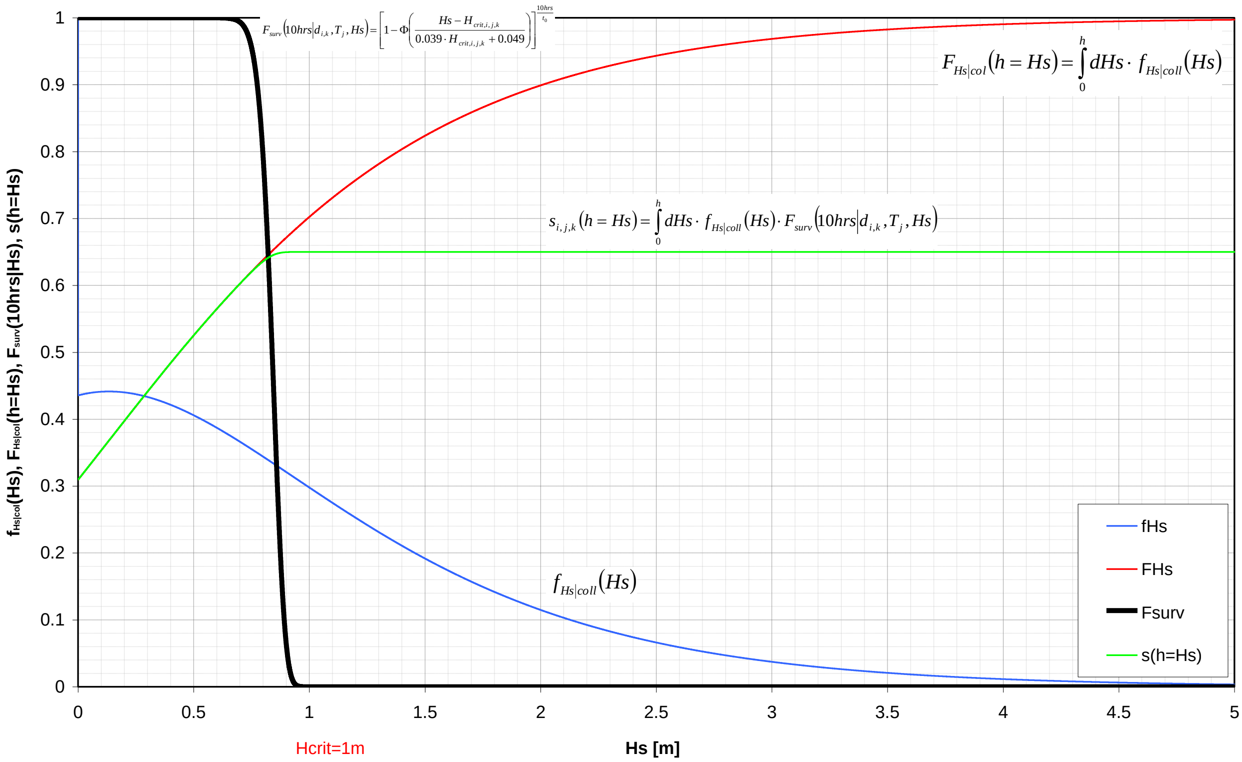


Figure 32 - Probability s as an averaging of survivability (3)

Figure 32 shows the process of assigning the probability s as an averaging (marginalisation) of survivability for a flooding case resulting in $Hcrit_{50\%}$ = 1m, based on (10) for t = 10 hours.

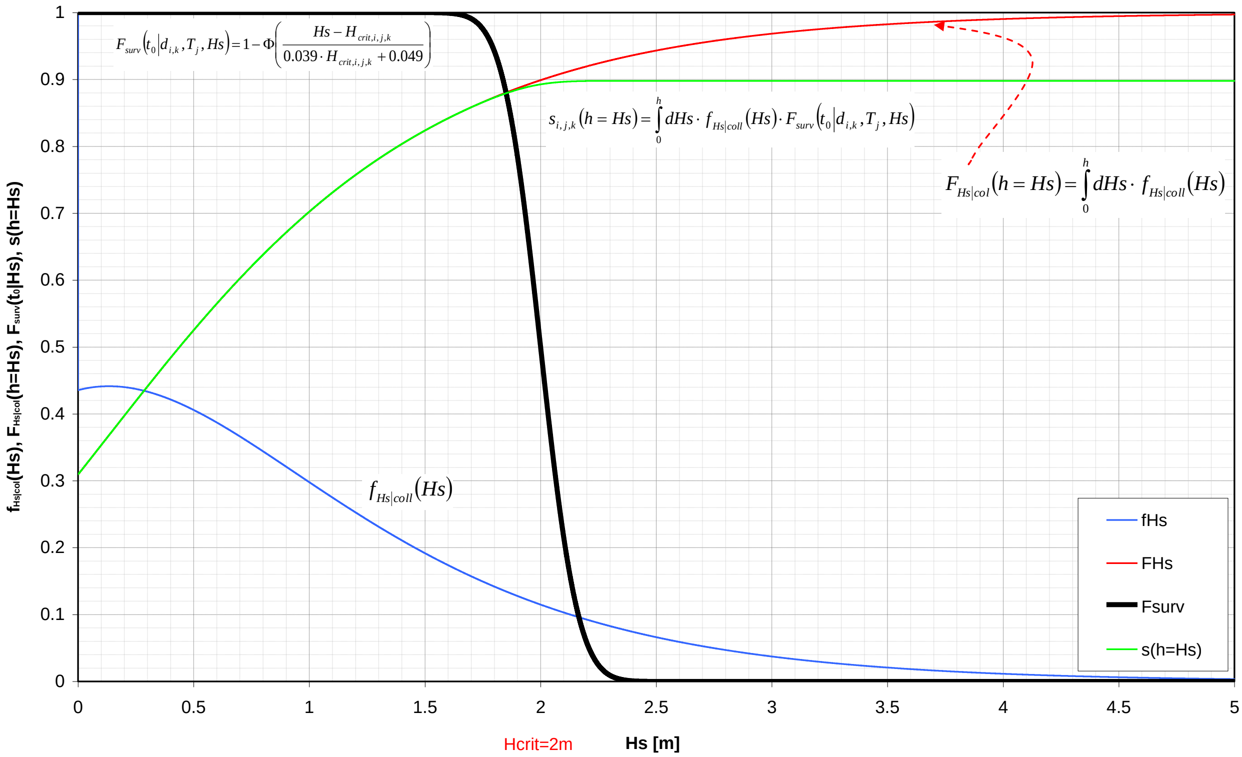


Figure 33 - Probability s as an averaging of survivability (4)

Figure 33 shows the process of assigning the probability s as an averaging (marginalisation) of survivability for a flooding case resulting in $Hcrit_{50\%}$ = 2m, based on (10) for t = 30min.

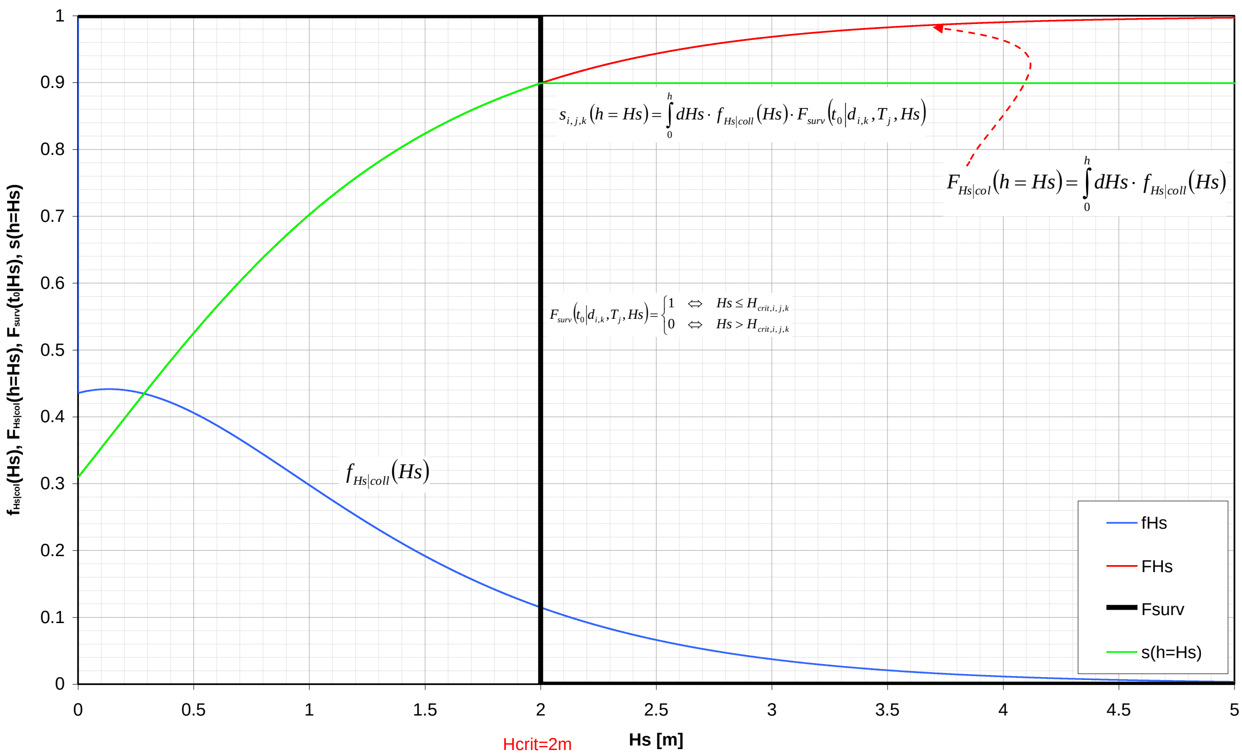


Figure 34 - Probability s as an averaging of survivability (5)

Figure 34 shows the process of assigning the probability s as an averaging (marginalisation) of survivability for a flooding case resulting in $Hcrit_{50\%}$ = 2m, based on (12) for Hcrit assumed to be median (50%) survival sea state.

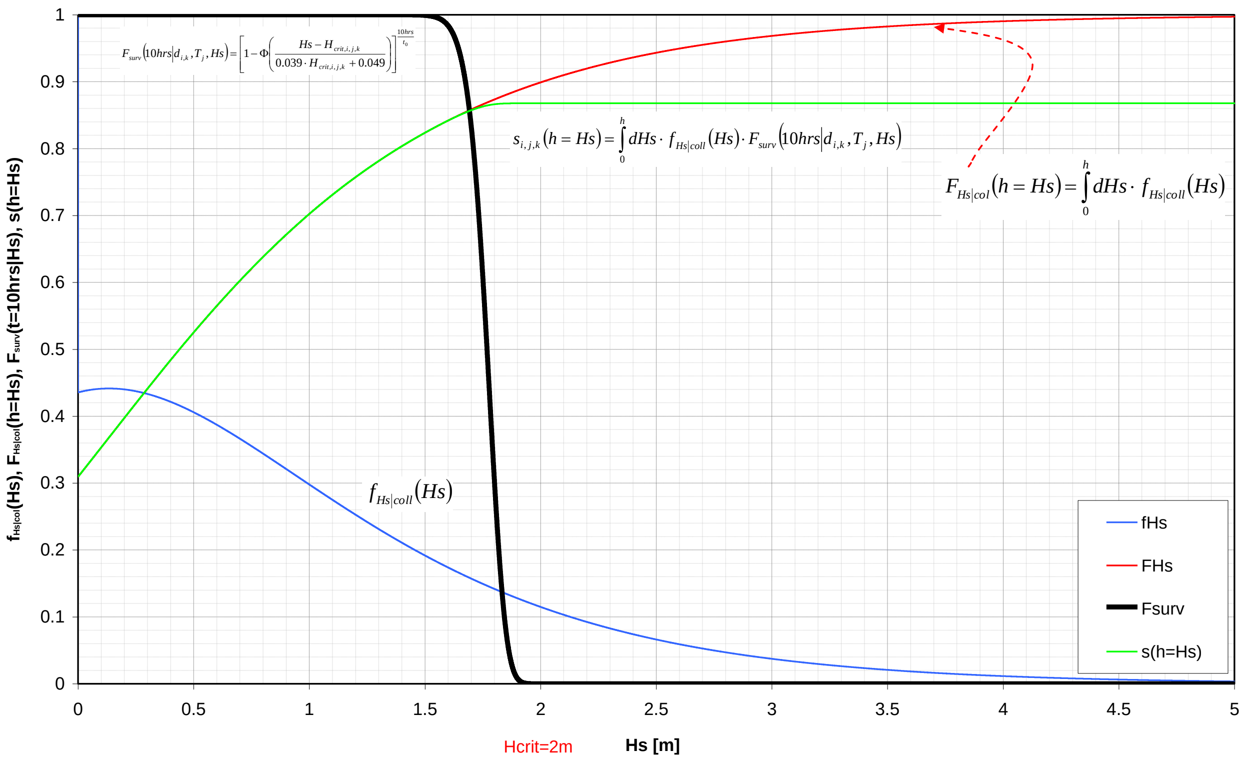


Figure 35 - Probability s as an averaging of survivability (6)

Figure 35 shows the process of assigning the probability s as an averaging (marginalisation) of survivability for a flooding case resulting in $Hcrit_{50\%}$ = 2m, based on (10) for t = 10 hours.

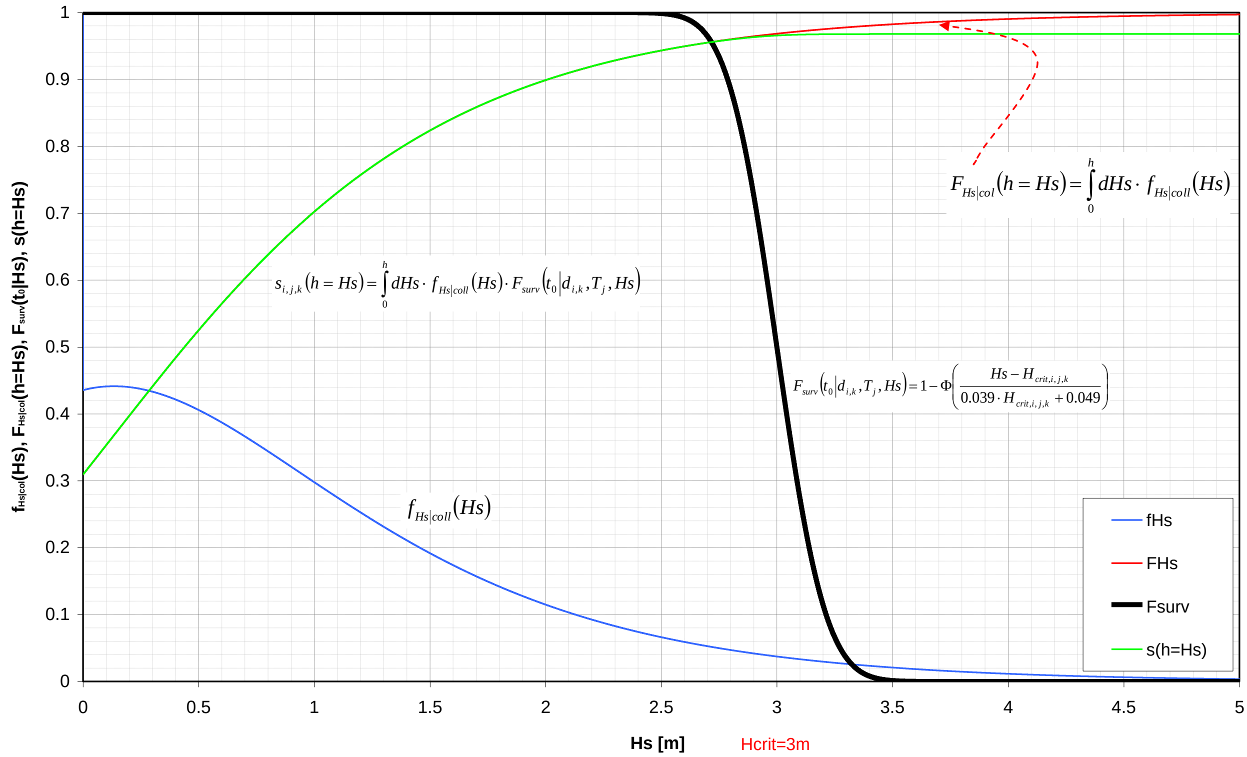


Figure 36 - Probability s as an averaging of survivability (7)

Figure 36 shows the process of assigning the probability s as an averaging (marginalisation) of survivability for a flooding case resulting in $Hcrit_{50\%}$ = 3m, based on (10) for t = 30min.

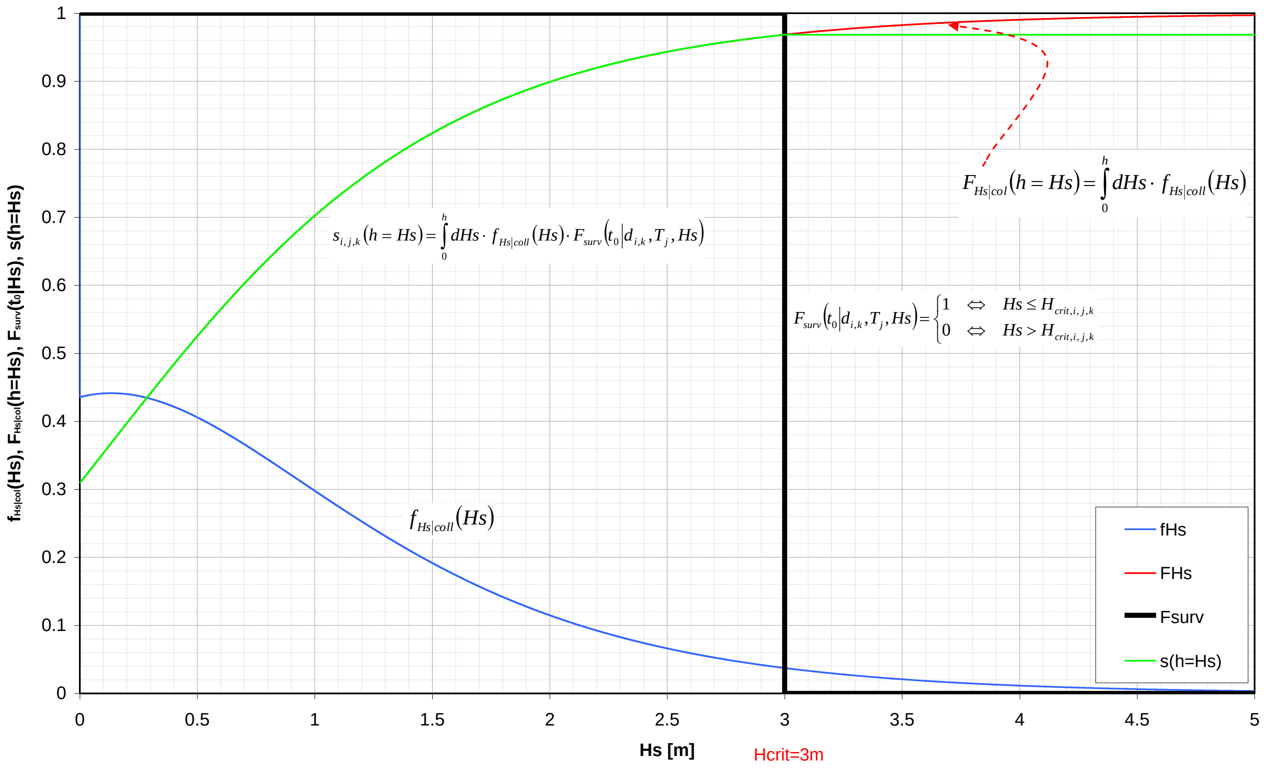


Figure 37 - Probability s as an averaging of survivability (8)

Figure 37 shows the process of assigning the probability s as an averaging (marginalisation) of survivability for a flooding case resulting in $Hcrit_{50\%}$ = 3m, based on (12) for Hcrit assumed to be median (50%) survival sea state.

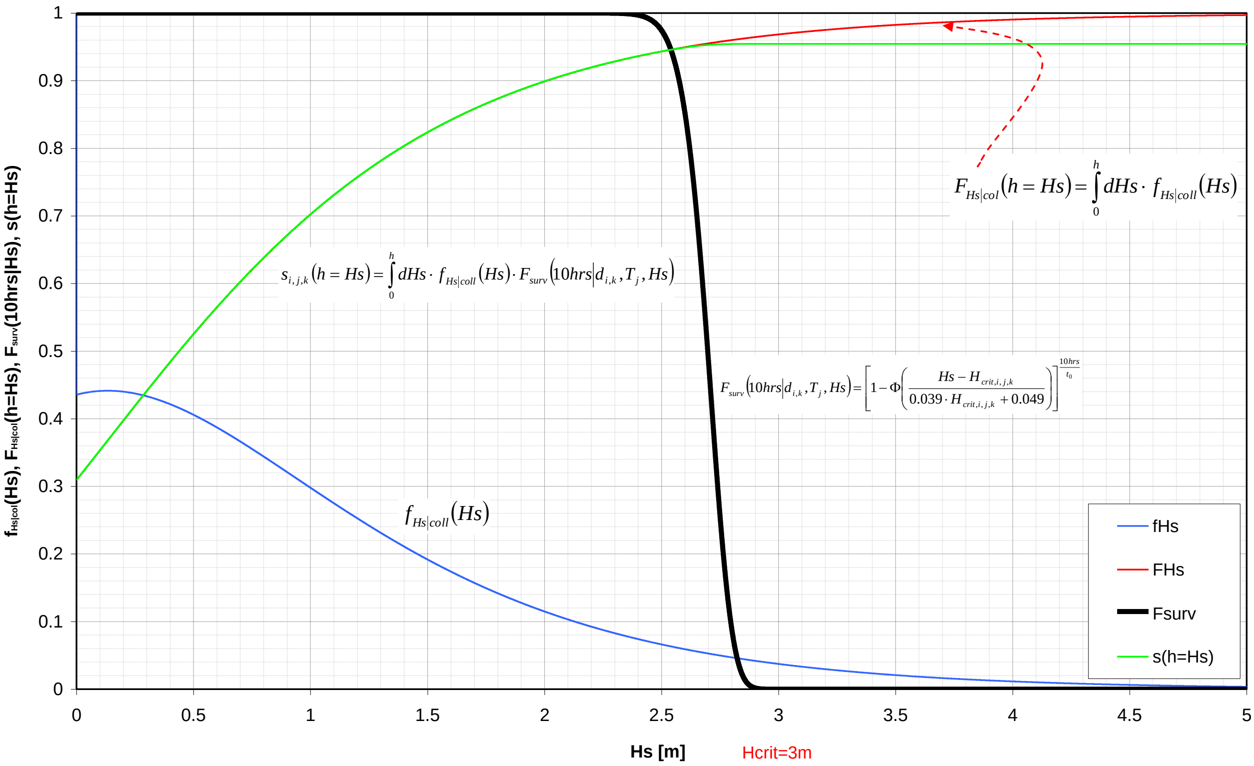


Figure 38 - Probability s as an averaging of survivability (9)

Figure 38 shows the process of assigning the probability s as an averaging (marginalisation) of survivability for a flooding case resulting in Hcrit$_{50\%}$ = 3m, based on (10) for t = 10 hours.

Level of approximations and water on deck

Figure 30 to Figure 38 show how probability s comes into being, with its interpretation of marginalised probability of survival for all feasible sea states expected during collisions. The technicalities of various assumptions can be examined from these figures.

The key result is that presented in Figure 29, which endorses the engineering foresight not only during the HARDER project, but also already during development of standard A265 when the actual unsubstantiated concept that model (3) can be approximated by (14) was made. It transpires that this approximation only marginally overestimates what is intended to be the probability of survival in waves to be encountered during collision. See the bars for modelling (a) and (b) shown in Figure 29 for each of the three flooding cases with Hcrit=1, 2 and 3m, respectively.

Hence it can be stated that model or assumption (12) is an adequate approximation of the observable survivability (10), for the purpose of marginalisation, i.e. solution of (3).

In other words, the current formulation for probability s, as given by model (1), adequately accounts for the process of ship survivability in waves, that is $F_{surv}(t_0|d_{i,k},T_j,Hs)$ as given by equation (6), even though in a simplistic manner based on median (i.e. 50th percentile) sea state H_{crit} leading to capsize in less than 30 minutes and expressed eventually by (14).

Moreover, since H_{crit} is established through physical model experiments, which result, among others, from water accumulation on the vehicle deck, it should be emphasised that current formulation for probability s, equation (1), does implicitly include effects of floodwater on the car deck.

Furthermore, not yet mentioned is the fact that a more conservative assumption has been made in approximating the distribution of probability for occurrence of particular sea states expected during collisions. Rather than use theoretical fit (4) as shown in Figure 21, the following model (15) has been used to combine together with (14) and (11) into formulae (1).

$$F_{Hs|coll}(Hs) = \left(\frac{Hs}{4}\right)^{1/4} \quad \text{adopted by MSC216} \qquad (15)$$

Figure 39, which shows approximation (15), underestimates survivability s for flooding cases with H_{crit} between 1 and 4m, and overestimates survivability s for flooding cases with H_{crit} below 1m, which can also be seen by the "yellow bars" marked as (d) in Figure 29, which have been derived by solving (3) and using (15) for $f_{Hs|coll}(Hs) = \frac{dF_{Hs|coll}}{dHs}$.

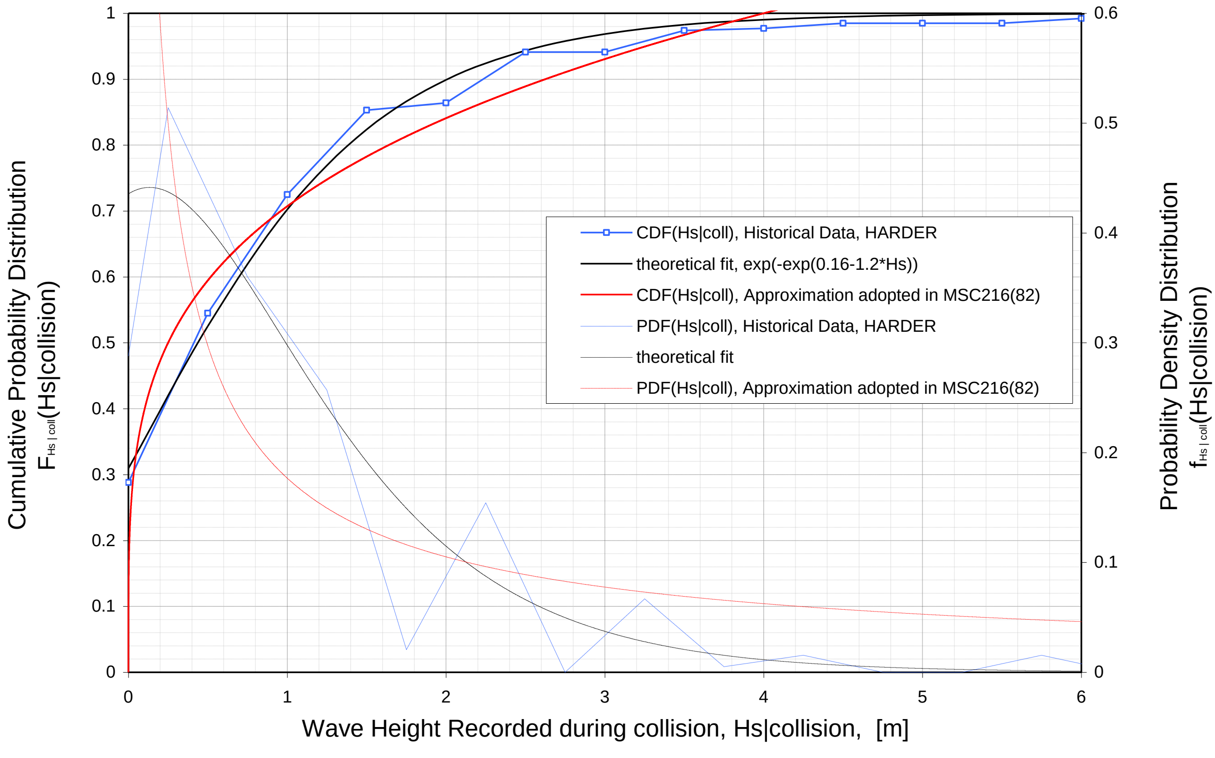


Figure 39 - Probability distributions for recorded wave height during collisions

Figure 39 in general presents the probability distributions for recorded wave height during collisions; data from Table 3. It fits the model given in [19] and compared with the model adopted for constructing probability s in MSC216(82).

There seems to have been considerable conservatism built into the construct of the probability s, to the extent that its current form also resolves the issue that $F_{surv}\left(t_0 \middle| d_{i,k}, T_j, Hs\right)$ in equation

(3) has been assessed for $t_0 = 30\min$ rather than longer periods, say 10 hours. Note again that the solution to (3) is based on (14) with H_{crit} such that $F_{surv}\left(t_0 = 30\min \middle| d_{i,k}, T_j, H_{crit}\right) = 0.5$, as already mentioned.

It can be seen in Figure 21 that using a representative model of sea conditions during collisions, model (4), and solving (3) based on (10) for 10 hours, results in more generous survivability than solving (3) based on (10) for 30 minutes but approximating $f_{Hs|coll}(Hs)$ based on (15), at least for higher H_{crit}, compare bars marked as (c) and (d).

To summarise, it would appear that all the conceptual elements of the construct (1) are robust and accommodative for the purpose of assigning probability s for survival for some 10 hours in any sea conditions that might be encountered in a collision incident, even though achieved by various degrees of mutually cancelling approximations.

However, whilst all the conceptual aspects of probability s have now been thoroughly discussed, one essential detail remaining is to examine the robustness of the parameter on which the whole concept of s, as is currently adopted, depends, namely the critical sea state H_{crit} in (14).

Figure 40 shows that H_{crit} is currently related to ship stability parameters through regressive relationship (11), and based on tests performed in this project (see Annex 3), as well as many previous tests, it can be seen that there is considerable spread in H_{crit} for exactly the same set of ship parameters.

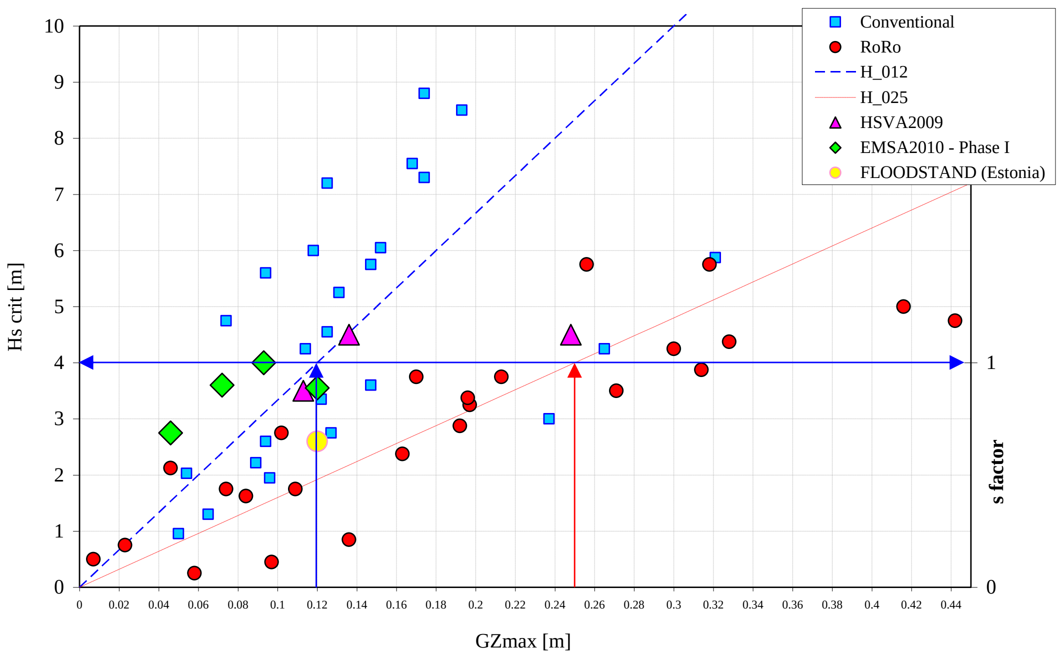


Figure 40 - Critical sea state for conventional and RoRo / RoPax ships in relation to GZmax values

Figure 40 in general shows the critical sea state[4] for conventional and RoRo / RoPax ships. The assumption underlying MSC216 relates GZ_{max} = 0.12m to the critical sea state of 4m for a specific flooding case on any ship type. As can be seen, a RoRo ship only survives a sea state of 4m after flooding, if GZ_{max} in this flooding case approaches an approximate value of 0.25m or above.

Indeed, when comparing model (11) with experimentally established H_{crit}, shown in Figure 41, it appears that the relationship (11) may seriously underestimate H_{crit} otherwise derived by physical testing, and following from that, probability s may be assigned erroneously.

There is no clear explanation that could be put forward on the reasons for spread between these results, and instead it can be speculated that:

- the relationship (11) is not comprehensively accommodating for all ship parameters that affect what H_{crit} is;
- the physical tests are subject to considerable uncertainty, such as sampling uncertainty, see Annex 1;
- the numerical estimates of parameters of (11) are subject to computational uncertainty.

Resolving these questions to any degree of precision is beyond the resources of this project, and rather an engineering solution may be proposed that can account for all the observed spread in results.

Namely, it is proposed to adopt a conservative margin in assessing H_{crit} by modifying parameters of the relationship (11) to $GZ_{\max} = 0.25m$ and $Range = 25\deg$, which would result in some 90% of all existing data to have been satisfactorily predicted by the modified equation (16), as can be seen in Figure 42 and Figure 43.

$$H_{crit,i,j,k} = 4 \cdot \left(\frac{GZ_{\max,i,j,k}}{0.25} \cdot \frac{Rnage_{i,j,k}}{25} \right) \qquad (16)$$

In other words, it could be argued that model (16) can guarantee prediction of H_{crit} to no lesser than what can be expected from physical testing, and thus most adequate assignment of probability s that science affords today.

[4] Critical Sea State – a sea state subject to which a ship can capsize sometimes within 30 minutes from an instant of a hull breach in a ship-to-ship collision and probability of which event is assigned to p_f=0.5 based on data. The critical sea state is determined through a number of model experiments. The p_f=0.5 implies that half of experiments will lead to capsize, whilst another half the ship survives for the test time of 30 minutes. The sea state is expressed in terms of significant wave height H_s

$$Hs = 4 \cdot \frac{GZ_{\max}}{0.12m} \cdot \frac{RANGE}{16\deg}$$

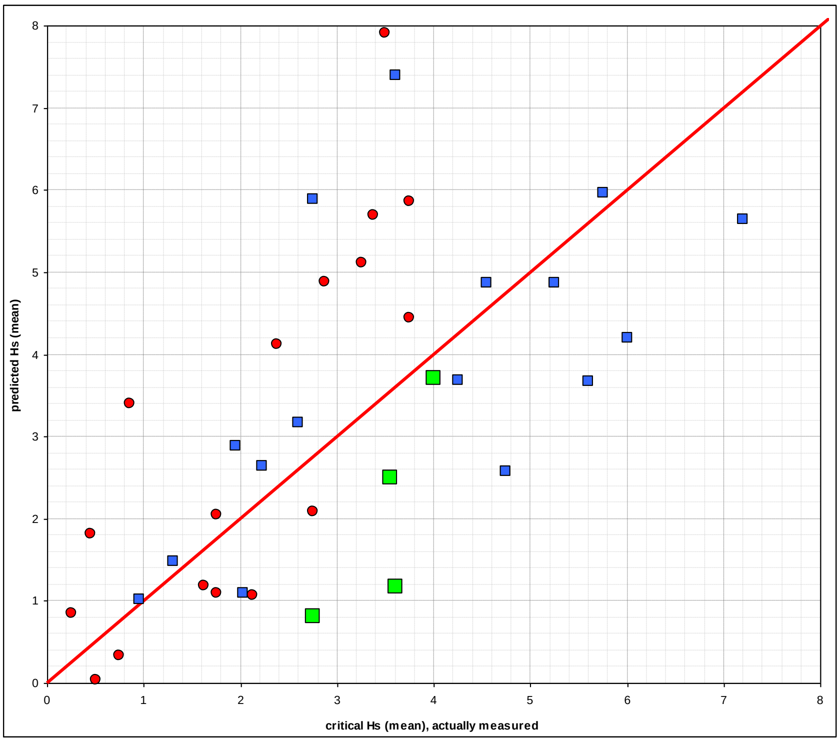


Figure 41 - Theoretical and experimental critical sea state4 values for conventional and RoRo / RoPax ships

Figure 41 shows the critical sea state[4] for conventional and RoRo / RoPax ships. There is a comparison of the theoretically and experimentally derived quantities. The theoretical model demonstrates poor correlation; in many cases it under-predicts the survival sea state.

$$Hs = 4 \cdot \frac{GZ_{\max}}{0.25m} \cdot \frac{RANGE}{25\deg}$$

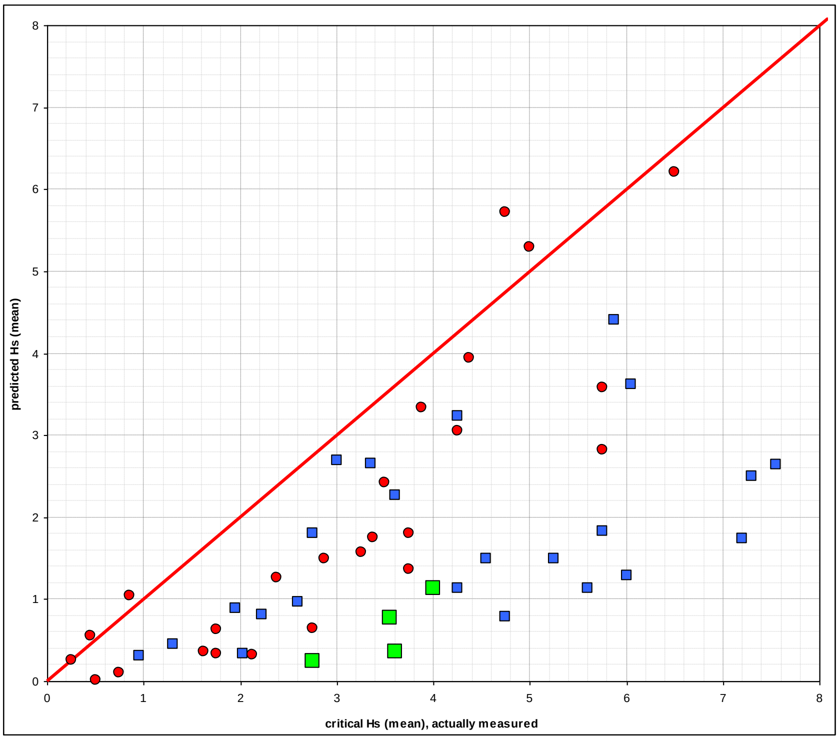


Figure 42 - Theoretical and experimental critical sea state4 values for conventional and RoRo / RoPax ships

Figure 42 shows the critical sea state[4] for conventional and RoRo / RoPax ships. There is a comparison of the theoretically and experimentally derived quantities. The theoretical model can be adjusted to address inherent uncertainty very effectively.

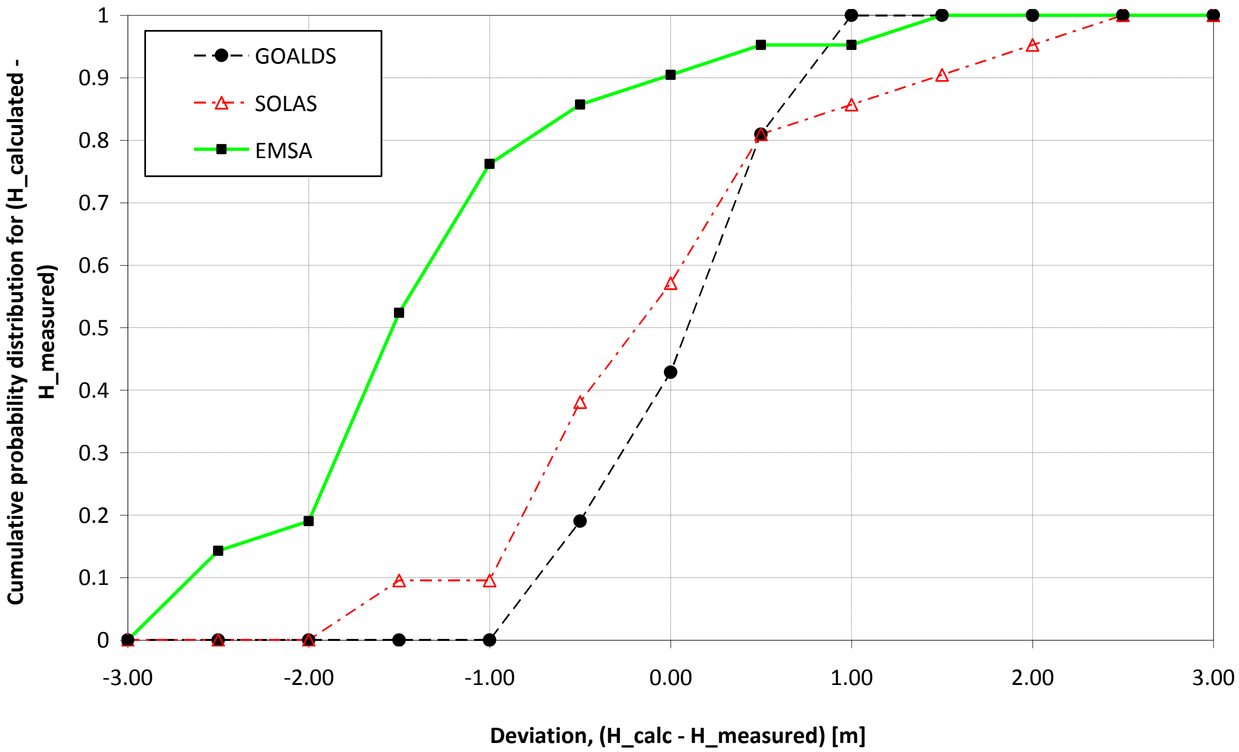


Figure 43 - Deviation of calculated Hcrit from the measurements

Figure 43 shows the deviation of the calculated H_{crit} from the measurements. A comparison of three methods is presented: "SOLAS" – existing formulation, "EMSA" – proposal (16), "GOALDS" – proposal advanced in project [56]. Model (16) ascertains that some 90% of calculated H_{crit} are lower than the observed measurements for the same conditions, i.e. it is a conservative approximation.

There has been considerable effort spent on development of methods alternative to (11), notably the Static Equivalent Method (SEM) advanced in [46]. However, it appears that due to computational inefficiencies involved in implementing such methods, and lack of convincing improvements in predictions of H_{crit}, there does not seem to be any more robust solution than those presented in Figure 43. As mentioned, formulae (16) is proposed in this study as the most efficient solution.

Model (16) is the key in addressing the core objective of this project. By appropriate assignment of probability s, and thus probability A, an argument could be put forward on indirect ways to accommodate for provisions of the Stockholm Agreement under the instrument of SOLAS 2009 by setting an appropriate level of probability A, as discussed in §5.1.4. However, an alternative and more direct methods can be proposed, as discussed next.

Survivability intended by the Stockholm Agreement

This project sets to address the question of compatibility between the Stockholm Agreement and SOLAS 2009, and one of the key issues arising is the ship survivability implied by both standards.

Unlike SOLAS 2009, which aims at setting an expected survivability for 30 minutes in any sea state likely to be encountered during a collision event, as shown in the foregoing, the Stockholm Agreement provisions stipulate "complete" survivability in specific sea conditions for a subset of flooding extent cases feasible, see discussion in §5.1.4 and Figure 50. Although it is not explicitly disclosed, the alternative procedure for compliance through physical testing, see [1] to [4], instructs a minimum of 10 tests in a given sea state to be survivable for 30 minutes, which stipulates "a guarantee" (99%)[5] that $F_{surv}(Hs)$ is at least 0.6, when accounting for sampling uncertainty (see Annex 1).

Although the latter is never mentioned in any of the assumptions underlying [1] to [4], it should be borne in mind for in-depth interpretations of physical significance of given safety standards. Here it is merely pointed out that the Stockholm Agreement aims at survivability $F_{surv}(t_0|d_{i,k},T_j,Hs)=1$ for $t_0=30\min$ in an assumed specific (not random) sea state Hs (consult [1] to [4] for the definition of the pertinent sea state), although the standard ascertained by model testing can only provide evidence with 10 tests of $F_{surv}(t_0|d_{i,k},T_j,Hs)>0.6$. Note that the uncertainty spread applies also to survivability observed during tests of HARDER leading to formulation of factor s, as discussed above.

Therefore, the Stockholm Agreement requirement of $F_{surv}(t_0|d_{i,k},T_j,Hs)=1$ at say $Hs=4m$ is not directly resolvable in terms of SOLAS 2009, since the relation (3) between probability s and $F_{surv}(t_0|d_{i,k},T_j,Hs)$ is rather complex.

However, considering the approximations of (3) discussed above, and among them approximation (14) and (15), one can observe the following:

$s=\left(\frac{H_{crit}}{4}\right)^{1/4}$	(17)

As mentioned above, in SOLAS 2009 it is assumed that $F_{surv}(t_0|d_{i,k},T_j,Hs=H_{crit})=0.5$, however, again considering approximations, especially stemming from (15), it seems adequate to propose that the sea state Hs to be "completely" survivable in Stockholm Agreement tests to be regarded as H_{crit} in (16).

Therefore, the requirement by Stockholm Agreement that $F_{surv}(t_0|d_{i,k},T_j,Hs)=1$ at $Hs=4m$ would be equivalent of requiring that $s=\left(\frac{H_{crit}=4}{4}\right)^{1/4}$, that is $s=1$, with s calculated by (1).

And to reiterate again, requiring $s=1$ for a given flooding case, "ensures" that the vessel may survive for some 10 hours in seas of up to Hs=4m, which shall be regarded as equivalent between both the Stockholm Agreement and SOLAS 2009. For any sea state other than Hs = 4m to be used for the Stockholm Agreement, it would imply different values of probability s to be required for the flooding cases specific to the Stockholm Agreement, calculated from (17), as shown in Figure 44.

[5] Confidence interval on binomial proportion (here ratio of observed survived cases among all pertinent tests) implies that if such an experiment series was performed 100 times (10 tests each time), then only once would the F_{surv} be out of the range of 0.6 to 1.0

Hs [m]	s
0.5	0.595
1	0.707
1.5	0.783
2	0.841
2.5	0.889
3	0.931
3.5	0.967
4	1.000

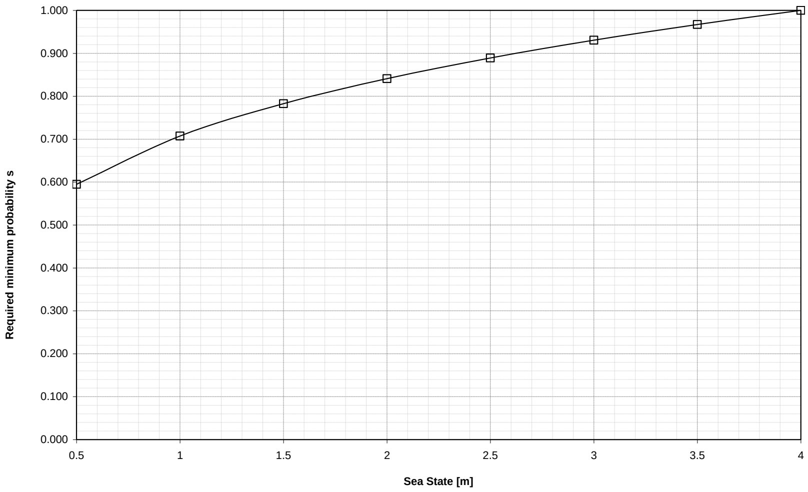


Figure 44 - Required probability s for equivalent compliance with the Stockholm Agreement for given sea state

Intermediate stages of flooding

According to Regulation 7-2.1.2 and 7-2.2, a passenger ship shall have all flooding cases be subject to verification of intermediate stages of flooding, as follows:

$$s_i = \text{minimum}\ \{ s_{\text{intermediate,i}} \ \text{ or } \ s_{\text{final,i}} \cdot s_{\text{mom,i}} \}$$

This requirement is one step further in ensuring a conservative assignment of probability s not required by the Stockholm Agreement.

There were insufficient resources available for quantitative investigation into the relative importance and effect of this regulation on the overall assessment, but since it can only result in lessening of probability s, it is hereby considered as its positive approximate element.

5.1.2. Factor K

The formulation for probability s includes a correction coefficient K, as given in Table 4, which aims at encouraging designers to choose watertight architecture solutions that result in as few asymmetrical arrangements as possible, so that ship abandonment is facilitated in case of flooding.

The undesirable effect of the factor K is to discourage design choices providing stability that contribute at higher angles of heel, since any such contribution is nullified. Based on ship designs developed in this project and given in Table 14 and Figure 78, some 0 to 3.7% contribution to probability A could be attributed due to stability at higher angles of heel, depending on design configuration.

Table 4 - Regulation 7-2.3 of IMO MSC.216(82)

$$s_{\text{final},i} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}}$$

where:

GZ_{max} is not to be taken as more than 0.12 m;

Range is not to be taken as more than 16°;

$K = 1$ if $\theta_e \leq \theta_{min}$

$K = 0$ if $\theta_e \geq \theta_{max}$

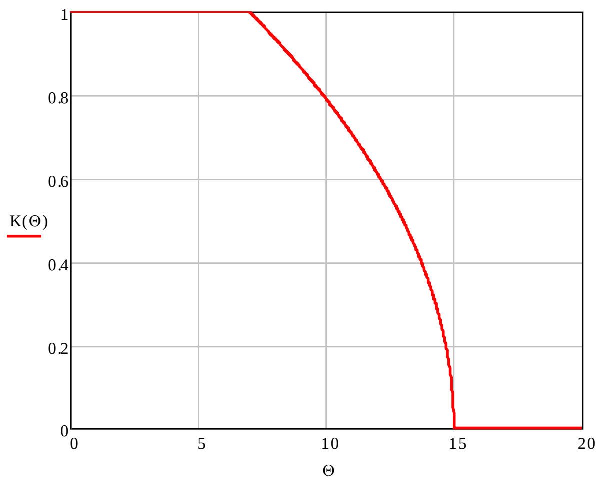
7.

$K = \sqrt{\frac{\theta_{max} - \theta_e}{\theta_{max} - \theta_{min}}}$ otherwise,

where:

θ_{min} is 7° for passenger ships and 25° for cargo ships; and

θ_{max} is 15° for passenger ships and 30° for cargo ships.



Whilst higher angles of heel are not desirable in general, it is a viable solution that could save many lives should such a scenario occur. This is in contrast to the alternative of current stability legislation which permits many cases to not have any stability whatsoever, as is shown in Figure 46, and §5.2.3. Approximately 12% of feasible flooding cases on SHIP 4 would not be survivable at all, even though the design complies with SOLAS 2009.

Therefore, it is proposed that every measure of inbuilt passive stability onboard ships is credited fully for its capacity to prevent capsizing, and instead the intent of coefficient K to enforce functioning of abandonment systems is retained in the form of an alternative purposeful requirement.

It could be required, for instance, that all vital systems, as specified currently by Reg. 8.1, be operational for heel angles of up to 25deg.

An example of the stability solution implemented in SHIP 4 modified can be used to demonstrate that only some 0.18% of flooding cases would result in a final stage angle of heel of more than 25deg, with the remaining 0.6% still having no stability whatsoever in this design solution (see Figure 46). Such a regulation would almost completely convey the intent of having coefficient K. In the meantime, designers would be encouraged to seek solutions that completely eradicate flooding cases on modern ships that are characterised by a complete lack of stability and which could not possibly be achieved without resorting to upper spaces of the ship, such as side casing on vehicle decks. An equation for probability s with K set to 1 would then allow quantifying contribution of such solution to the overall survivability.

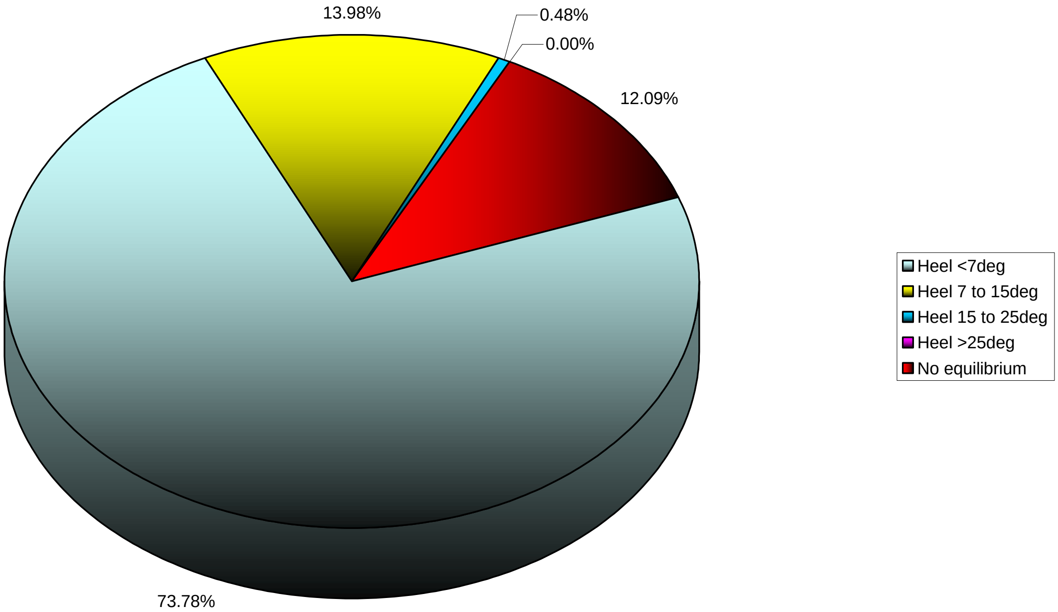


Figure 45 - Distribution of probability for angle of heel. SHIP 4, original design

Figure 45 shows the distribution of probability for the angle of heel. The selected cases are based on the "Alternative 3" of the proposed changes to SOLAS 2009, see Table 14 (SHIP 4, original design, loading condition deepest subdivision draught "DS").

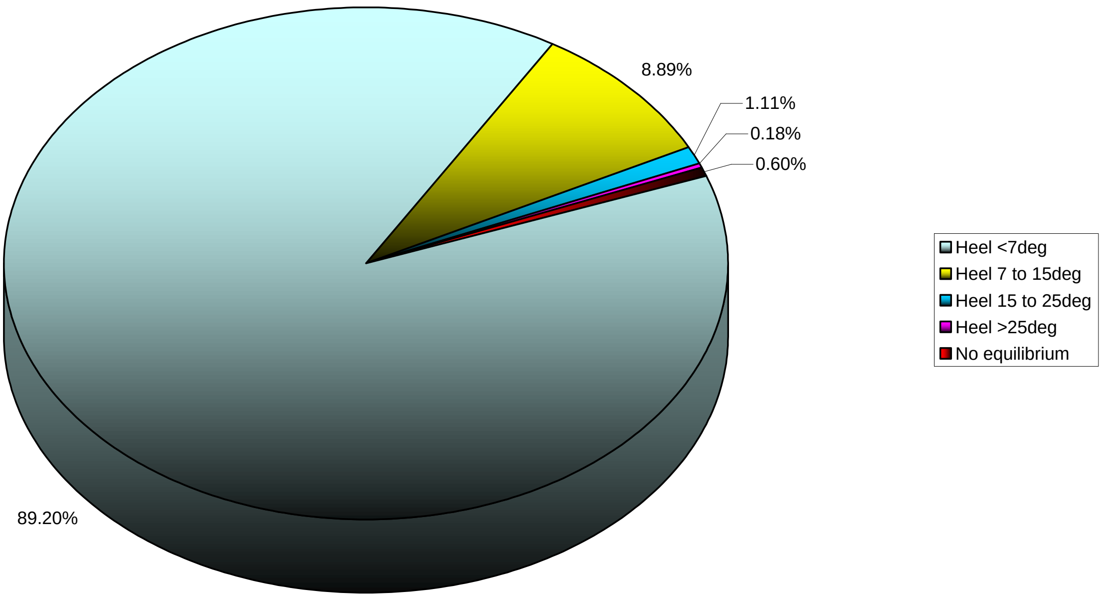


Figure 46 - Distribution of probability for angle of heel. SHIP 4, modified design

Figure 46 shows the distribution of probability for the angle of heel. The selected cases are based on the "Alternative 3" of the proposed changes to SOLAS 2009, see Table 14 (SHIP 4, modified design, loading condition deepest subdivision draught "DS").

5.1.3. Factor w

It was assumed in the European Commission project HARDER and earlier developments that the probability of survival s_i (for at least $t_c = 30\min$) is not determinate because it depends on such random quantities as loading condition (draught T, trim θ, metacentric height GM and permeability σ) and the vertical extent of flooding H. It was thereafter proposed that so referred to "composite" (in other words marginal) probability s is obtained by the process of marginalisation, [46], namely:

$s_i^* = \int_\Omega d\Omega \cdot f_\Omega(\sigma,T,\theta,GM)\cdot(s_i \vert \sigma,T,\theta,GM)$	(18)

Where $(s_i|\sigma,T,\theta,GM)$ is the probability s_i calculated according to (3), or indeed (14), for a set of σ,T,θ,GM, and $f_\Omega(\sigma,T,\theta,GM)$ is the joint probability density distribution for random variable set σ,T,θ,GM.

As a simplification step it was eventually assumed, e.g. [46], that marginalisation with respect to draught as the only *random variable* is adequate, and thus (18) has been suggested to be calculated as (19):

$s_i^* = \int_T dT \cdot f_T(T)\cdot(s_i \vert T)$	(19)

With σ,θ,GM assumed as fixed variables, and $(s_i|T)$ calculated for draught T and marginalised over the range of vertical flooding extents h_k, currently according to SOLAS Chapter II, Regulation 7.2.6, as shown in (20).

$s_i \vert T = \sum_{k=2}^{n}(s_i \vert T \,\&\, h_k)\cdot(v_k - v_{k-1})$	(20)

Where v_k is the probability of flooding extending up to horizontal subdivision number k, and referred to as "reduction factor v", and $(s_i|T\,\&\,h_k)$ is probability of survival, assessed according to (3), or indeed (14), for very specific draught T and flooding cases extending up to horizontal subdivision number h_k (noting also that "worst" case of flooding from horizontal subdivision k is considered for $(s_i|T\,\&\,h_k)$).

Since draught was considered to be *a random variable* during ship operation, a distribution of probability $f_T(T)$ for typical operation was undertaken to be developed, and even though issues during project HARDER were raised as regards validity of such assumptions applicable to any ship type, a specific discrete set of three draughts was accepted, and (19) has since been assumed to be as follows:

$s_i^* = \sum_{j=1}^{3} w_j \cdot s_{i,j}$	(21)

With the probabilities w_j assumed to be 0.2, 0.4, 0.4 for light T_1, “partial” T_2 and deepest T_3 subdivision draughts, respectively, and $s_{i,j} = (s_i | T_j)$ as given by (20).

Note that the “overall” probability, as currently adopted in MSC216, has the form (22), or the more commonly known, re-written format (23).

$A = \sum_i p_i \cdot s_i^*$ $= \sum_i p_i \cdot \sum_{j=1}^{3} w_j \cdot s_{i,j} = \sum_{j=1}^{3} w_j \cdot \sum_i p_i \cdot s_{i,j}$ $\sum_{j=1}^{3} w_j \cdot A \vert T_j$	(22)

$A = 0.2 \cdot A_{DL} + 0.4 \cdot A_{DP} + 0.4 \cdot A_{DS}$	(23)

Where $A|T_j$ is the probability of survival at draught j.

The key recommendation that is being made in this report is that of acknowledging that draught (and corresponding loading), must not be considered as random variables during the design process, as assumed in development of MSC216(82).

The probability A should be the same for any draught. In other words equation (19) or its numerical version (21) shall take the form (24), as follows.

$s_i^* \equiv (s_i \vert T)$ for every operational and actual T	(24)

Subsequently the attained index must be at least R or more at any draught, as expressed by equation (25).

$A \vert T \geq R$ for every operational T	(25)

Whilst it is impossible to know the exact frequency w_j with which any given draught the ship will be operated at, the range of feasible, or permissible draughts, is known. The limits on loading (specifically on the minimum metacentric height GM) can be imposed for compliance with minimum stability (intact / damaged conditions) for each of the draughts and given by model (25), as is the traditional manner to convey legislative limits on operations to the crew.

The undesirable effect of adopting of draught as a random variable and thus subsequently resulting to (21) can be shown in the hypothetical cases in Table 5 and Table 6.

If the design was developed in such a manner as to result in the probability A to be constant for every draught, A_j=R, as is shown in Table 5, then it can be noticed that, irrespective of which frequency is assumed for operation at any given draught, the overall (marginal) probability A remains unchanged. This ship will be operating at exactly the same level of stability at all draughts.

Therefore, the factors w_i for such a case are redundant.

On the other hand, if the ship is designed in such a manner, whereby the probability A_j is 0.856, 0.712 and 0.640, for light, partial and deepest subdivision draughts, as shown in Table 6, and the ship was de-facto operated at given draughts with exact proportions of 0.2, 0.4, 0.4 for light, "partial" and deepest subdivision draughts, respectively, then the overall probability A would be the same, A=0.712=R.

However, it should be noted that the level of stability of A_{DS}=0.64 at deepest draught is lower than the level of stability assumed for lightest draught, or lower than the stability level given by the "overall" R=0.712. Such different standards of stability for different draughts implies that low stability in one draught can be "compensated" for regulatory purposes with higher stability at other draughts.

Table 5 - Neutral impact of w_i "factor" on survivability

$$A = \sum_{i=1}^{3} \sum_{j=1}^{n_{flood}} w_i \cdot p_j \cdot s_{ij}$$

$$A = \sum_{i=1}^{3} w_i \cdot \left(\sum_{j=1}^{n_{flood}} p_j \cdot s_{ij} \right)$$

$$A = 0.2 \cdot A_{DL} + 0.4 \cdot A_{DP} + 0.4 \cdot A_{DS}$$

D	w	A	w*Ai	1-w*Ai
DL	0.2	0.712	0.142	0.058
DP	0.4	0.712	0.285	0.115
DS	0.4	0.712	0.285	0.115
			0.712	

w-reality	w*Ai
0.05	0.036
0.4	0.285
0.55	0.391
	0.712

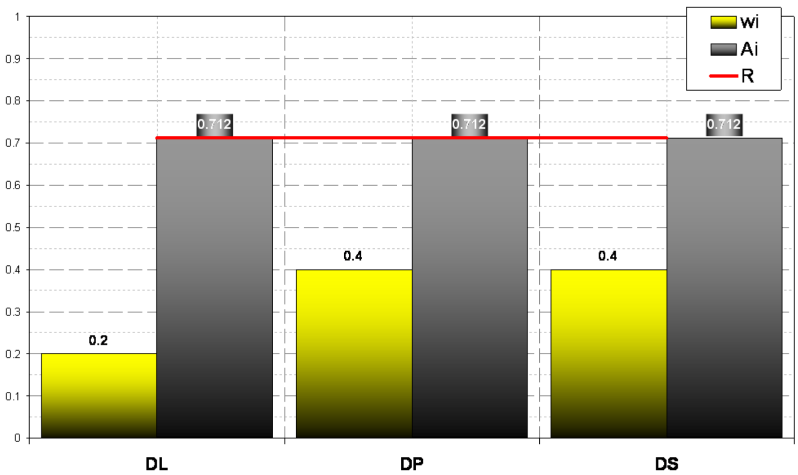


Table 6 - Negative impact of w_i "factor" on survivability

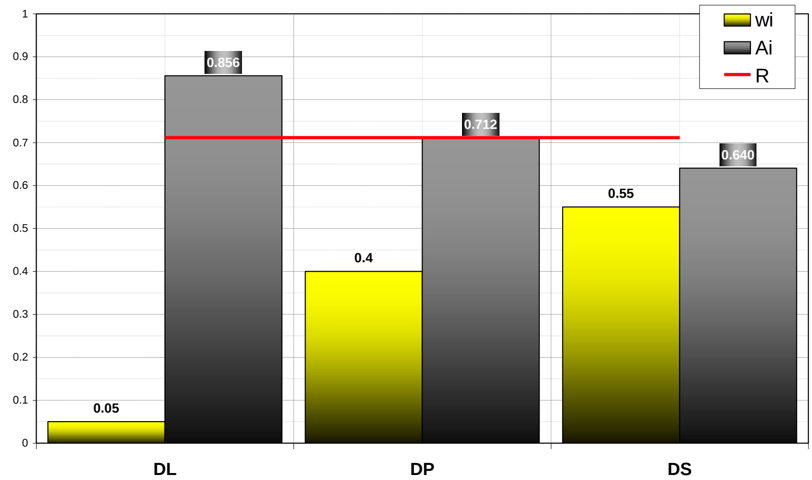
$$A=\sum_{i=1}^{3}\sum_{j=1}^{n_{flood}} w_i \cdot p_j \cdot s_{ij}$$

$$A=\sum_{i=1}^{3} w_i \cdot \left(\sum_{j=1}^{n_{flood}} p_j \cdot s_{ij}\right)$$

$$A=0.2\cdot A_{DL}+0.4\cdot A_{DP}+0.4\cdot A_{DS}$$

D	w	A	w*Ai	1-w*Ai
DL	0.2	0.856	0.188	0.012
DP	0.4	0.712	0.263	0.137
DS	0.4	0.640	0.260	0.140
			0.712	

w-reality	w*Ai
0.05	0.043
0.4	0.285
0.55	0.352
	0.680



Furthermore, if the frequency of operation at given draughts in real life is different to that assumed in current regulations, e.g. 0.05, 0.4 and 0.55 in light, "partial" and deepest subdivision draughts, respectively, then the actual overall probability of survival A will be lower, namely 0.680, than what is meant as the minimum standard R=0.712.

Therefore, the SOLAS Chapter II compliance by a given ship designed to A>R, or **0.9R** permissible for any draught, would not in fact be achieved in real life, even though "on paper" it would be demonstrated as satisfactory.

For this reason the current concept of index A should be adjusted by disposing of the factor w, and take the form (25).

5.1.4. Factor A

This chapter provides analytical reasoning on the interpretation of the meaning of "factor" A.

Consider the following set of key parameters affecting ship stability after flooding: (a) the hull breach, characterised by set $\Omega=\{x,\lambda,b,h\}$ of its location, length, depth and height, (b) ship draught T and (c) the environment expected in a collision $Hs|coll$. For clarity it is proposed to consider this as a set of "external" parameters, as these do not relate to design controllable parameters (the draught is only considered for consistency with current assumptions of it being a random variable, which has been recommended above to be reconsidered).

Consider that there is a function $F_D(t_0|x,\lambda,b,h,T,Hs)$ that allows assigning probability that a ship will survive for a specific period of time t_0, for every specific set of these external parameters.

Then a probability, denoted as probability A, that the vessel will survive for any set of external parameters may be obtained by marginalisation, as shown by (26).

$$A = \int_\Omega \int_T \int_{Hs=0}^{\infty} d\Omega \cdot dT \cdot dHs \cdot f_{Hs|coll}(Hs) \cdot f_T(T) \cdot f_\Omega(x,\lambda,b,h) \cdot F_D(t_0|x,\lambda,b,h,T,Hs) \qquad (26)$$

Note earlier chapters describing the interpretation of all functions and symbols of model (26), which assigns "average" (or marginal) probability of survival for time t_0 after any feasible flooding due to collision at any sea state expected during collision $Hs|coll$ and resulting in hull breach characterised by set $\Omega = \{x,\lambda,b,h\}$ for a ship at any operational draught T.

The probability may be assigned for a specific draught T, namely:

$$A|T = \int_\Omega \int_{Hs=0}^{\infty} d\Omega \cdot dHs \cdot f_{Hs|coll}(Hs) \cdot f_\Omega(x,\lambda,b,h) \cdot F_D(t_0|x,\lambda,b,h,T,Hs) \qquad (27)$$

Considering the limited scope of available statistics on hull breach characteristics, the joint probability distribution $f_\Omega(x,\lambda,b,h)$ may be assigned based on marginal probability distributions, shown in Figure 47, whilst accounting for non-rectangular integration domain, stemming from geometrical relationships between them, leading to (28).

$$A|T = \int_\Omega \int_{Hs=0}^{\infty} d\Omega \cdot dHs \cdot f_{Hs|coll}(Hs) \cdot f_\lambda(\lambda) \cdot f_{X|\lambda}(x|\lambda) \cdot f_{B|x}(b|x) \cdot f_H(h) \cdot F_D(t_0|x,\lambda,b,h,T,Hs) \qquad (28)$$

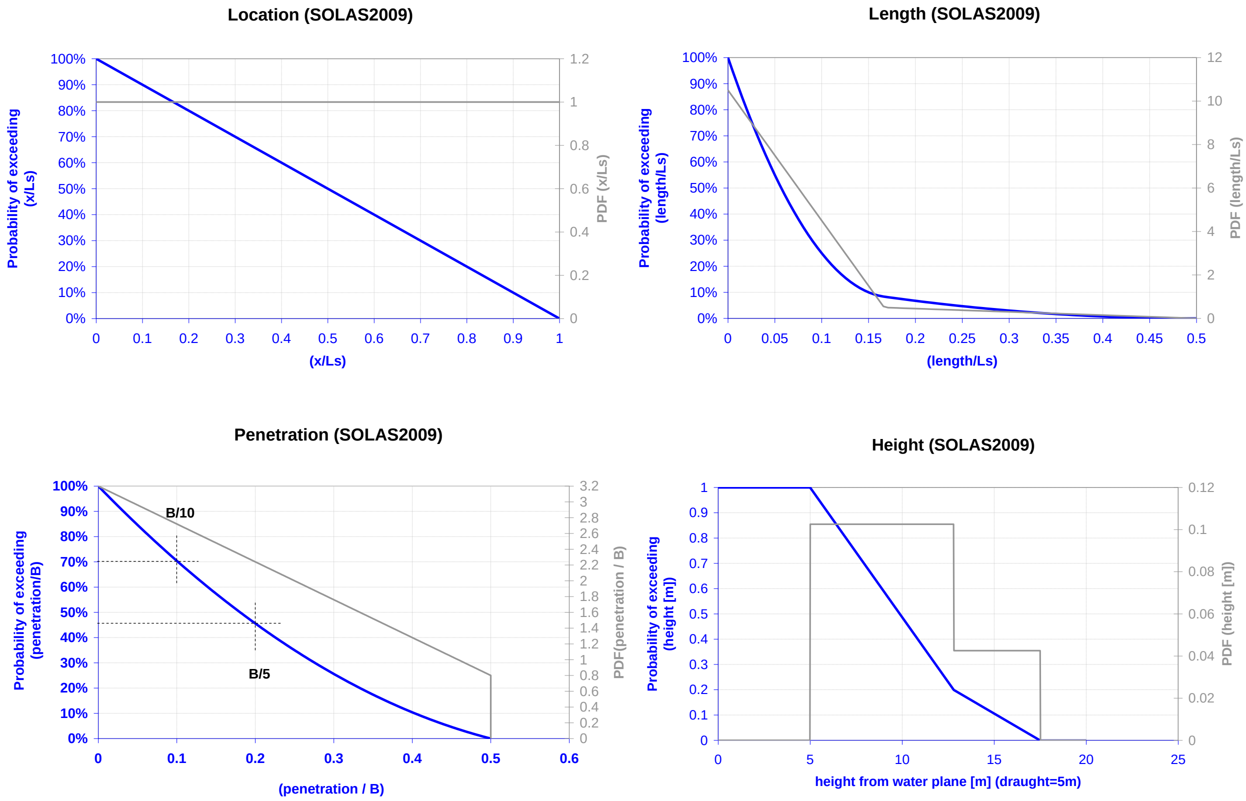


Figure 47 - Probability distributions for damage characteristics

Figure 47 shows the probability distributions for damage characteristics and the marginal probability distribution functions for flooding case location $f_x(x)$, length, $f_\lambda(\lambda)$, penetration $f_B(b)$ and height $f_H(h)$.

In order to solve (26), the geometry domain may be broken down into a set of mutually exclusive flooding cases Ω_i (see Figure 48), with horizontal subdivision for each zone, leading to model (29).

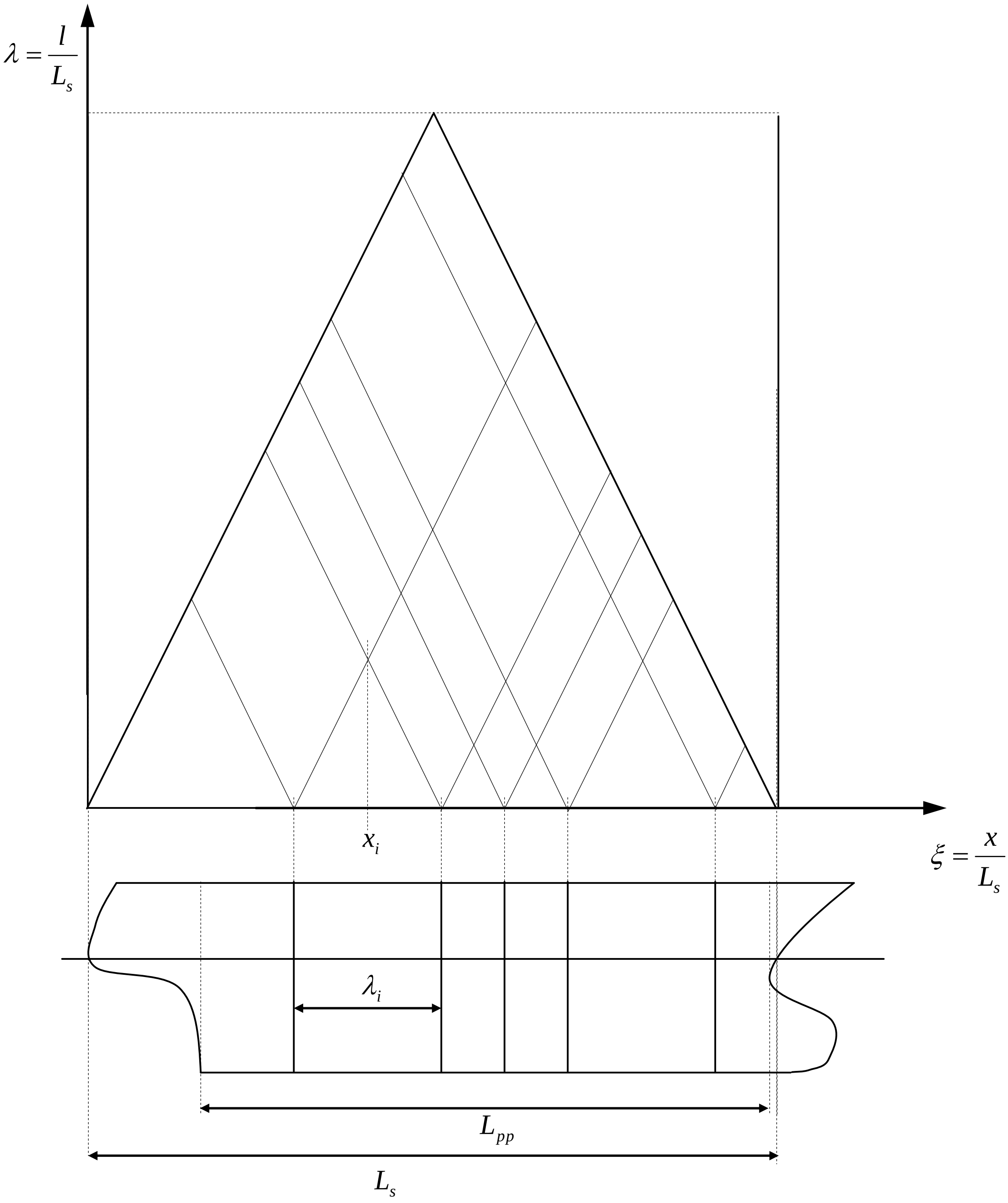


Figure 48 - Concept of the domains of probability integration

$$A = \sum_i \int_{\Omega_i / H} d\Omega_i \cdot f_\Omega(x_i,\lambda_i,b_i)\cdot\left(\sum_{j=1}^{3}\sum_{k=1}^{n_{Hk}} w_j \cdot (v_k - v_{k-1})\cdot \int_{Hs=0}^{\infty}\int_{\Omega_i / H} dHs \cdot d\Omega_i \cdot f_{Hs|coll}(Hs)\cdot f_\Omega(x_i,\lambda_i,b_i)\cdot F_D\left(t_0 | x_i,\lambda_i,b_i,h_k,T_j,Hs\right)\right) \quad (29)$$

Where probability that any zone i becomes flooded given by (30) and probability that the ship survives any flooding case for a discrete set of horizontal subdivisions $H = h_k$ within that zone, any sea state $Hs|coll$ and concrete set of draughts T_j, is given by (31).

$$p_i = \int_{\Omega_i / H} d\Omega_i \cdot f_\Omega(x_i, \lambda_i, b_i)$$	(30)

$$s_{i,j,k} = \int_{Hs=0}^{\infty} \int_{\Omega_i / H} dHs \cdot d\Omega_i \cdot f_{Hs\vert coll}(Hs) \cdot f_\Omega(x_i, \lambda_i, b_i \vert h_k) \cdot F_D(t_0 \vert x_i, \lambda_i, b_i, h_k, T_j, Hs)$$	(31)

Noting that the probability of surviving a flooding due to any breaches leading to specific flooding zone "i" can be approximated by (7), allowing (31) to be assigned as (3), or shown below as (32).

$$s_{i,j,k} = \int_{Hs=0}^{\infty} dHs \cdot f_{Hs\vert coll}(Hs) \cdot F_{surv}(t_0 \vert d_{i,k}, T_j, Hs)$$	(32)

Thus, as noted already in §5.1.3, the probability (29) can be assigned as (33), and given equation (20), the probability can be assigned as (34).

$$A = \sum_i p_i \cdot \left(\sum_{j=1}^{3} \sum_{k=1}^{n_{Hk}} w_j \cdot (v_k - v_{k-1}) \cdot s_{i,j,k} \right)$$	(33)

$$A = \sum_i p_i \cdot \left(\sum_{j=1}^{3} w_j \cdot s_{i,j} \right)$$	(34)

Since probability p_i is independent of draught, equation (34) can be rearranged as follows:

$$A = \sum_{j=1}^{3} w_j \cdot \sum_i p_i \cdot s_{i,j}$$	(35)

Noting further that the probability of surviving A may be assigned for every draught, as given by (28), the following notation for conditional probability $A \vert T$ may be adopted:

$$A \vert T_j = \sum_i p_i \cdot s_{i,j}$$	(36)

Thus equation (35) becomes (37):

$$A = \sum_{j=1}^{3} w_j \cdot A \vert T_j$$	(37)

Adopt notation for $A|T_j$ with $j \equiv DS$ for first draught, and DP, DL for the two other draughts, and subsequently (37) may be written in the more familiar form (38), which has already been mentioned as (22).

$A = 0.2 \cdot A_{DL} + 0.4 \cdot A_{DP} + 0.4 \cdot A_{DS}$	(38)

The purpose of the derivation presented above is to highlight that the construct (38) is a rigorous model for assigning marginal probability of survival, "averaged" over all external parameters deemed of relevance to setting the level of ship stability.

Therefore, the referred to Attained Index of Subdivision, A, as SOLAS Chapter II assumes, should be regarded as a probability of not observing capsize for $t_0 = 30\,\mathrm{min}$ after a flooding incident due to collision and in waves.

The fundamental importance of recognising the above fact, lies in the ensuing interpretation of the meaning of the complement $(1-A)$ to this function, namely that $(1-A)$ denotes marginal probability that the vessel will not survive for $t_0 = 30\,\mathrm{min}$ after any of the external parameters (that is the environment or hull breach) occur.

Since it is marginal probability, it is of no relevance how likely any of the subsets of external parameters, e.g. a two-zone flooding cases, are since the overall level A conveys all the information about the capability of the ship to deal with an event of flooding, sea state, etc (i.e. the onset of external parameters).

To explain the significance of the above observation, consider the scenarios shown in Figure 49, followed by Table 7. The two graphs represent domain of flooding extents partitioned according to probability of each feasible extent occurring, as given by (30). Assume that because of stability characteristics, both would result in different likelihoods of catastrophic events of capsizing within $t_0 = 30\,\mathrm{min}$ occurring, as assigned based on (32).

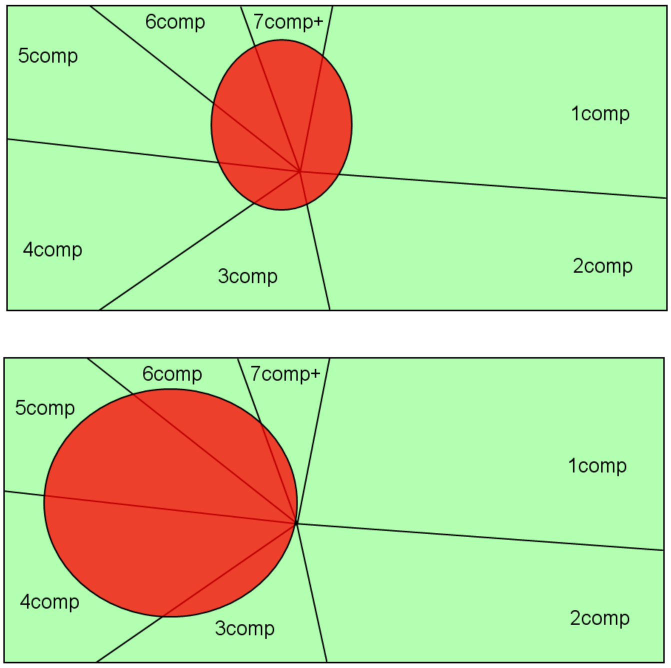


Figure 49 - Illustration of the Bayes' theorem on total probability

Figure 49 shows an illustration of the Bayes' theorem on total probability. The event marked by the "red" circle should be viewed in the context of the total domain of the feasible flooding cases denoted by the square. A ship with the smaller circle is the less risky design.

Table 7 - Results from Table 15 used to demonstrate the above concept with the real data

SHIP3	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.28471	0.28320	0.00151	0.99470	0.00530
2-ZONE	0.35960	**0.33748**	**0.02212**	0.93849	0.06151
3-ZONE	0.17255	0.12221	0.05034	0.70826	0.29174
4-ZONE	0.09486	0.05673	0.03813	0.59804	0.40196
5-ZONE	0.05188	0.02578	0.02610	0.49692	0.50308
6-ZONE	0.02283	0.00661	0.01622	0.28953	0.71047
7-ZONE +	0.00951	0.00192	0.00759	0.20189	0.79811
	0.99594	**0.83393**	**0.16201**		

SHIP4	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.35107	0.35050	0.00057	0.99838	0.00162
2-ZONE	0.38742	**0.33653**	**0.05089**	0.86864	0.13136
3-ZONE	0.17370	0.12723	0.04647	0.73247	0.26753
4-ZONE	0.06025	0.03427	0.02598	0.56880	0.43120
5-ZONE	0.02054	0.00908	0.01146	0.44206	0.55794
6-ZONE	0.00572	0.00195	0.00377	0.34091	0.65909
7-ZONE +	0.00053	0.00022	0.00031	0.41509	0.58491
	0.99923	**0.85978**	**0.13945**		

Table 7 shows the results from Table 15 used to demonstrate the above concept with the real data. Ship 4 would result in 13.5% of flooding cases in rapid capsize (5% being 2-zone), while Ship 3 would allow 16.2% of flooding cases to result in rapid capsize (2.2% being 2-zone). Ship 4 poses lesser risk to life than Ship 3 (assuming all other key variables are the same).

The probability A (green area) indicates the proportion of survival cases among all feasible cases denoted by the square. The probability 1-A (red circle) indicates the proportion of cases among all feasible ones that are expected to result in rapid capsize.

The design case with a smaller "red" area is a superior case to the one with a larger "red" area, even though the one with the smaller area contains cases such as 1 and 2 compartment flooding that contribute to non-surviving cases. It is irrelevant what the likelihood for sub-domain occurrence is (e.g. that contributing 1-compartment flooding is more likely than 3-compartment flooding, etc.), as the event of interest in setting any stability standard is the event of capsize and not occurrence of any given flooding case. A summary of these probabilities for designs considered in this project are given in §5.2.3.

It is for this reason, that the only quantity of importance is the marginal, overall or total, probability of survival. That quantity is given by probability A.

Regulating the level of ship stability based on A allows the designer freedom in setting architecture arbitrarily, without the regulation "imposing" a set of solutions that will ensure compliance (e.g. B/5 bulkhead imposed by the Stockholm Agreement). On the other hand, probability A is the first comprehensive regulation that considers all feasible cases, not just some of the flooding cases, that will be analysed before compliance can be attained or not.

For instance, the provisions of the Stockholm Agreement only consider flooding cases of certain class, e.g. those that span no more than two adjacent compartments and do not penetrate deeper than B/2, the probability of occurrence of which, between ships developed in this project, are shown in Figure 50. Ensuring that a level of survivability is attained for these classes of damages is obviously affecting the level of survivability of every other scenario that might occur, not only those that are smaller but also those that are more extensive. However, the Stockholm Agreement would not quantify the overall level of attained survivability.

The latter will inevitably result in an inconsistent level of safety attained between different ships, even though designed to the same standard of the Stockholm Agreement.

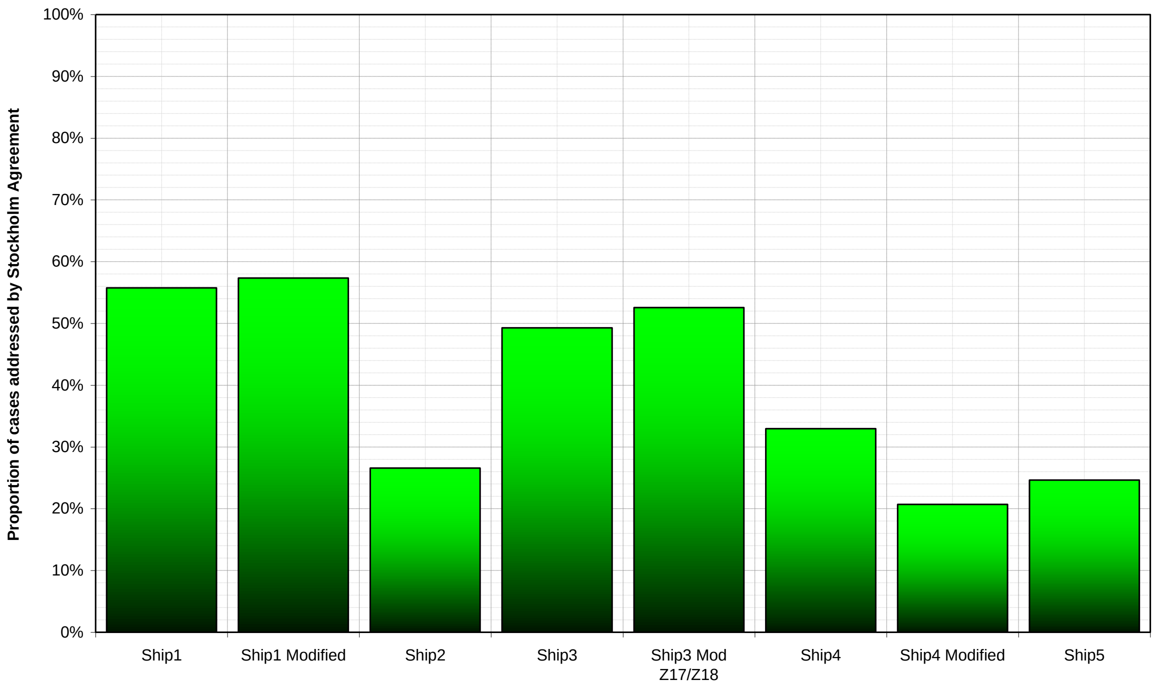


Figure 50 - Flooding cases addressed by the Stockholm Agreement for assurance of level of stability

SOLAS 2009 allows consistent quantification of level of safety. The overall survivability A that will result from ensuring survivability for the Stockholm Agreement cases will reflect the intention of the Stockholm Agreement, as is shown in Table 14, Figure 77 and Figure 6. Hence probability A can be used as a measure for comparisons between standards alternative to traditional GM limiting curves, given in §5.2.2.

It would be most advisable, therefore, that the task of setting a stability standard focuses on choosing the level of the required probability A appropriately to achieve adequate stability for any case that might occur rather than only some of such cases, as the Stockholm Agreement addresses, see Figure 50.

What is "adequate" stability and consequently the required probability A is the most substantial question in this study. A suggestion for the answer is given in the next chapter.

5.1.5. Factor R

Setting of the current level of index R has been performed in [32, Chapter 5], with the following goals set:

a) To find equivalent levels of safety between the requirements resulting from the current rules in SOLAS, and the probabilistic regulatory framework as expressed by the attained and required subdivision indices A and R, respectively.

b) To rationally specify the required subdivision index R, for various types of ships taking into account the equivalence to the particularly valid deterministic stability and compartmentation standard for new buildings (for passenger ships: SOLAS 90, two compartment standard), the load line requirements, the variation of typical ship design parameters, particularly ship size, construction concept and arrangements.

c) To consider the impact of local operational criteria, particularly Resolution 14 of SOLAS 95 and the Stockholm Agreement.

It was also stated in the HARDER project that:

"Taking into account that current damage stability regulations for new-buildings reflect a satisfactory level of safety, it follows that the harmonization of relevant rules on the basis of the probabilistic damage stability concept should have aimed at keeping these levels of safety on average unchanged. Thus, the calculation of the new Required Index, R_{new}, has been based on the "equivalence of safety" of the new harmonized regulations with the currently valid deterministic or probabilistic standards".

The basic modelling of the "equivalence of safety" has been expressed by the following formula:

$$\frac{Anew}{Rnew} \approx \frac{A_{EXISTING}}{R_{EXISTING}} \Rightarrow Rnew = Anew \cdot \frac{R_{EXISTING}}{A_{EXISTING}}$$

It was also observed that:

"… the direct comparison of the deterministic SOLAS 90 standard with the probabilistic HARDER and SLF concepts raises some fundamental questions regarding the sufficiency of SOLAS 90 two compartment standard for large passenger ships and importance of the relation of the SOLAS damage length to the compartment length and the required ship's subdivision standard for large passenger ships."

The latter has only been addressed partially, e.g. [33], and hence ineffectively as yet to date. Therefore, to set a new and rational framework for a decision on an appropriate level of the required index of subdivision R, principles of the FSA are adopted according to general guidelines of the FSA of MSC/Circ.1023, MEPC/Circ.392, [36].

An FSA[6] should comprise the following steps:

- Identification of hazards,
- Risk analysis,
- Risk control options,
- Cost benefit assessment; and
- Recommendations for decision-making.

The depth or extent of application of the FSA methodology should be commensurate with the nature and significance of the problem, and hence is subject to specifics of the problem addressed.

5.1.5.1. Identification of Hazards

The key objective of the exercise of hazard identification is to construct a list of all relevant accident scenarios with potential causes and outcomes that need to be considered in performing risk assessment.

As the purpose of the FSA is to help[6], among others, in the evaluation of new regulations for maritime safety, or in making a comparison between existing and possibly improved regulations, with a view to achieving a balance between the various technical and operational issues, including the human element, and between maritime safety and costs, it is of importance that the addressed problem is clearly defined, together with any relevant boundary conditions or constraints.

The problem of "ship stability in flooded state" is strictly set out as terms of reference for this project, with primary consequence of loss of life to be prevented. Furthermore, although the RoPax ship type has been specified, the analyses should relate to other ship types, especially Cruise/Pax ships, since SOLAS 2009 contains standards of stability "harmonised" for any ship type.

Moreover, the problem of "flooded state" must be clarified, since it can arise due to various events, such as explosion, grounding, ship-to-ship collision, contact (e.g. pier), opened enclosures (bow doors, side doors), fire-fighting systems (sprinklers), and possibly others.

Since, the terms of reference for this project address the Stockholm Agreement and SOLAS Chapter II, both of which have been developed solely based on a very specific cause of flooding, namely that of side shell damage, caused likely by ship-to-ship collision, this FSA will address only this type of event as the most potent hazard. The constraint of data availability as well as the project resources, which allow limited extent of experimental studies, imposes further this type of event as the study subject.

However, even when focusing on only this specific type of event, it transpires that the issue of stability is very serious. This derives from basic principles of physics reasoning, namely a ship which has no residual stability in a flooded state will result in rapid capsize with loss of life by those onboard. Any of the existing regulations permit today's ships to be designed with no residual stability for many feasible and likely flooding cases.

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[6] http://www.imo.org/OurWork/HumanElement/VisionPrinciplesGoals/Pages/Formal-Safety-Assessment.aspx

Whilst a sensible argument may be to address reasons/causes for flooding events in the first place, it is assumed in this study that such causal factors are at the present time and the foreseeable future beyond any clear definition, auditability and, therefore, beyond any regulatory control. It is observed that flooding events have occurred every year since records began and no strategy seems to be effective in countering this trend. However, whilst reasons, scenarios and causes for flooding to occur, are many and varied, all result in exactly the same consequence, namely "loss of stability", which may well be catastrophic in nature.

Therefore, "loss of stability" can be seen as the root cause for large and intolerable consequences, such as loss of many persons in one accident, and therefore, it is the most critical hazard that must be addressed.

As a rough guiding figure, a typical passenger ship is allowed under SOLAS stability regulations to have little or no residual stability for some 10%-30% of feasible collision damage cases. On average, one collision, grounding or other similar event takes place per month among the passenger fleet and at least once per year serious flooding occurs. Estimated once every 5 to 10 years on average it can be expected that serious loss of stability takes place. This level of risk seems of great concern as it recurs in the maritime industry with perceptible regularity.

The field of ship stability is a considerably well-researched scientific field, it has an advanced regulatory framework, expertise and experience, and it is auditable and, therefore, enforceable. It is therefore proposed that addressing the hazard of loss of stability, as a first step, resulting from side shell damage, may be regarded as one of the most effective measures to avert serious accidents from occurring in the future.

5.1.5.2. Risk Analysis

5.1.5.2.1. Risk Model

For practical purposes, only risk to human life is considered[7] in this report.

It is proposed that the risk is understood as a *"chance of a loss"*, whereby the "chance" is quantified by means of statistics of the loss, and "the loss" is measured by an integer number of fatalities, N (no type of injury is considered).

Two commonly used statistics of "the loss" are considered[8], namely "FN curve", as given by equation (39) and expected number of fatalities, commonly referred to as "potential loss of life" or *PLL*[9].

$F_N(N) = \sum_{i=N}^{N_{\max}} fr_N(i)$	cumulative distribution of frequency for occurrence of N or more number of fatalities per ship per year, known as an "F-N curve"	(39)

[7] Risk to property, business, economy, environment or other is not considered here, however the principles can well be adopted.
[8] Note that any other aggregate number describing the loss can be considered, if found to be more efficient statistic.
[9] Note that this ubiquitous terminology is grossly misleading, since potential loss of life on a ship of say 1,000 persons is exactly 1,000 persons, and this contrasts to expected loss of life which accounts for probability of it happening, so say if p=0.2 that all persons will be lost, then E(N) = 0.2 x 1,000 = 200 persons.

Where $N_{\max}$ is the number of persons considered (e.g. number of crew, or number of passengers, or both, onboard the ship), and $fr_N(N)$ is the frequency of occurrence of exactly N number of fatalities per ship per year, given by equation (41).

The second statistic often considered is the expected number of fatalities $E(N)$, given by model (40) and often referred to as the "potential" loss of life PLL [9].

$Risk_{PLL} \equiv E(N) \equiv PLL \equiv \sum_{i=1}^{N_{\max}} F_N(i) \equiv \sum_{i=1}^{N_{\max}} i \cdot fr_N(i)$	(40)

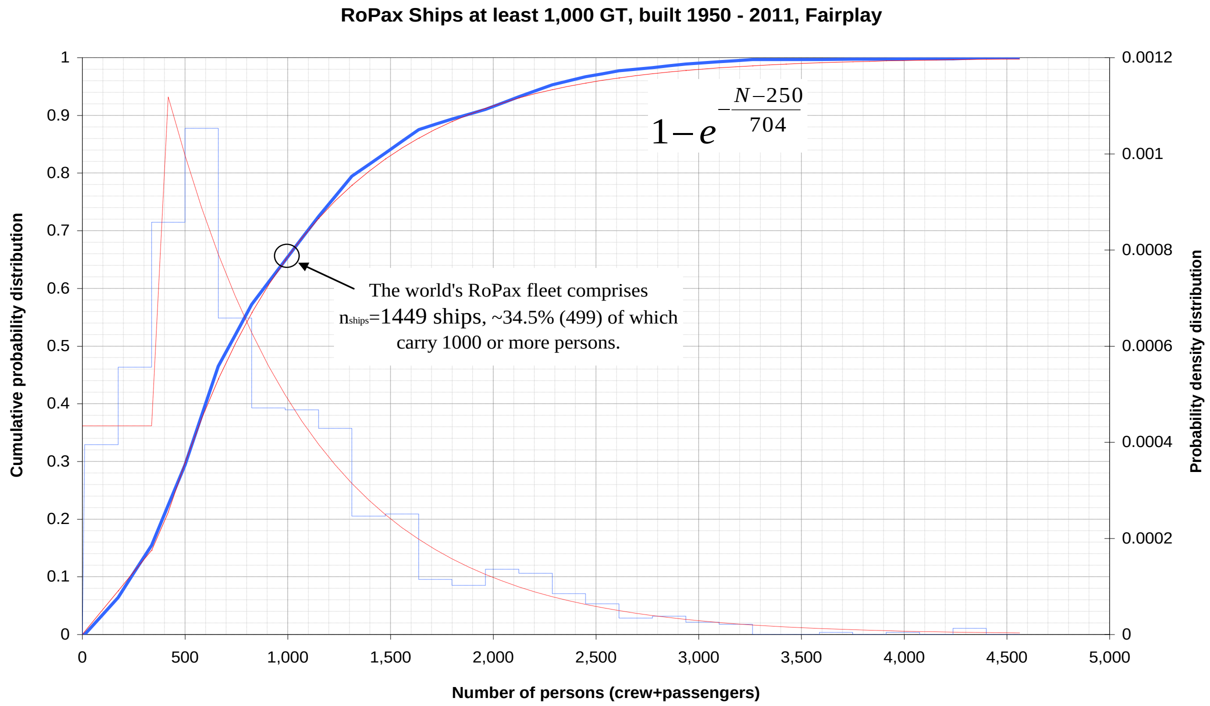
The frequency of occurrence of exactly N number of fatalities per ship per year, $fr_N(N)$, can be derived from a conservative "rare event" approximation to disjunction of a set of scenarios, [40], and a form of Bayes' theorem on total "frequency", namely:

$fr_N(N) = \sum_{j=1}^{n_{hz}} fr_{HZ}(hz_j) \cdot \left(1 - cdf_{N_{\max}}(N_{\max})\right) \cdot p_{N\mid HZ}(N \mid hz_j)$	(41)

Where n_{hz} is the total number of loss scenarios considered as exhaustively contributing to risk to life and hz_j represents an event of the occurrence of a chain of events HZ (a loss scenario) identifiable by any of the considered principal hazards, such as collision and flooding, fire, grounding and flooding, and possibly others.

Furthermore, $fr_{HZ}(hz_j)$ is the frequency of occurrence of a scenario $HZ = hz_j$ per ship per year and $p_{N\mid HZ}(N \mid hz_j)$ is the probability of occurrence of exactly N fatalities, given loss scenario hz_j occurred.

The $cdf_{N_{\max}}(N_{\max})$ is the probability that a ship has the capacity of up to $N_{\max}$ persons (crew and passengers) in the fleet of given ship types, as shown in Figure 51.



Source: Fairplay database

Figure 51 - Probability distribution of number of persons onboard RoPax ships

The probability of the ship being of given size $cdf_{N_{\max}}(N_{\max})$ in equation (41) allows to recognise that the actual size of the vessel will determine how likely a given maximum level of fatalities can be incurred among the fleet. For instance if only 1 ship in a fleet of 1,000 vessels can carry say 4,000 persons, i.e. $cdf_{N_{\max}}(4{,}000)=0.999$ and frequency $fr_{HZ}(hz_j)$ of hazard hz_j remains unchanged for all 1,000 vessels, then the frequency that 4,000 fatalities can be observed among the fleet as a result of specific hazard hz_j must be $fr_N(N=4{,}000)=fr_{Hz}(hz_j)\cdot(1-0.999)\cdot p_{N|HZ}(N|hz_j)$. On the other hand, if say 950 ships among the 1,000 are carrying say 80 persons onboard or more, then the frequency that 80 fatalities occurs must be $fr_N(N=80)=fr_{Hz}(hz_j)\cdot(1-0.050)\cdot p_{N|HZ}(N|hz_j)$.

Equation (41) allows for consistent and comprehensive accommodation of any conceivable loss scenario contributing to risk to life and, for which reason, the risk model (40) or (39) can be referred to as "holistic".

As mentioned above, only one loss scenario $Hz = collision \cap flooding$ is considered in this project, and hence equation (41) can be re-written as follows:

$$fr_N(N)=fr_{HZ}(coll\cap flooding)\cdot\left(1-cdf_{N_{\max}}(N_{\max})\right)\cdot p_{N|HZ}(N|coll\cap flooding)$$

Or for short:

$$fr_N(N)=fr_{coll}\cdot\left(1-cdf_{N_{\max}}(N_{\max})\right)\cdot p_{N|coll}(N) \quad (42)$$

Where fr_{coll} refers to frequency of an event of collision (or contact) and subsequent flooding occurring among the worldwide fleet of RoPax ships.

Thus the model (39) can be rewritten as follows:

$F_N(N) = fr_{coll} \cdot \left(1 - cdf_{N_{\max}}(N_{\max})\right) \cdot \sum_{i=N}^{N_{\max}} p_{N\|coll}(i)$	(43)

To further resolve equation (43) it is to be noted that many among the feasible flooding cases are not survivable in calm seas or waves (see “red” and “grey” pieces of the pie chart in Figure 52), and with expected rapid capsizes, e.g. [8] to [10].

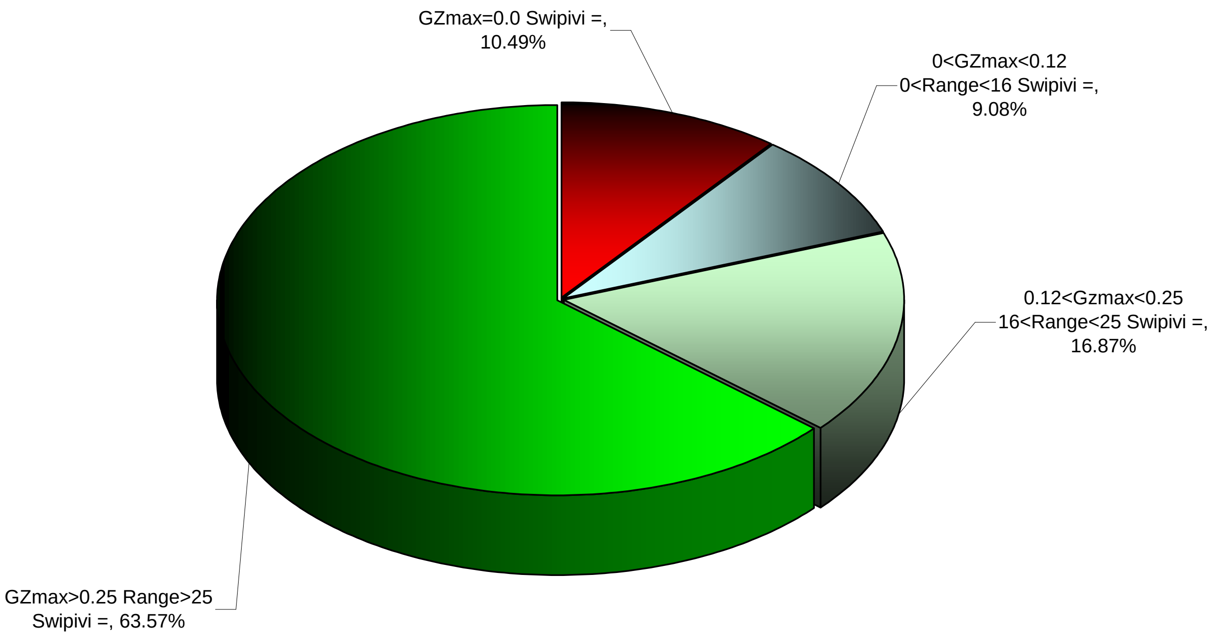


Figure 52 - Distribution of probability for GZmax. SHIP 1, all loading conditions, A=0.857

Figure 52 shows the distribution of probability for GZ_{max} (occurrence of flooding cases with given range of parameter of residual stability GZ_{max}). The selected cases are based on the Alternative 1 of the proposed changes to SOLAS 2009, see Table 14 (SHIP 1, all loading conditions, A=0.857).

To demonstrate the meaning of this observation, consider a case of a ship with stability characteristics as given in Table 8. On the basis of these ship characteristics as well as typical assumptions on the process of abandonment, the probability distribution $p_{N|coll}(i)$ for “i” number of fatalities can be derived analytically or through stochastic integration as shown in Figure 53 and Figure 54, respectively. It can be seen that the probability that 100% fatality rate will occur is approximately $p_{N|coll}(N_{\max}) \sim 26\%$. That is in 26% of flooding cases or (1-A)x 100% (see comparative Figure 55) will result in extensive loss of life. The remaining proportion (A x 100%) of flooding cases will either sustain stable condition for a sufficient time for orderly abandonment or be in a position to return to port, with no or indeed a minimal loss of life.

Table 8 - Stability characteristics of typical RoPax vessel

ATTAINED AND REQUIRED SUBDIVISION INDEX

Subdivision length 156.033 m

Breadth at the load line 23.600 m

Breadth at the bulkhead deck 23.600 m

Attained subdivision index **A = 0.74130**

INIT	DAMTAB	T	GM	KG	SUBD	WCOEF	ASI
		m	m	m			
DS	REG71P	5.390	1.167	10.62	REG7	0.200	0.06969
DS	REG72P	5.390	1.167	10.62	REG7	0.200	0.07585
DS	REG71S	5.390	1.167	10.62	REG7	0.200	0.06837
DS	REG72S	5.390	1.167	10.62	REG7	0.200	0.06933
DP	REG71P	5.234	1.083	10.62	REG7	0.200	0.06974
DP	REG72P	5.234	1.083	10.62	REG7	0.200	0.08368
DP	REG71S	5.234	1.083	10.62	REG7	0.200	0.06889
DP	REG72S	5.234	1.083	10.62	REG7	0.200	0.07613
DL	REG71P	5.000	1.036	10.62	REG7	0.100	0.03488
DL	REG72P	5.000	1.036	10.62	REG7	0.100	0.04702
DL	REG71S	5.000	1.036	10.62	REG7	0.100	0.03473
DL	REG72S	5.000	1.036	10.62	REG7	0.100	0.04300

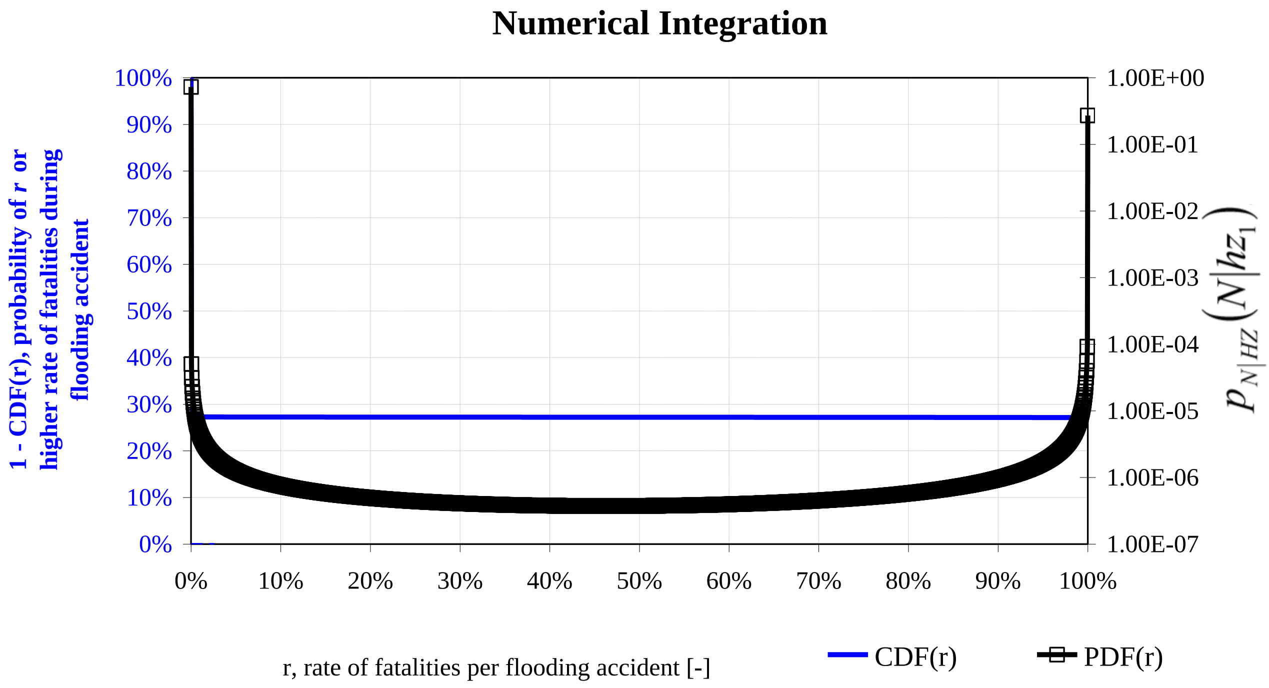


Figure 53 - Probability distribution function $p_{N|coll}(N|hz = coll)$, direct numerical integration

Figure 53 shows the probability distribution of function $p_{N|coll}(N|hz = coll)$; direct numerical integration. The key characteristic of this function is its bimodality, with maximum values typically obtained for N = 0 and N = N_{max}. It is noted that the compliment of cumulative distribution function converges to the value of (1-A).

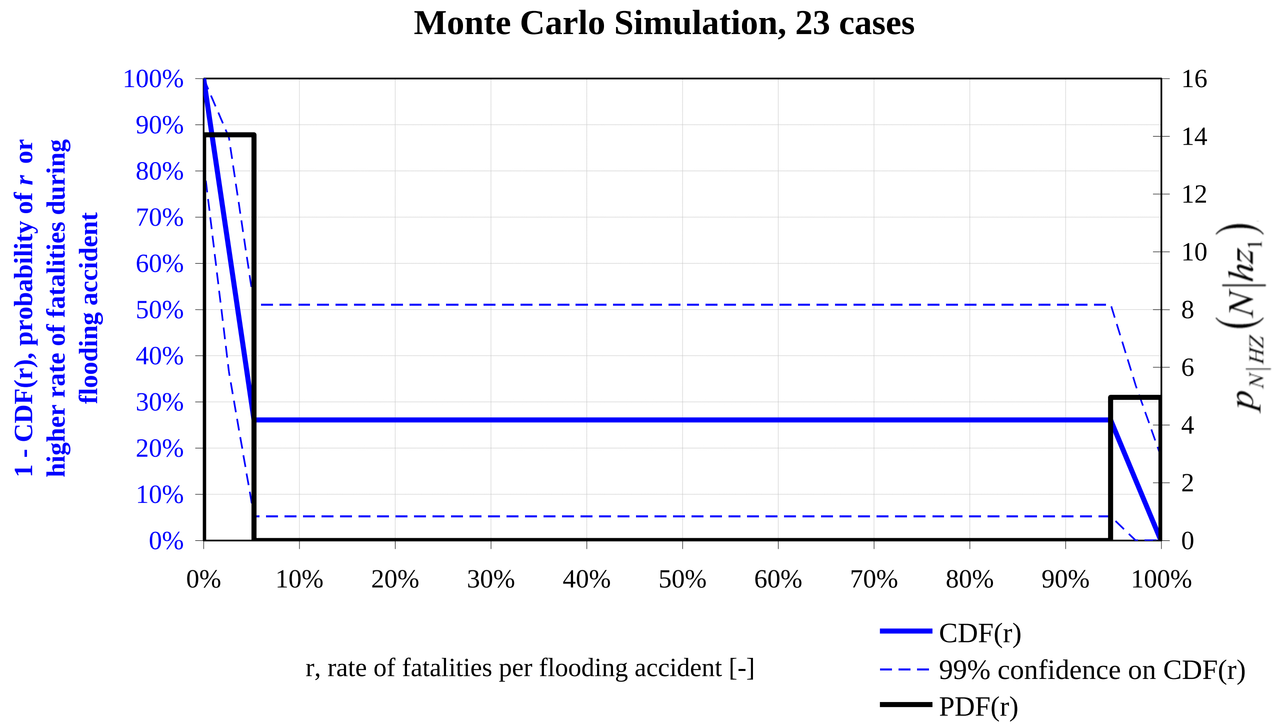


Figure 54 - Probability distribution function $p_{N|coll}(N|hz = coll)$, stochastic simulation

Figure 54 shows the probability distribution of function $p_{N|coll}(N|hz = coll)$; stochastic simulation. The key characteristic of this function is its bimodality, with maximum values typically obtained for N = 0 and N = N_{max}. It is noted that the compliment of cumulative distribution function converges to the value of (1-A).

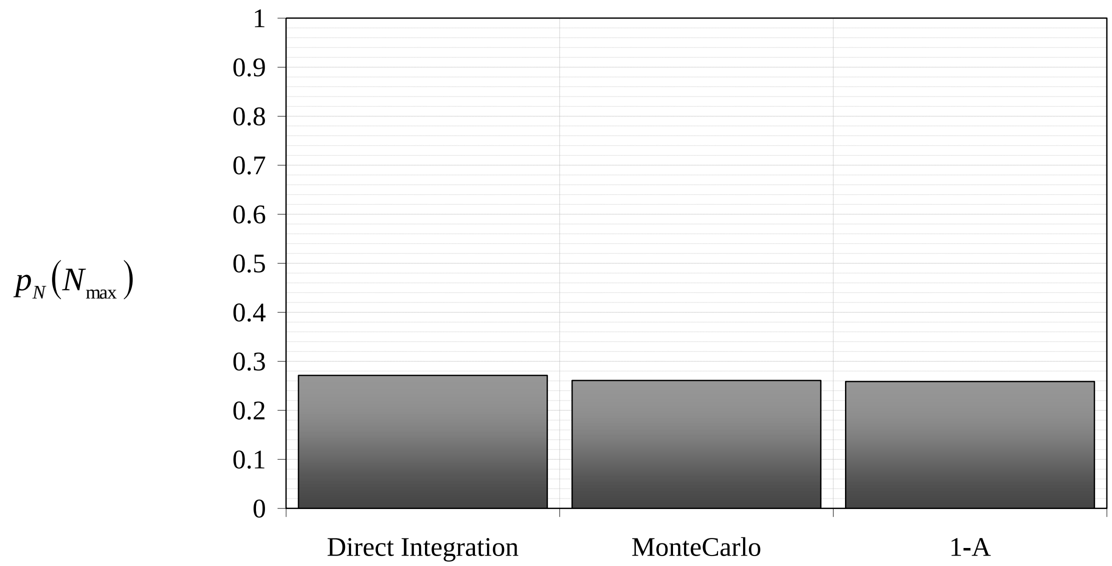


Figure 55 - Comparison of prediction of probability $p_{N|coll}(N_{max}|coll) \sim (1 - A)$ by different techniques

Figure 55 shows the probability $p_{N|coll}(N_{max}|coll) \sim (1-A)$ that exactly N_{max} number of fatalities occur on a ship due to flooding accident, through comparison of quality of prediction by different techniques.

Therefore, the probability of exactly N fatalities occurring due to hull breach in a collision / contact and flooding can be assigned for analyses in this project, as follows:

$p_{N\|coll}(i) = \begin{cases} 0 & if \quad 1 < i < N_{max} \\ 1-A & if \quad i = N_{max} \end{cases}$	(44)

That is, it can be assumed that the vessel has either sufficient stability or the stability is deficient and rapid capsize ensues with 100% fatality rates.

Therefore, an adequate and robust risk model for the F_N curve adopted for analyses in this project is given as follows:

$F_N(N) = fr_{coll} \cdot (1 - cdf_{N_{max}}(N_{max})) \cdot (1-A)$	(45)

Where A is the probability of a vessel staying afloat and stable after flooding, known as the Attained Index of Subdivision, see [4], and no assumption is made on the vessel load factors (maximum number of persons onboard at all times) for the sake of reasonable conservatism.

The $cdf_{N_{max}}(N_{max})$ may be approximated by (46):

$cdf_{N_{max}}(N) = \begin{cases} 4.34 \cdot 10^{-4} \cdot N & if \quad N \leq 375 \\ 1 - e^{-\frac{N-250}{704}} & if \quad N > 375 \end{cases}$	(46)

The expected number of fatalities per ship per year can be then assessed as:

$E(N_{max}) = fr_{coll} \cdot (1 - cdf_{N_{max}}(N_{max})) \cdot (1-A) \cdot N_{max}$	(47)

5.1.5.2.2. Risk Acceptance Criteria

A set of risk acceptance criteria has been presented to the IMO MSC 72/16 in document [35] and subsequently used in a recent submission on the FSA studies for RoPax ships in [33]. The following equation (48) and Figure 56 presents these societal criteria for the ALARP range of tolerable frequencies of accidents, based on the "FN curve" concept $F_N(N)$.

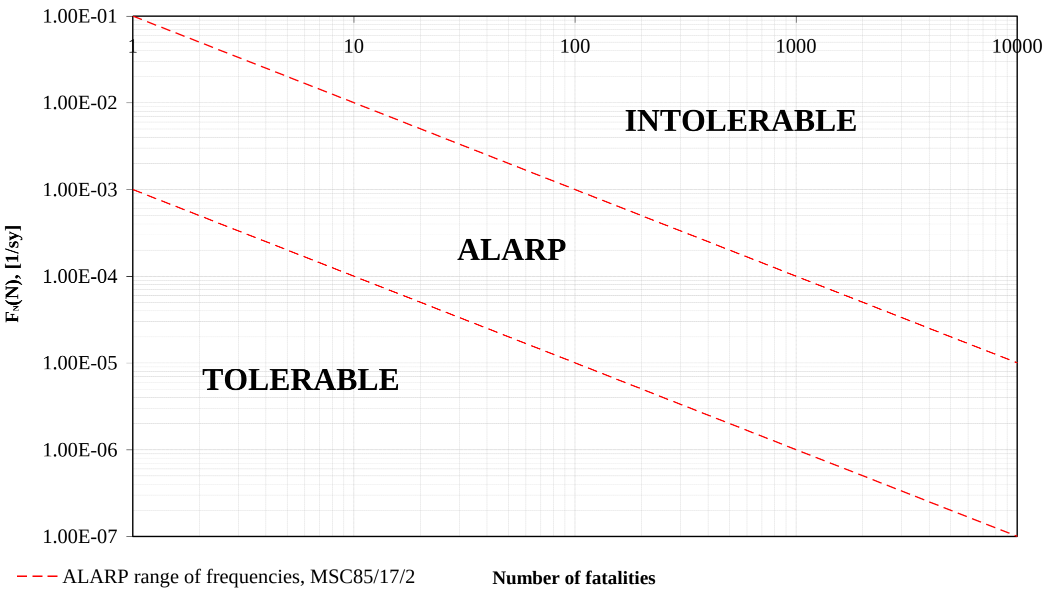
$\frac{10^{-3}}{N} \leq F_N(N) \leq \frac{10^{-1}}{N}$, per ship per year, $\frac{1}{s \cdot y}$	(48)

The $F_N(N)$ curve is chosen customarily to denote the complement of cumulative distribution of the rate for N or more fatalities that can occur annually, as already mentioned above. In the maritime context, it implies fatalities occurring on a specific ship (due to an accident).

For a convenient interpretation of criteria (48), consider a specific number of fatalities $N = 1{,}000$ on a ship which can carry at least 1,000 persons. The "upper" criterion (48) indicates "tolerable" frequency that such number of fatalities occurs on a ship annually, which is as follows:

$F_N(1{,}000) \leq 1 \cdot 10^{-4} \cdot \frac{1}{s \cdot y}$	(49)

The criterion states that it is not intolerable that 1,000 fatalities or more occur on an "average" RoPax ship 10^{-4} per annum.



Source: [35] "FORMAL SAFETY ASSESSMENT - Decision parameters including risk acceptance criteria", MSC 72/16, 14 February 2000.

Figure 56 - Risk acceptance criteria

Consider this criterion in the context of a fleet of ships complying with such a criterion.

According to the Fairplay database there have been 1,449 RoPax ships worldwide in 2011, $n_{ships} =$ **499** of which carry 1,000 persons or more. Data available from Fairplay has been used to assign probability distribution for the maximum number of passengers among this fleet of ships, as shown in Figure 51 and given by (46).

So, a fleet of $n_{ships} = 499$ pertinent ships is said to not pose intolerable risk to society if <u>each</u> ship meets criterion (48) and then (49).

This implies that the tolerable annual rate of N=1,000 or more fatalities for the fleet of n_{ships} is:

$F_{fleet}(1{,}000) = F_N(1{,}000)\cdot n_{ships} = 1\cdot 10^{-4}\cdot\frac{1}{ship\cdot year}\cdot 499\cdot ships = 0.0499\cdot\frac{1}{year}$	(50)

This means, furthermore, that the proposal of MSC72/16, given above by (48), considers it **not intolerable** that every $T_{mri} = \frac{1}{F_{fleet}(1{,}000)} = \frac{1}{0.0499\cdot\frac{1}{year}} = 20\cdot years$ there is an accident among the fleet of $n_{ships}=499$ of RoPax ships involving 1,000 fatalities or more. The mean recurrence interval T_{mri} (or MRI) given by (51) implies average repetition of such an accident every 20 years, see Figure 57.

$T_{mri} = \frac{1}{F_N\cdot n_{ships}}$ [years]	(51)

Consider now the historical data as presented in [33] and Table 9, together with the Al-Salam Boccaccio 98 accident which claimed approximately 1,000 lives on 3rd February 2006. This indicates that at least two major accidents involving most persons onboard occurred over a span of approximately 10 years. Before the MV Estonia accident in 1994, another large accident: the Herald of Free Enterprise preceded it in 1987, and "near misses" for large accidents in between have occurred.

All these accidents involved stability impairment situations, and whilst the flooding initiation varied (e.g. open bow doors), the ultimate mechanism that failed to contain the escalation was the lack of stability, an event common to every flooding. The recurrence interval of 6 to 20 years implies that events are bound[10] to occur within 40 to ~100 years, see equation (55). Therefore, whilst the mentioned accidents did not initiate through collision, they corroborate the expectation of the outcome in case of stability impairment situation. Therefore, it seems that the mean recurrence interval implied by the criterion (48) is not even complied with by the current fleet (large accidents repeat more often than once every 20 years implied by tolerability criterion (48), (49) and (50) (see information below and Figure 63 and Figure 65).

Although criteria (48) of MSC72/16, seem to have been developed from rational premise of relevance of RoPax ships to economies, it reflects prevailing acceptance of state-of-the-art level of safety, which given the historical evidence from the past two decades, no longer seems obviously tolerable, see Figure 57. Therefore, the following alternative reasoning based on engineering pragmatism and with reference to guidelines in other engineering professions might be proposed as follows:

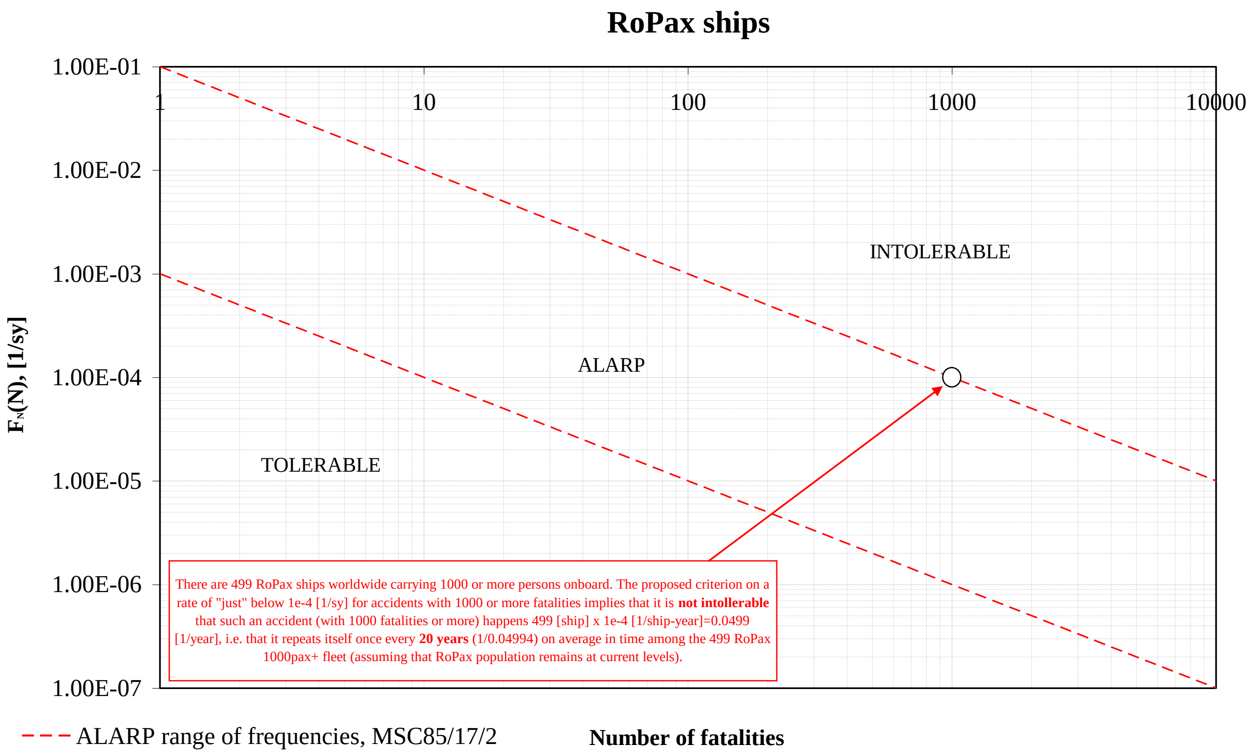
It is hereby proposed, that a criterion for intolerability is based on a principle of at least 100-years mean recurrence interval $T_{mri} \geq 100 years$ (for the fleet) for catastrophic accidents, such as loss of 1,000 lives in one accident.

[10] *for instance in an experiment of throwing a die and event of "6" is expected to occur once every 6th throw on average, but it might be 40 throws before it is observed eventually.*

Table 9 - RoPax fatal accidents - worldwide fleet (1994 – 2004)

Incident Date	Vessel	Year Built	Event	Incident Location[1]	Fatalities
18.05.1994	Al-Qamar Al-Saudi Al-Misri	1970	Fire/Explosion	RED	21
28.06.1994	Tag Al Salam	1969	Fire/Explosion	BAL	1
28.09.1994	Estonia	1980	Flooding	BAL	852
18.09.1998	Princess of the Orient	1974	Flooding	SCH	94
01.11.1999	Spirit of Tasmania II	1988	Fire/Explosion	EME	14
25.11.1999	Dashun	1983	Fire/Explosion	SCH	282
23.12.1999	Asia South Korea	1972	Fire/Explosion	SCH	56
16.07.2000	Ciudad de Ceuta	1975	Collision	WME	6
17.08.2000	Gurgen 2	1966	Fire/Explosion	EME	1
26.09.2000	Express Samina	1966	Grounding	EME	94
22.06.2002	Al Salam Petrarca 90	1971	Fire/Explosion	RED	1
11.08.2002	Tacloban Princess	1970	Fire/Explosion	SCH	2
22.10.2002	Mercuri 2	1984	Flooding	EME	49
01.07.2003	Paglia Orba	1994	Collision	WME	1

Source: [33] "Formal Safety Assessment FSA – RoPax ships", Details of the Formal Safety Assessment Submitted by Denmark, MSC 85/17/2, 21 July 2008.



Source: [35] "FORMAL SAFETY ASSESSMENT - Decision parameters including risk acceptance criteria", MSC 72/16, 14 February 2000.

Figure 57 - Interpretation of risk acceptance criteria of MSC72/16

Figure 57 shows the interpretation of risk acceptance criteria of MSC72/16, [35]. The criterion implies that it is not intolerable to observing an accident resulting in 1,000 fatalities or more every 20 years on average.

To reiterate, it is proposed that only if an accident involving 1,000 fatalities or more among the fleet occurs not more than once every 100 years on average, then such risk might be considered not intolerable. That is:

$$\frac{1}{F_N(1{,}000) \cdot n_{ships}} \geq 100 \cdot years \qquad (52)$$

Hence;

$$F_N(1{,}000) \leq \frac{1}{n_{ships} \cdot 100 \cdot years} \qquad (53)$$

$$F_N(1{,}000) \leq \frac{1}{499 \cdot ships \cdot 100 \cdot years} = 2.0 \cdot 10^{-5} \cdot \frac{1}{s \cdot y} \qquad (54)$$

So, if today's fleet of 499 RoPax ships capable of carrying 1,000 persons or more, were each upgraded to such a standard given by criterion (54), the fleet would not experience an accident involving 1,000 fatalities or more, greater than once per 100 years on average, see Figure 58 below.

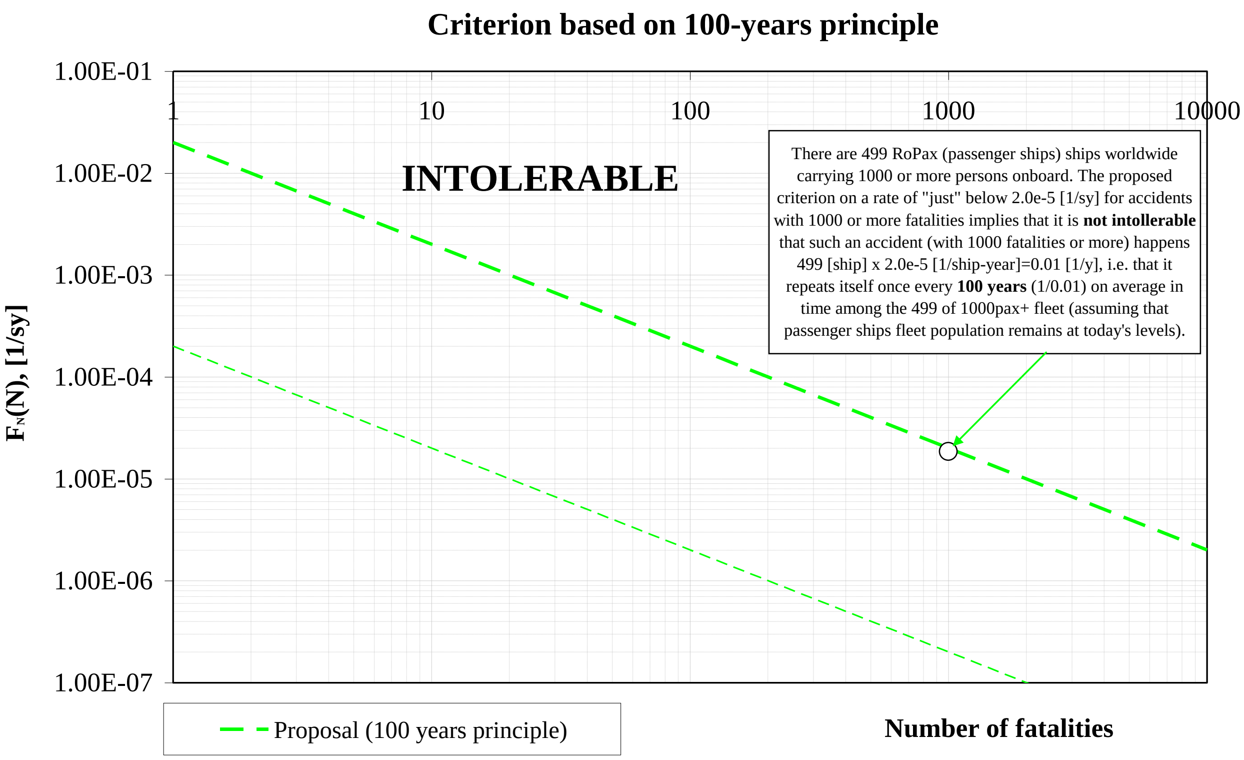


Figure 58 - Proposal of an absolute risk acceptance criteria of MSC72/16, [35] (100 years principle)

Figure 58 shows a proposal of an absolute risk acceptance criteria of MSC72/16, [35] with the goal of setting it as intolerable to observe an accident resulting in 1,000 fatalities or more, greater than once per 100 years.

It is noted, however, that since the mean recurrence interval of $T_{mri} = 100$ years only implies that such an accident would occur on average every 100 years; there remains a question how likely is it that such an accident will actually occur anytime within the next 100 years?

Likelihood of a catastrophic accident

An assignment of probability for such an event can be made based on the univariate geometric distribution, as follows:

$P(n) = 1 - \left(1 - \frac{1}{T_{mri}}\right)^n$	probability of at least one accident occurrence in n-years, where $p = 1/T_{mri}$ is the annual probability of accident occurrence	(55)

The distribution of probability (55) is shown below, for example, MRI's of 6, 20, 100, 3,300 and 10,000 years.

It can be seen, for instance, that the intolerability criterion based on a mean recurrence interval of 100 years implies 63.4% probability for occurrence of such an accident within 100 years[11].

[11] *Engineering interpretation of this probability starts becoming difficult, but to help the imagination consider that there are 10 planets Earth, each with exactly the same fleet of ships. The question is how often an accident involving 1,000 fatalities or more would happen among these 10 planets in 100 years, given that all ships are designed to 100-years criterion? Model (55) implies that in between 6 to 7 cases, 63.4% of 10, the accident would take place in the first 100 years.*

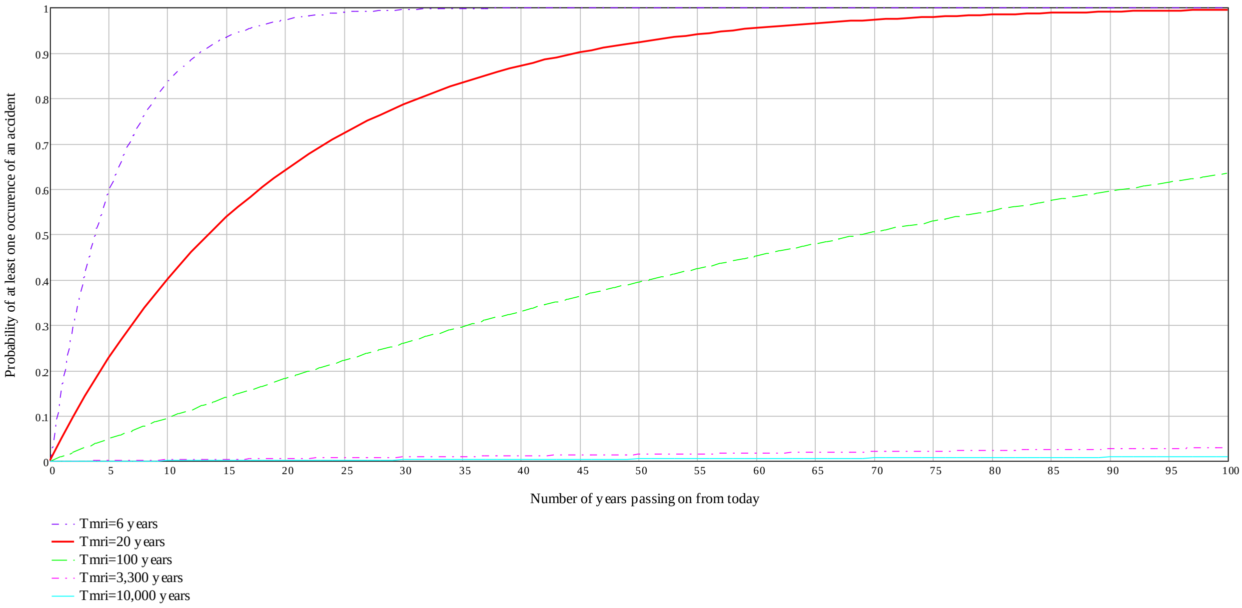


Figure 59 - Probability distribution for n number of years during which at least one accident occurs

A 100-year[12] (or often higher) criterion on MRI or 100-year "reference period" for which the probability of occurrence of an undesirable event is assigned, seems to be quite a common engineering criterion for design of sensitive objects, such as bridges, highways, dams, houses, tornado shelters, etc., [50], [52], [53], [54].

A 100-year MRI on wind loading for bridge design capacity would be used in San Francisco, [50]. The probability that such loading could occur in 100 years is 63.4%, see Figure 59.

A freeboard for bridge clearance above river elevation would be designed for MRI of 100 years for a flood in the State of Wisconsin, [52]. The probability that such flooding could occur in 100 years is 63.4%.

Maximum elastic surface response earthquake spectrum for MRI of 3,300 was used to aid the design of Suramadu Bridge. The probability for such response to occur in 100 years is 3%.

A community shelter, a shelter that could be occupied by 12 or up to several hundred persons, would be designed for "near absolute protection" against e.g. a tornado in Kansas, [54], whereby the design criterion for wind loading would be based on $T_{mri} = 10{,}000$, i.e. winds which could be exceeded within 100 years with less than 1% probability.

Comparisons of probabilities for catastrophic scenario occurrence within 100 years for either of these design criteria are shown in Figure 59.

On this background it is proposed that the reasoning behind the aforementioned criterion given in (54) derived on the basis of prevention of catastrophic accidents among a fleet of large (>1,000 persons) passenger ships, is appropriate. Although the principle of mean recurrence

[12] http://www.prs.pl/pages/konferencje/safe_shipping_2010/Safe_Shipping_on_the_Baltic_Sea.pdf

interval of 100 years as ship design target seems rather conservative when compared to current proposals of [35], equation (48), it is still rather relaxed (accident occurrence in 100 years with 63% probability) when compared to design basis of, e.g. community hurricane shelters, which sets out to assure that MRI for catastrophic collapses is not less than 10,000 years, with key motivation for it deriving from its purpose of housing a large number of people (several hundred).

It is hence compelling to adopt the principle of MRI to be not less than 100 years $T_{mri} \geq 100 years$ for prevention of large accidents among the passenger ships fleet. It is therefore proposed that standard (57) is considered as a risk tolerability criterion alternative to (48).

$F_N(N) \leq \frac{1,000}{N} \cdot \frac{1}{\left(1 - cdf_{N_{\max}}(1,000)\right) \cdot n_{ships} \cdot 100 years} = \frac{1,000}{N} \cdot \frac{1}{0.345 \cdot 1449 \cdot 100 years} = \frac{1}{N \cdot 50}$	(56)

Or if presented in the form of ALARP region:

$\frac{10^{-2}}{N \cdot 50} \leq F_N(N) \leq \frac{1}{N \cdot 50}$, per ship per year $\frac{1}{s \cdot y}$	(57)

It can be seen from (56) or (57) that if every one of the fleet of approximately 499 passenger ships that carry 1,000 or more persons onboard is designed to this standard, the expected annual rate of accidents (involving 1,000 persons or more) would be 0.01 = 499 x 1/(1,000 x50), i.e. on average it would repeat not more often than once every 100 years.

Note, however, that criterion (57) does not assure the recurrence interval of 100 years for accidents involving number of persons less than 1,000. This is due to the slope of the ALARP lines, used widely across the industry, and which element should also be reviewed if e.g. the 100-year principle is to also apply to smaller ships.

Whilst some of the details, such as the distribution shown in Figure 51 could be revised, it seems that such a framework for setting a criterion is robust and logical for debate and (57) is proposed as future ship safety standards, as well as basis for derivation of index R as intended in this project.

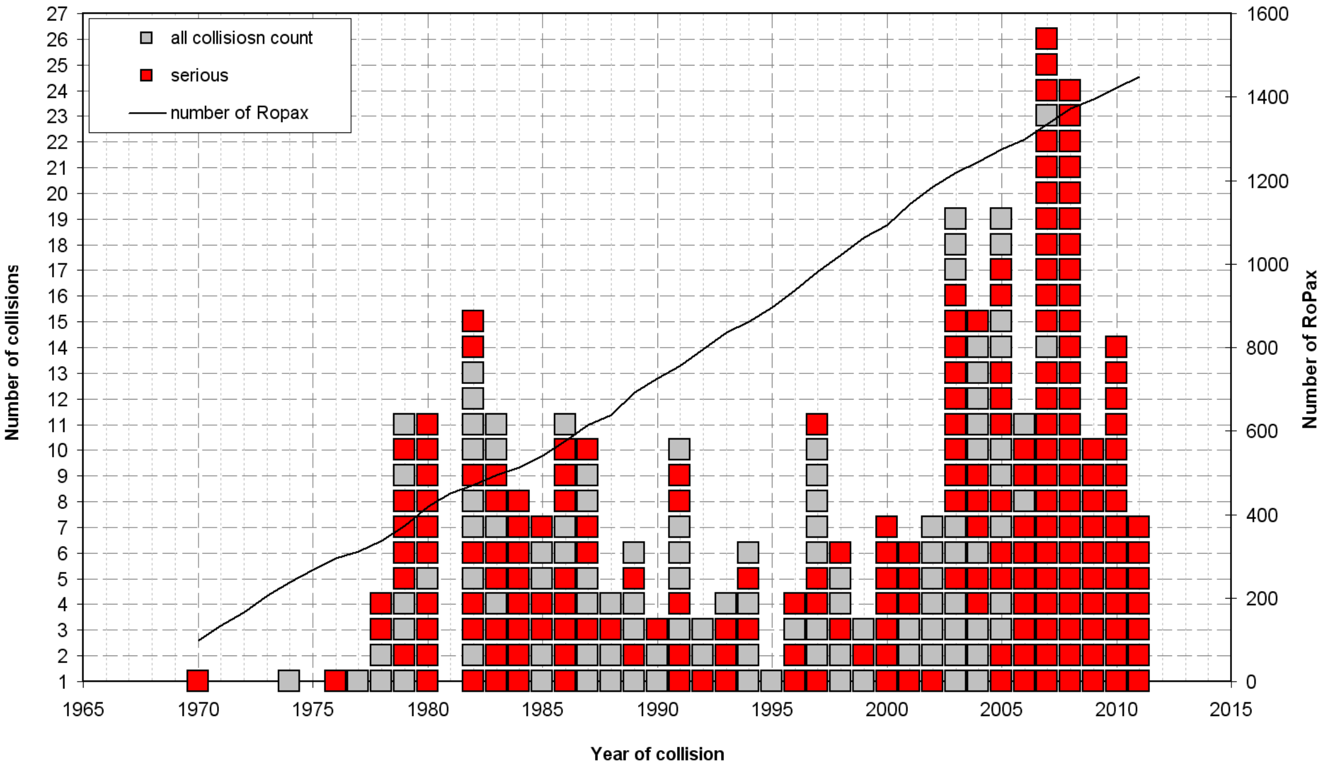
5.1.5.2.3. Accident Frequencies

A review of the various studies addressing the issue of repeatability of serious flooding accidents among the RoPax fleet has been performed. In particular, studies [34], [37], [41], [45], [55] were considered alongside the analyses of the data available in the Fairplay database performed in this project.

Considerable spread in estimates of frequency of a collision resulting in flooding were noted in these studies. It is clear that the reporting of accidents, the assessment of their seriousness, as well as the choice of the fleet in question are all subject to uncertainty and judgment.

However, irrespective of the noted uncertainty, it is hereby proposed that a representative accident frequency is sufficient for the disclosure of the risk to life posed by the operation of the RoPax ship concept. The representative frequency is assessed here based on the Fairplay record of collision incidents referenced to the RoPax (>1,000 GT) fleet, considered in 2011 and thus comprising 1,449 vessels, see Table 32.

In the past ten years, the number of collisions occurring annually is between approximately 7 and 26, with an average of 14 accidents per annum (see Table 10 and Figure 60). That is, currently, approximately once every month a serious collision incident occurs. An annual variation of the frequency of a collision event taking place among the RoPax fleet at the time is shown in Figure 61, where an average Poisson's frequency is approximately 10e-3 events per each ship per year (311 accidents, 30,693 ship years). As can be seen in Table 10, various studies estimate this frequency to fall within the spread of frequency assessed as the uncertainty.



Source: Fairplay database

Figure 60 - Annual number of occurrence of collision events among the RoPax fleet (>1,000GT)

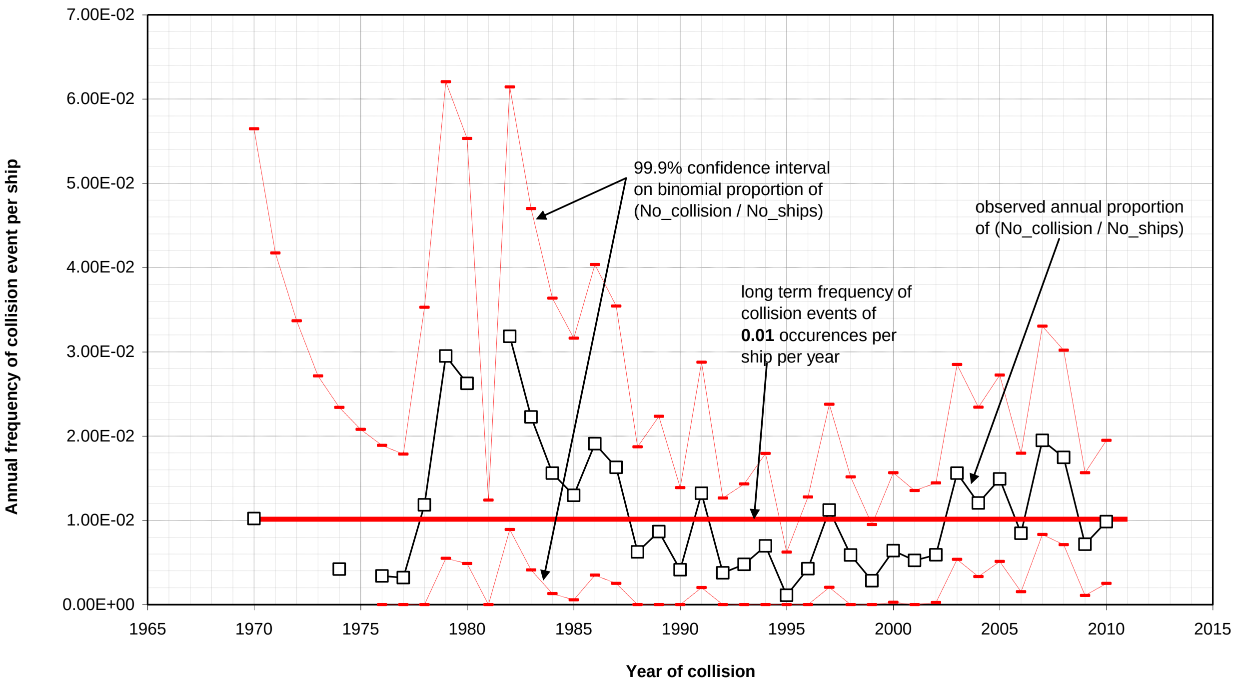


Figure 61 - Annual frequency of occurrence of collision events among the RoPax fleet (>1,000GT)

Figure 61 shows the annual frequency of occurrence of collision events among the RoPax fleet according to Fairplay (>1,000GT). The range of estimated representative frequency is shown in red at year 2010. It can be seen that the 99.9% confidence interval on binomial proportion (Annex 1) contains the representative frequency in 32 out of 34 years of historical data.

Among these collision incidents, approximately 67% are deemed serious according to Fairplay criteria (see Figure 60). Also, the incidents relate to both striking and struck ships, here assumed as an equiprobable event. Finally, according to common observations, e.g. [34] and [37], approximately half of these events lead to eventual flooding (hull breach takes place).

The derived range of frequencies of serious collisions with subsequent flooding is shown in Table 10 and Figure 62.

Table 10 - RoPax collision accidents. Fairplay data and other studies

	EMSA	GOALDS	Vanem & Skjong	MSC85/INF.3, July 2008
Total number of ship years, 1970-2010	30,693			
Number of collisions, 1970-2010	311			
fr_collision	**1.01E-02**	**7.78E-03**	**5.16E-03**	**1.25E-02**
probability of serious casualty	6.69E-01	1.00E+00	1.00E+00	1.60E-01
probability of struck ship	0.5	0.69	0.5	0.5
probability of flooding	0.5	0.43	0.5	0.5
fr_colll&flooding	**1.69E-03**	**2.31E-03**	**1.29E-03**	**5.00E-04**

In the above table, where a comparison between analysis of Fairplay data and other studies[13] is made, the ultimate frequency of serious collision, the ship being the one that is the struck ship and with the consequence of flooding is also calculated, denoted here as fr_collision & flooding, and fr_{coll} thereafter.

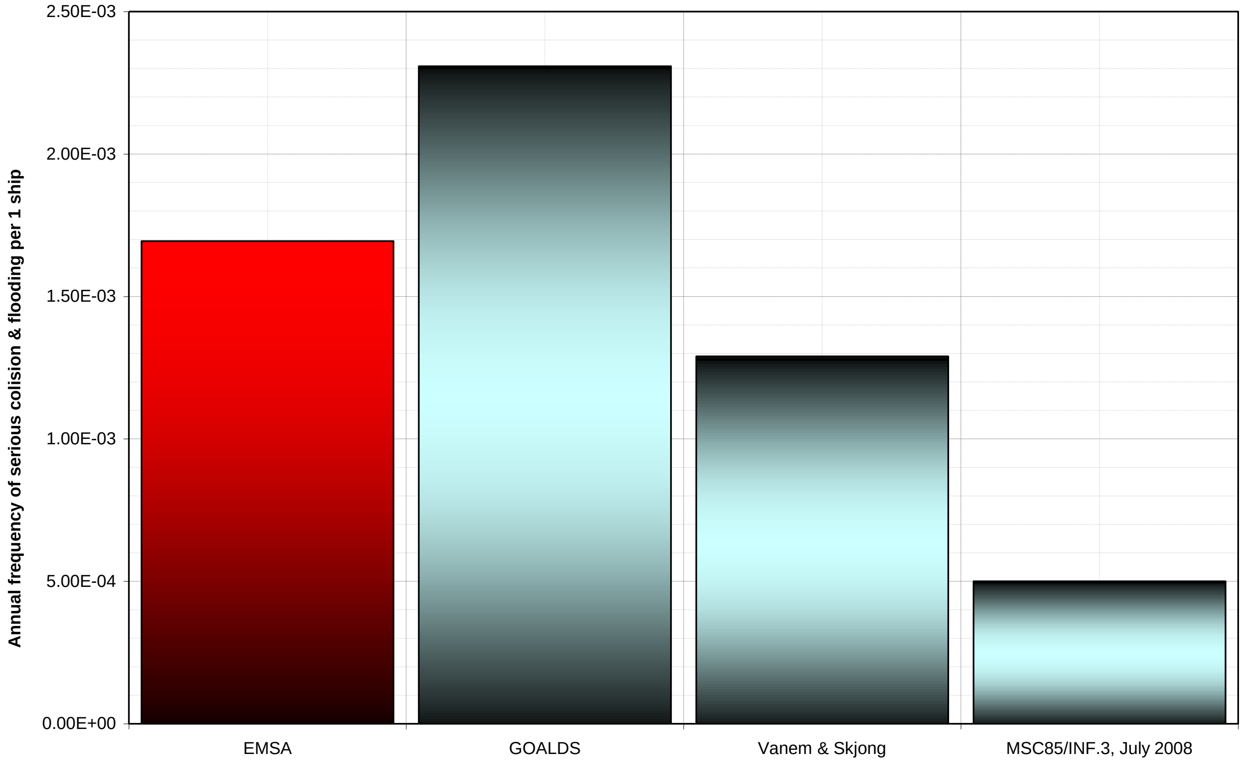


Figure 62 - Frequencies of serious collision and flooding

Figure 62 shows the frequencies of serious collision and flooding according to estimates by different studies. The red-marked frequency is used as the representative order of magnitude for frequency of collision and flooding in this study.

Based on the above, the frequency of serious collision and flooding fr_{coll} is therefore set as shown in (58):

$$fr_{coll} = 0.00169 \frac{1}{ship, year} \quad (58)$$

It is noted that none of the foundering, contact or stranding accidents are considered in this study, which would indicate possible higher frequency of flooding events, although the consequence would also differ.

[13] *Note that various assumptions about probabilities for flooding, struck ship and serious events are hereby made, if no explicit suggestions are made in studies used. Some of figures are preliminary estimates.*

5.1.5.2.4. Risk Calculation Results

A risk assessment can now be performed for the five RoPax ship designs considered in this project, as well as for the whole RoPax fleet.

Figure 63 presents the calculation of risk for the whole fleet of RoPax ships based on (45) and (58), with the assumption that each vessel is designed to SOLAS 2009 standards with A=R and set to be between a wide range of 0.7 and 0.9. Uncertainty in the frequency of occurrence of the event of hull breach and flooding is also demonstrated. Historical data reported in [33] for world-wide fleet is included. Two sets of risk tolerability criteria and the so referred to As Low As Reasonably Practicable (ALARP) "region" are also shown.

Whilst some degree of uncertainty in the risk calculation can be seen in Figure 63, it seems a good impression of current understanding of the observations of real life historical data. Note that the F_N for historical data, included in the graph, also comprises other hazards, such as fire, and hence some higher frequencies for smaller scale fatality events are visible.

The most marked result to be noted in Figure 63 is that of the repeatability level estimated according to model (51) with (45) for events of 1,000 or more fatalities occurring, which indicates that such accidents are expected to occur every ~17.2 years $= \frac{1}{0.00169 \cdot (1-0.8) \cdot (1-0.655) \cdot 499}$ on average among the fleet.

Irrespective of the noted uncertainties with the numeric model used or with the underlying statistics derived from databases, it is possible to relate this frequency to the historical occurrences of accidents.

Such accidents resulting from loss of stability after flooding have occurred numerous times in the past 20 years or so, with this level of frequency. As mentioned earlier, considering the Herald of Free Enterprise in 1987 (capable of carrying 1,400 persons onboard), MV Estonia in 1994 (2,000 persons) and Al-Salam Boccaccio 98 (1,400 persons) in 2006, indicates frequency of 1 per 10 years (T_{mri}= 10). Even without considering other relevant accidents to highlight stability problems, these cases alone are more frequent than the T_{mri}=20 set by model (48). To reiterate, the analytical risk model presented above assumes full load capacity and disregards disorderly abandonment, which is of relevance for comparisons to observed historical data, where the actual number of persons carried during accidents varies. It seems reasonable to consider risk in terms of design criteria for orderly evacuation and ship full capacity. Whilst collisions have not resulted in substantial loss of life in the past, it is recognised that it is a serious hazard (e.g. Stockholm Agreement considers collision damages for stability criterion or model testing), occurring more frequently than foundering (such as e.g. loss of bow visor) and consequences for which are calculable. The three casualties mentioned suffice to corroborate on the degree to which consequences may escalate as a result of rapid stability impairment. Therefore, it is suggested to consider the risk calculated for initiating event of collision according to (45) and (47), as a fair quantitative approximation of the real-life risk to life presented by RoPax ships.

Figure 63 demonstrates the calculated risk range, which exceeds the tolerability criteria (48) of MSC72/16 and therefore do not seem justifiable on the basis of economic importance of the RoPax fleet to society, since it allows catastrophic accidents involving 1,000 fatalities or more in a single event to occur once every 20 years. If the proposition (57) is considered, shown as a "green belt" in Figure 63, then it transpires that the current risk of large accidents is in the intolerable region, even considering the wide range of uncertainties. Therefore, mitigation measures would need to be considered irrespective of costs involved.

Calculations of risk in terms of both $F_N(N)$ and the expected number of fatalities per ship per year E(N), as well as in its 30 year life cycle $E^*(N)$ for the five designs considered in this project are shown in Table 11 and Figure 64.

Note that the risk in terms of expected number of fatalities in a ship's lifetime of 30 years can be derived as (59).

$E^*(N_{\max}) = fr_{coll} \cdot 30 \cdot \left(1 - cdf_{N_{\max}}(N_{\max})\right) \cdot (1 - A) \cdot N_{\max}$	fatalities per ship in 30 years	(59)

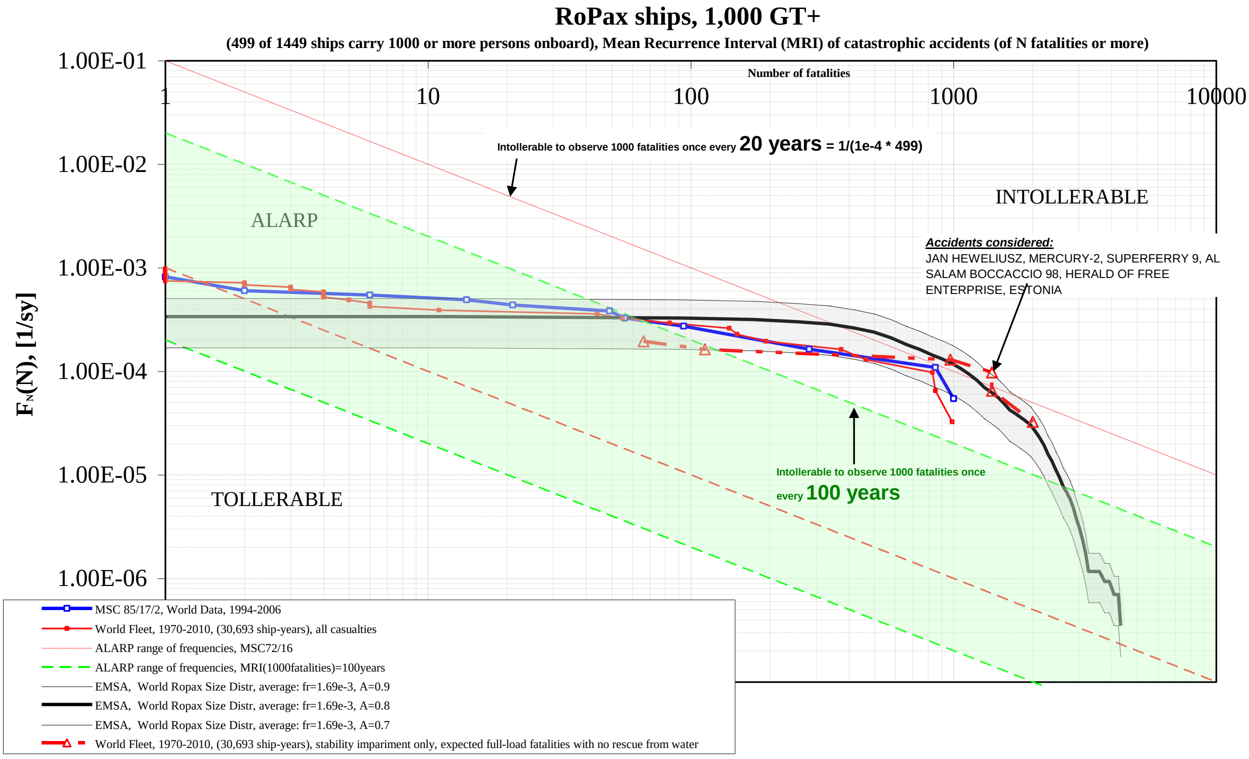


Figure 63 - FN curves for the worldwide fleet of RoPax ships, assuming range of probability A=0.7 to 0.9

Figure 63 shows risk calculations; F_N curves for the worldwide fleet of RoPax ships, assuming a range of probability A=0.7 to 0.9. Two sets of risk tolerability criteria are shown, the MSC72/16 and proposed 100 year principle. Historical data assessment reproduced from [33] are also shown. It is noted that no uncertainty has been given for the historical data assessment of [33].

Table 11 - Risk calculations for the five ships considered and their modifications

fr(breach & flooding) 1.69E-03

	A	1-A	Nmax	cdf(Nmax)	1- cdf(Nmax)	FN(N=Nmax)	E(N) [f/s y]	Fatalities in 30 years, E*(N) [f/s 30y]	Averted fatalities ΔE(N) [f /s y]	Averted fatalities in 30 years ΔE*(N) [f /s 30y]
Ship1	0.833	0.167	500	0.294	0.706	0.000199918	0.100	3.0		
Ship1 Modified	0.964	0.036	500	0.294	0.706	4.31324E-05	0.022	0.6	7.8E-02	**2.4**
Ship2	0.693	0.307	318	0.144	0.856	0.000445048	0.142	4.2		
Ship3	0.793	0.207	2000	0.915	0.085	2.96921E-05	0.059	1.8		
Ship4	0.878	0.122	1645	0.876	0.124	2.55915E-05	0.042	1.3		
Ship4 Modified	0.988	0.012	1645	0.876	0.124	2.49402E-06	0.004	0.1	3.8E-02	**1.1**
Ship5	0.803	0.197	2100	0.929	0.071	2.37108E-05	0.050	1.5		
							average	1.8		

A summary of risk calculations for the five ships considered and their modifications is presented in Table 11. The probability A shown in this table is based on “Alternative 3” of Table 14 (except of Ship 5 where Alternative 1 was used).

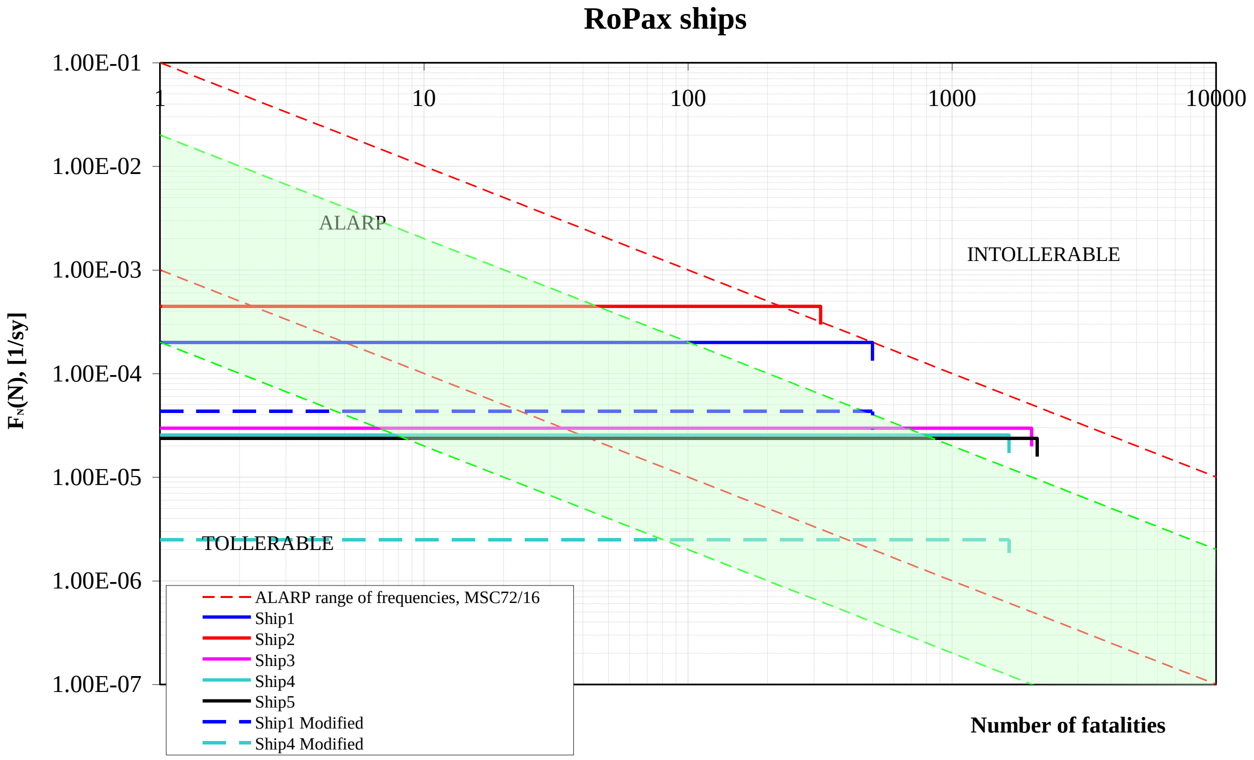


Figure 64 - FN curves for the five ship designs and their modifications

Figure 64 shows risk calculations; F_N curves for the five ship designs and their modifications. Two sets of risk tolerability criteria are shown; the MSC72/16 and the proposed 100 year principle.

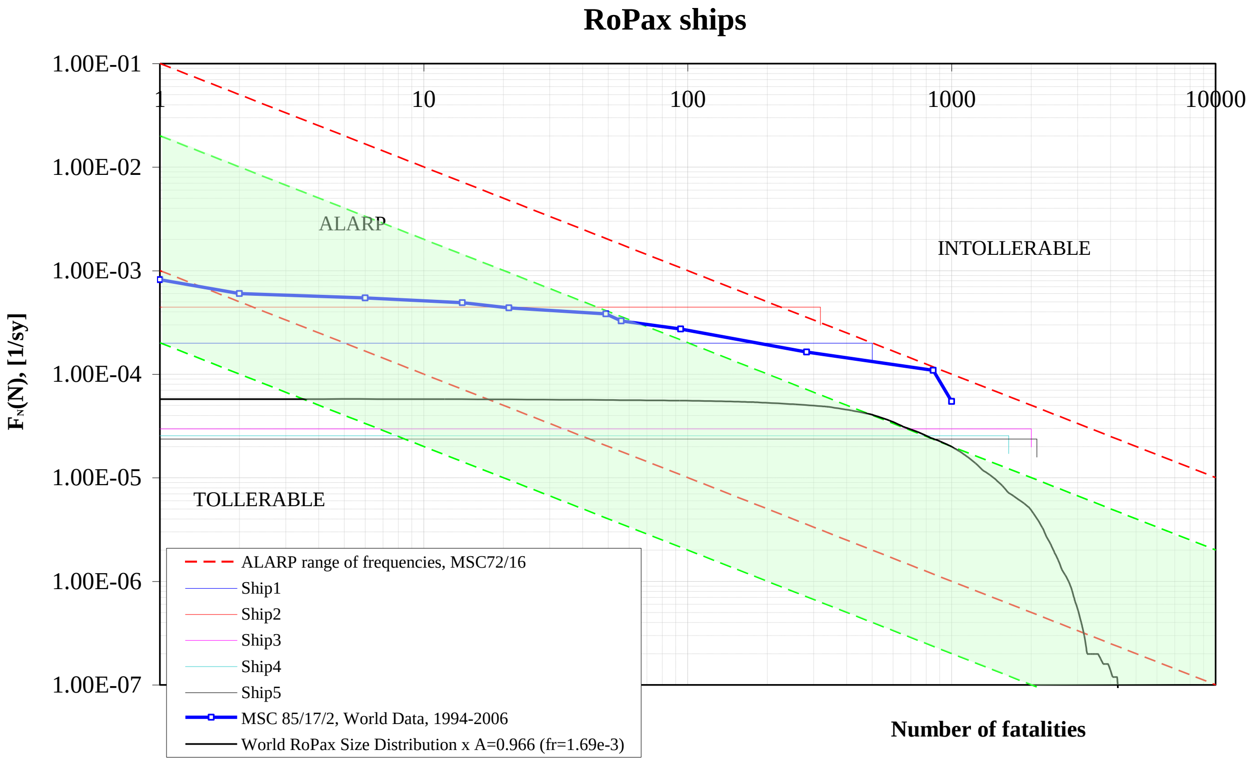


Figure 65 - FN curves for the worldwide fleet of RoPax ships for A=0.98

Figure 65 shows risk calculations; F_N curves for the worldwide fleet of RoPax ships, assuming that each of them was designed for A=0.98. Two sets of risk tolerability criteria are shown; the MSC72/16 and the proposed 100-year principle.

Results shown in Figure 64 reflect the, currently expected in the maritime industry, level of risk, since all of them comply with current standards. The risk for each of the ships is on the verge of complying with the existing tolerability criteria MSC72/16, but it is not compliant with the proposed standard (57) to ensure large accidents do not occur more often than once every 100 years on average.

The modified version of Ship 4 demonstrates that risk can be lowered to the ALARP level as set by the new criterion (57), see Figure 64.

If criteria of MSC72.16 were to be accepted, then, as a minimum, each of the vessels would need to be shown to comply with the ALARP principle, that is, cost-effectiveness criteria would need to be considered, as discussed below.

Note again that if a target for aversion of catastrophic accidents was set as outlined with criterion (57), then neither of the ship designs would be regarded as tolerable and measures of mitigation would need to be implemented regardless of costs.

In either of the cases, it seems quite compelling that further attention needs to be spent on risk mitigation measures and cost-effectiveness is considered for this purpose in the next chapter.

5.1.5.3. Risk Control Options

The risk control design solutions to address the problem of stability relate to any changes to the water-tightness architecture, that is distribution of buoyancy, weight distribution and openings on the ship.

All such changes can be consistently accounted for through the methodology of MSC216. Therefore, the primary risk control option that ought to be considered is the probability R as the key design risk mitigation measure. Risk tolerability criterion (57) can be used as the principle for setting R at a level appropriate for mitigation of what transpires as intolerable risks of loss of life.

Deriving from risk model (45), the relation (60) can be shown as the tool for setting the minimum level of index R needed for attaining compliance with (57).

$fr_{coll} \cdot (1 - R(N_{\max})) \cdot (1 - cdf_{N_{\max}}(N_{\max})) \leq \frac{1}{N_{\max} \cdot 50}$, per ship per year $\frac{1}{s \cdot y}$	(60)

Criterion (60) states that the frequency of N fatalities or more $F_N(N_{\max}) = fr_{coll} \cdot (1 - R(N_{\max})) \cdot (1 - cdf_{N_{\max}}(N_{\max}))$ must never exceed the level set by (57), which aims to ensure that catastrophic accidents involving in excess of 1,000 persons do not repeat more often than once per 100 years on average. The frequency will be affected by the level of survivability, set by probability R, a ship is designed for, and therefore this level may now be derived to achieve target (60), assuming other elements of the risk affecting fr_{coll} remain unchanged. Note that the principle of 100 years is not assured by (60) for ships carrying less than 1,000 persons.

The index R for a given ship carrying maximum $N_{\max}$ number of persons could be set as follows:

$R(N_{\max}) \geq 1 - \frac{1}{N_{\max} \cdot 50 \cdot fr_{coll} \cdot (1 - cdf_{N_{\max}}(N_{\max}))}$	(61)

It should be noted that, whilst it can be regarded as rational that larger ships that carry, say, 3,000 persons, are less likely to have accidents in comparison to the rest of the fleet (since there are fewer of them among the fleet), it does not seem pragmatic to allow such larger ships to be of a lesser standard than smaller ships. The exact ship capacity where probability R would reach its maximum would be approximately N_{max} = 704, see Figure 51. Therefore, it is proposed that requirement (61) takes the following form:

$R(N_{\max}) \geq \begin{cases} 1 - \frac{1}{N_{\max} \cdot 50 \cdot fr_{coll} \cdot (1 - cdf_{N_{\max}}(N_{\max}))} & for \quad N_{\max} \leq 704 \\ 1 - \frac{1}{704 \cdot 50 \cdot fr_{coll} \cdot (1 - cdf_{N_{\max}}(704))} & for \quad N_{\max} > 704 \end{cases}$	(62)

It is proposed that $cdf_{N_{\max}}(N)$ is approximated by formula (46), which allows (62) to be approximated as follows:

$$R(N_{max}) \geq \begin{cases} 0.875 & for \quad N_{max} < 100 \\ 1 - \dfrac{1}{0.0845 \cdot N_{max} - 36.67 \cdot 10^{-6} \cdot N_{max}^{2}} & for \quad 100 \leq N_{max} < 375 \\ 1 - \dfrac{1}{0.0845 \cdot N_{max} \cdot \exp\left(\dfrac{-(N_{max} - 250)}{704}\right)} & for \quad 375 \leq N_{max} \leq 704 \\ 0.968 & for \quad N_{max} > 704 \end{cases} \qquad (63)$$

This criterion for index R is shown in Figure 65.

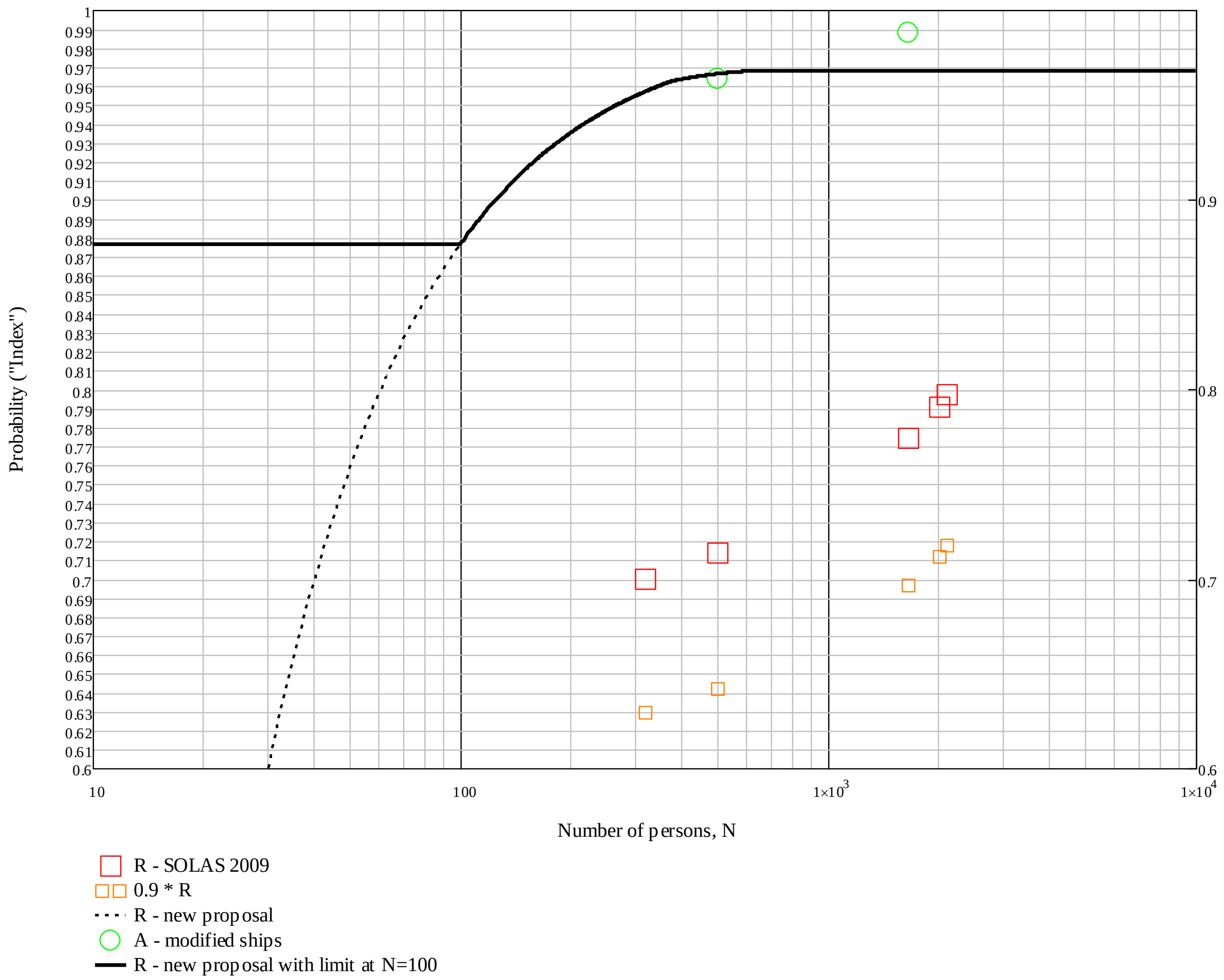


Figure 66 - Proposed index R for ships carrying Nmax persons onboard

Figure 66 shows the proposed index R for ships carrying N_{max} persons onboard. It is proposed that A≥R for any draught conditions. The values of R according to SOLAS 2009 for the ships considered in this project are also shown.

It is suggested that some limit on the level of stability on smaller ships, such as, for instance, ships carrying less than 100 persons, is retained equivalent to the minimum of R(100)=0.876. There is no specific basis in support of this proposal other than engineering judgement on what seems to be a reasonable degree of minimum stability on any ship relative to the level of stability for the rest of the fleet.

Some examples of possible solutions addressing criterion of enhanced R are shown in Figure 19 and Figure 20 for ships 1 and 4, respectively.

Other hypothetical design adjustments to given level R are considered, together with generic costs estimates reported in MSC85/16 for cost-effectiveness assessment discussed below.

The degree to which risk can be mitigated by means of design measures, such as those proposed for Ship 1 and Ship 4, is shown in the Table 14, whereas for all ships assumed upgraded to R given by (63) are shown in Table 12. All summaries are shown in Figure 67 and Figure 68.

Table 12 - Risk calculations for the five ships considered re-designed to the index R given by (63)

	A	1-A	Nmax	cdf(Nmax)	1- cdf(Nmax)	F_N(N=Nmax)	E(N) [f/s y]	Fatalities in 30 years, E*(N) [f/s 30y]	Averted fatalities ΔE(N) [f /s y]	Averted fatalities in 30 years ΔE*(N) [f /s 30y]
Ship1	0.966	0.034	500	0.294	0.706	4.04E-05	0.020	0.6	8.0E-02	**2.4**
Ship2	0.959	0.041	318	0.144	0.856	5.94434E-05	0.019	0.6	1.2E-01	**3.7**
Ship3	0.968	0.032	2000	0.915	0.085	4.58565E-06	0.009	0.3	5.0E-02	**1.5**
Ship4	0.968	0.032	1645	0.876	0.124	6.72355E-06	0.011	0.3	3.1E-02	**0.9**
Ship5	0.968	0.032	2100	0.929	0.071	3.84895E-06	0.008	0.2	4.2E-02	**1.3**
							average	0.4	0.07	**2.0**

All of the above results indicate that the 30 years life-cycle risk for each individual ship is reduced by approximately 1–3 fatalities. This compares to an approximate maximum of 4 fatalities assessed in [34] (see Figure 67). Although the assessment [34] considers other hazards, such as grounding, foundering and flooding as additional to key hazard used here, this study does not consider seasonal variation of actual persons onboard, considered in [34], with both sets of these assumptions expected to cancel each other's uncertainty effect, and hence this is not the explanation for this discrepancy. The key reason for what appears to be discrepancy is the size of ships used as a basis for representative risk assessment.

As can be seen from Figure 68, ships considered in this project are either small or very large, neither representative of the majority of the worldwide RoPax fleet, with the mean size being 940 persons, the latter of which was the approximate base size (1,000 persons) used in [34]. As is assessed in Figure 68, the risk reduction for such ship size is approximately 3 fatalities per ship in 30 years if criterion (63) is used as a basis. Therefore, it seems that the estimated risk in this study is fairly in line with earlier estimates, as reported in [33] and [34], and thus either Figure 67 and Figure 68 can be used as guidance on how much risk can be reduced with increased stability of ships. For example, for Ship 1 carrying 500 persons and designed to A=0.833, the risk can be reduced by 2.4 fatalities in 30 years, if the vessel is upgraded to A=0.966.

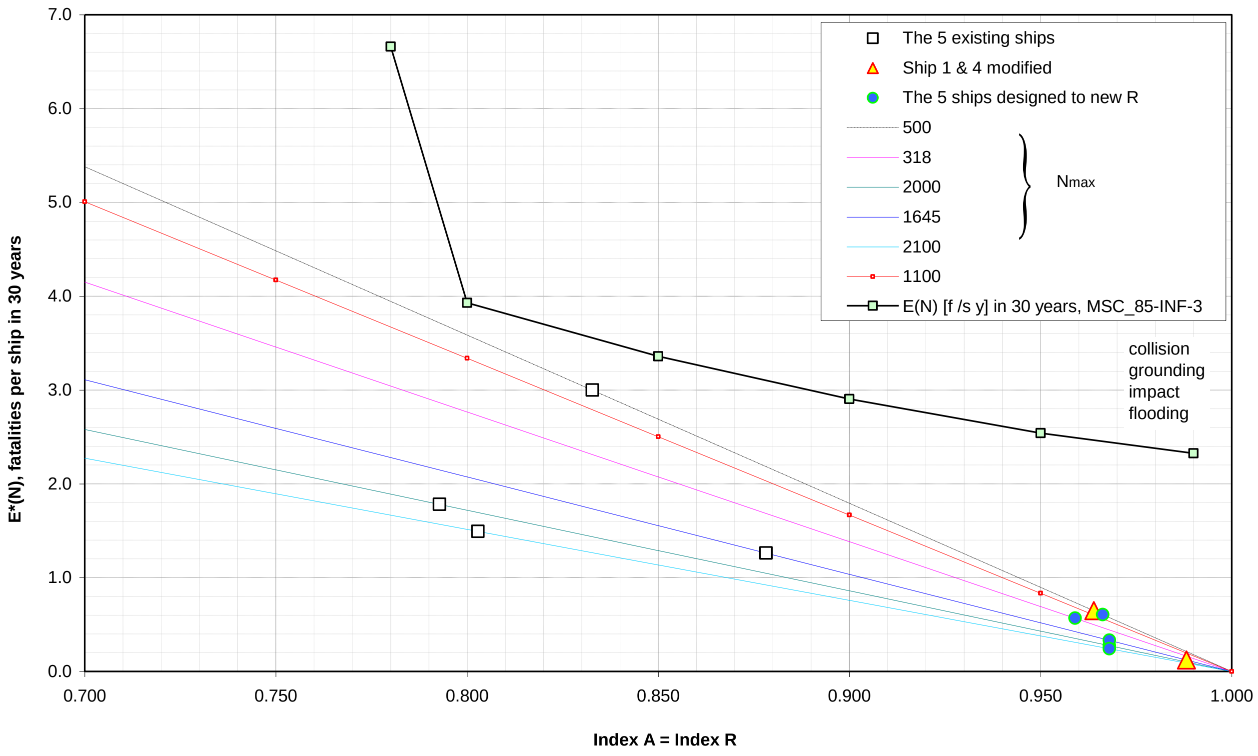


Figure 67 - Expected fatalities per ship in 30 years for the different hypothetical range of A=R requirements

Figure 67 shows the expected fatalities per ship in 30 years for the different hypothetical range of A=R requirements to which each of the ships shown is designed. The five ships considered in this project are also shown

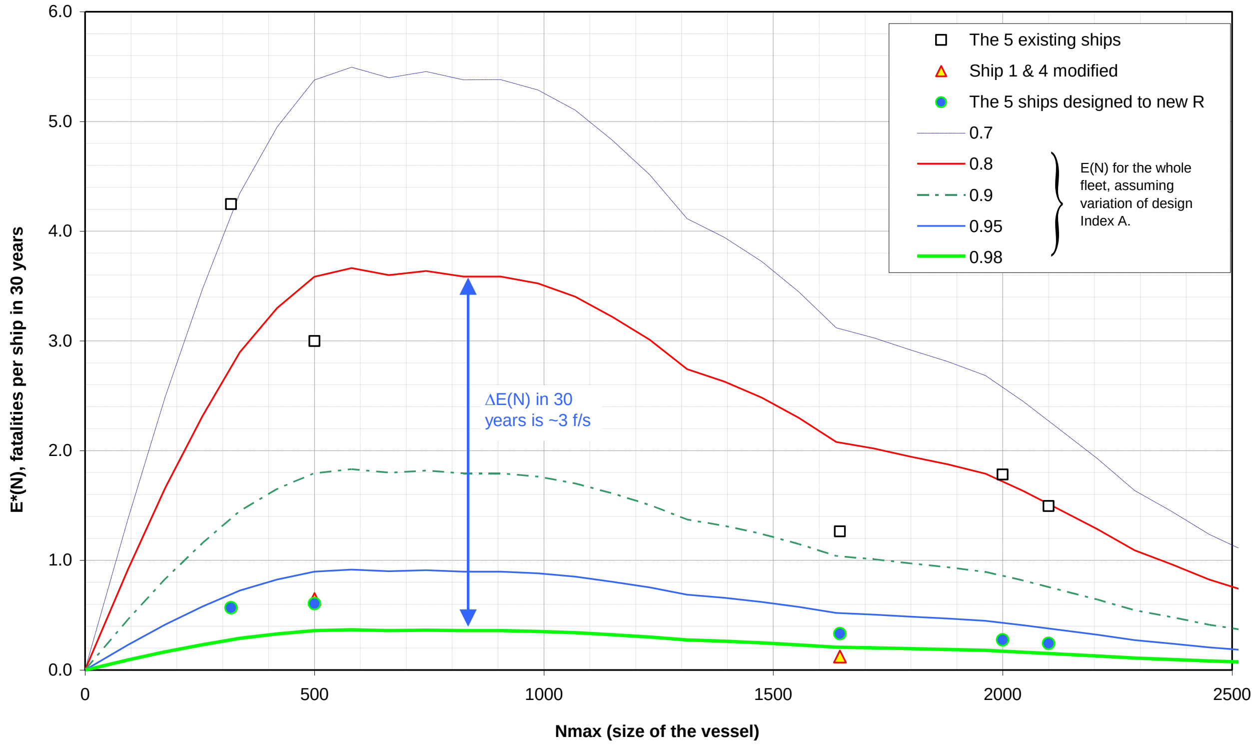


Figure 68 - Expected fatalities per ship in 30 years for different ship sizes and the hypothetical range of A=R requirements

Figure 68 shows the expected fatalities per ship in 30 years for the different ship sizes and assuming the hypothetical range of A=R requirements to which each of the ships shown is designed. The five ships considered in this project are also shown.

The key point to observe is that the risk expressed in terms of expected numbers of fatalities per ship results from "catastrophic" accidents, claiming the majority of lives onboard. Therefore, to state that two fatalities can be averted per ship over 30 years, implies that among the fleet of say 499 larger ships (capacity 1,000 persons or more), one accident involving 988 (= 2 x 499) persons would be averted. Note that this does not imply that such an accident could not take place, but rather that one less accident of this magnitude would occur on average in time.

In other words, what has been observed in the past, approximately 20 years, would not be expected to take place for another 100 years (on average), should each ship among the fleet be upgraded to criterion (63). Therefore, once again, the traditional cost-effectiveness criteria, as shown below, should be viewed in the context as a side argument rather than a primary reason for recommendation.

5.1.5.4. Cost Benefit Analyses

A cost-benefit analysis in the context of risk assessment is performed when a solution is shown to pose risk within a tolerable range, that is, the risk is within either range (48), currently considered adequate, or within the range proposed in this project, that is (57), if stricter expectations are set.

The basis for the recommendations on the cost effectiveness of a solution is the following:

A Risk Control Option (RCO) is considered cost-effective if the Gross Cost of Averting a Fatality (GCAF), equation (64), is less than US$3 million. This is the value suggested in MSC 72/16, and described in the consolidated text of the FSA Guidelines (MSC 83/INF.2).

$$GCAF = \frac{\Delta C}{\Delta R} \qquad (64)$$

Where:

ΔC marginal cost NPV per ship associated with the introduction of an RCO over its lifetime (includes the initial capital costs and annual associated costs).

ΔR risk reduction per ship, in terms of the expected number of fatalities averted over the lifetime of the vessel $E^*(N)$ [f / s 30years] associated with the introduction of an RCO.

The marginal costs were assessed in [34] to be in the range of between $3,075,531 and $5,850,952, to increase probability A from 0.78 to 0.95, and therefore the cost has been extrapolated linearly in this study to be between $180,913 and $344,173 per each 1% increase in the value of probability A. As a conservative approach, the upper estimate of marginal costs of $500,000 per each 1% in increased value to probability A has been assumed, as some generic expected higher costs were suggested in [34] as possible.

Results of the cost-effectiveness analysis are presented in Table 13 and Figure 69. The key observation to be noted is that the cost of averting a fatality by adopting standard (63) is below $7 million for specific ship sizes considered in this study, which are peripheral relative to the RoPax fleet. When considering a typical median ship carrying 1,000 persons onboard, it would be expected that setting stability standard (63) for the RoPax fleet would be even more cost effective, which concurs with conclusions derived in MSC85/16.

Table 13 - Summary of cost-effectiveness calculations

	ΔA	ΔE(N) [f/s 30y]	GrossCAF ($181K per 1% A)	GrossCAF ($500K per 1% A)
Ship1	0.133	2.4	$1,008,888	$2,788,315
Ship2	0.266	3.7	$1,307,629	$3,613,961
Ship3	0.175	1.5	$2,104,112	$5,815,241
Ship4	0.090	0.9	$1,744,760	$4,822,080
Ship5	0.165	1.3	$2,387,471	$6,598,373

	ΔA	ΔE*(N) [f/s 30y]	NPV ($181K per 1% A)	NPV ($500K per 1% A)
Ship1	0.133	2.4	$2,414,661.06	$6,673,520
Ship2	0.266	3.7	$4,810,333.34	$13,294,561
Ship3	0.175	1.5	$3,169,606.07	$8,760,000
Ship4	0.090	0.9	$1,624,604.02	$4,490,000
Ship5	0.165	1.3	$2,987,426.08	$8,256,500

In Table 13, the ΔA is based on a difference between current designs and requirement (63).

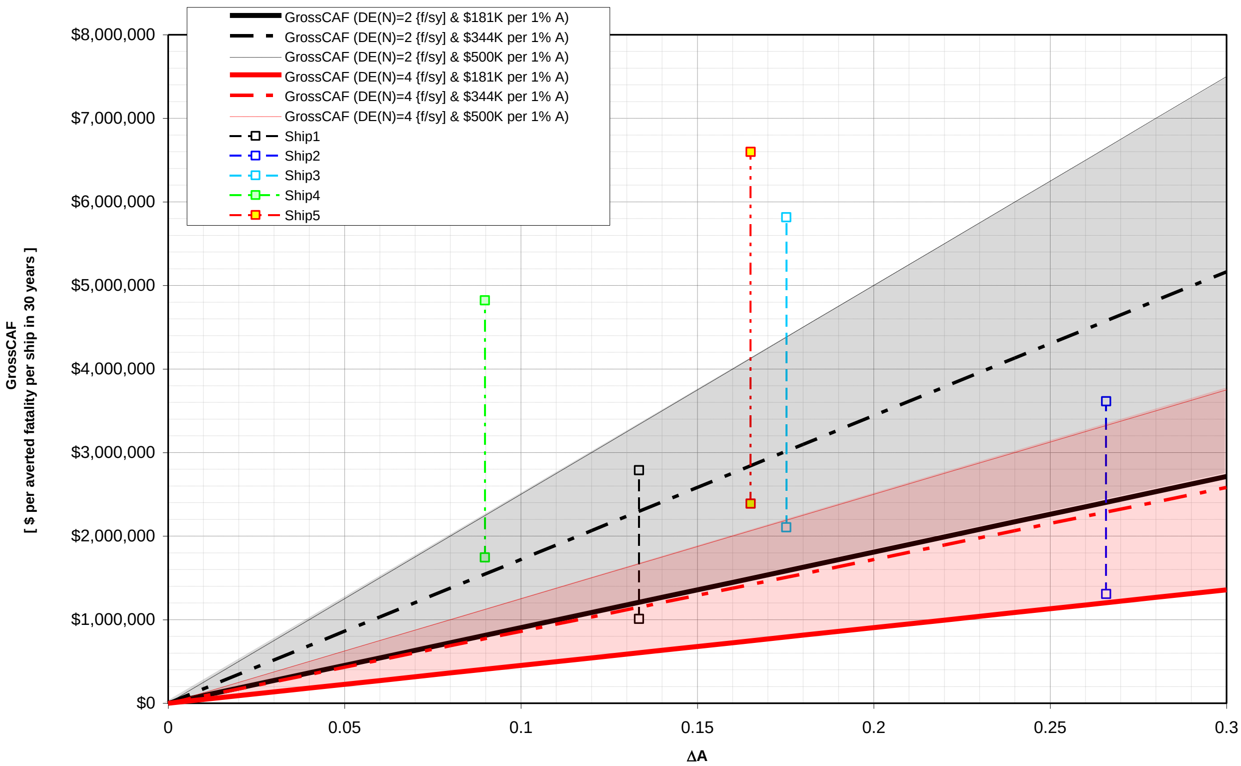


Figure 69 - GrossCAF estimates

The study of [33] demonstrated that the following RCOs provided considerable risk reduction in a cost-effective manner:

- *"All measures to improve the damage stability for RoPax vessels to levels consistent with current cost-effectiveness criteria and commensurate with the specialized operation of these ships. For the range of ships analysed, it was found that CAF values associated with the introduction of measures to improve survivability in flooded condition would be well below the current cost-effectiveness criterion (US$ 3M), even for pessimistic assumptions of marginal costs."*

As can be seen from Figure 69, it seems that each of the ships could be modified at a reasonable cost to drastically improve their stability and reduce the risk to life substantially.

5.1.5.5. Recommendations for Decision Making

If all of the RoPax ships were to be designed or upgraded to standard (63), then accidents involving 1,000 persons would not occur more often than once every 100 years on average, given that the frequency of hull breach and flooding remains unchanged.

It is therefore recommended that standard (63) is considered as the goal of future stability criteria of SOLAS.

5.2. Sensitivity Studies

5.2.1. Results Summary

This chapter presents the more detailed results that were obtained from testing the sensitivity of the ship stability parameters to the design solutions and the governing standards, and which are summarised in §5.2.2 and §5.2.3 and Annex 2.

The physical model tests are summarised in §0 and Annex 3, whilst numerical simulations are summarised in §1.1.1.

The following points of key relevance were derived from this study:

Observation 1 – Stockholm Agreement vs. SOLAS 2009

- The Stockholm Agreement proved to contain more stringent requirements than the current SOLAS 2009 set of regulations for all of the eight ship configurations considered in this study (see Figure 70 to Figure 76 for GM limiting curves.

  In each of these cases, the minimum GM required was the highest for compliance with the Stockholm Agreement. The resultant value of probability A can be seen in Table 14 (column "Alternative 4").

Observation 2 – Stockholm Agreement by s=1

- The possible requirements for the new version of probability s=1[14] for all flooding cases stipulated by the Stockholm Agreement can ascertain survivability at Hs=4m for prolonged time periods (~10 hours) for these flooding cases. The resultant value of probability A can be seen in Table 14 (column "Alternative 5"). This requirement (s=1, see label containing " … Stockholm Agreement s=1" in Figure 70 to Figure 76) is more strict than the Stockholm Agreement (by calculation) for Ship 4 and less strict for Ship 1 modified, Ship 3 modified and Ship 5, whilst it is prohibitive for Ship 1 and Ship 2.

- On one hand, given the newly proposed probability s accounts for observed uncertainties inherent to model testing, it can be concluded that provisions of the Stockholm Agreement are more restrictive than intended, or indeed the Stockholm Agreement is unrealistically stringent.

- On the other hand, for example case of Ship 4, Figure 74, shows that requirements by the Stockholm Agreement are not strict enough.

- Therefore, it is hereby concluded that the standard of the Stockholm Agreement is not consistent.

Observation 3 – Watertight architecture

- It can be seen in Table 14 that for Ship 4, it would be required that the GM attains values of some 20m before meeting the Stockholm Agreement by ensuring that s=1 for all requisite cases (see column "Alternative 5"). Such a high GM is impractical, but an

[14] *As given by equation (17) with (16) and indicated in column "Alternative 3" in Table 14.*

interesting example where one can see that the probability of survival still only reaches the level of A_{DS}=0.97708, which can be compared with the probability of 0.98368 for Ship 4 modified and a GM of 3.75m, (see column "Alternative 3"). This serves as a demonstration that ship watertight architecture remains the key to ensuring high survivability ships, and that probability A is a better basis for judgement of the overall stability level built into the design.

Observation 4 – Stockholm Agreement by updated R

- The proposed standard (63) would guarantee that the level of survivability A intended by the Stockholm Agreement is built in on ships for most of the reasonable cases (unrealistic GM dismissed) shown in Figure 77 and Table 14 (see Table 12 for values of the new probability A=R).

Observation 5 – General impact of survivability improvements

- The impact of an increased standard of probability R is "shifting" of the unsurvivable flooding cases towards larger extents, (see Table 15 and Figure 90 to Figure 104, as well as Annex 2 for more details). The overall variation in proportion of survivability is visually presented in Figure 78 to Figure 89. For instance, considering Ship 4 and Ship 4 modified, and based on the column "Alternative 3" in Table 14 for the modified standard of probability s, as given by equation (17) with (16), the probability for non-survivability of 2-zone flooding decreases from 4.721% down to 0.114% (see Figure 100 and Figure 103, respectively). The change in overall percentage of non-survival flooding cases can be shown in Figure 86 and Figure 89, respectively.

Observation 6 – Sensitivity to formulations for probability s

- The impact of the various options for modification to probability s is best summarised in Table 14, Figure 77, Figure 78 to Figure 104 and Annex 2. There are four "Alternatives" considered in the first four columns of Table 14, representing the four methods for amending probability s. The impact of the change to GZ_{max}, Range, K and "no-moments" format of formulae to assign probability s, ranges from -5.8% to approximately +3.8% in the total probability A between different ship configurations. That is, the net impact can be a reduction in the assessed probability A or a net gain in probability A.

Observation 7 – Numerical simulations

- The numerical simulations presented in §1.1.1 and summarised in Table 14 in column "Alternative 6" seem to relate closely with the results of survivability observed during model experiments for the few cases selected or result in slightly lower survivability. The theoretical projection based on SOLAS 2009 seems to be somewhat more conservative, which is perhaps the reason for the overall survivability being mostly higher when assessed by means of the numerical simulations. The suspected reason for higher survivability assessments, however, perhaps derives from use of the actual distribution for sea state during collisions, i.e. equation (4) rather than (17). Overall, on one hand, this comparison tends to ascertain that estimates based on current form of formulation s are conservative, while, on the other hand, they demonstrate that a ship may capsize within less than 30 minutes typically in 10% to 30% of feasible cases.

5.2.2. GM Limiting Curves

This chapter presents a set of traditionally used GM limiting curves for the five ship designs and some of their modifications for a range of sets of criteria, as well as variants of updated criteria. Linear interpolation for GM between three loading conditions considered were used on the understanding that the actual exact limiting GM for draughts other than the three considered would need to be separately established.

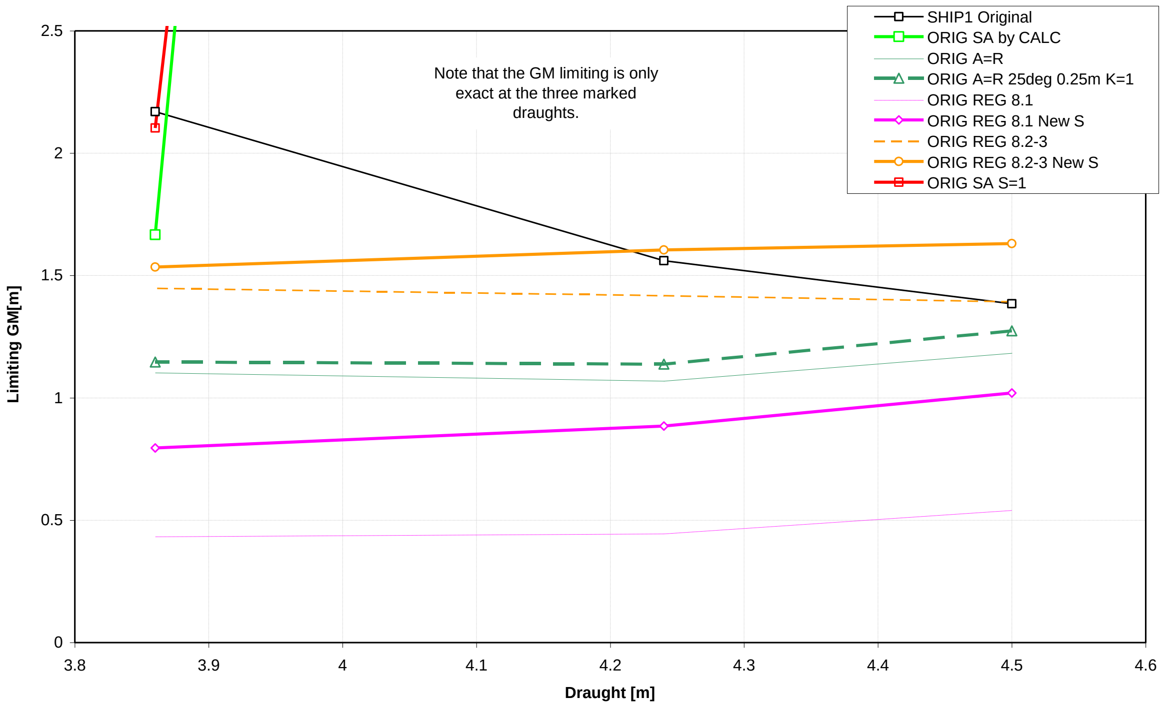


Figure 70 - Limiting GM values, SHIP 1

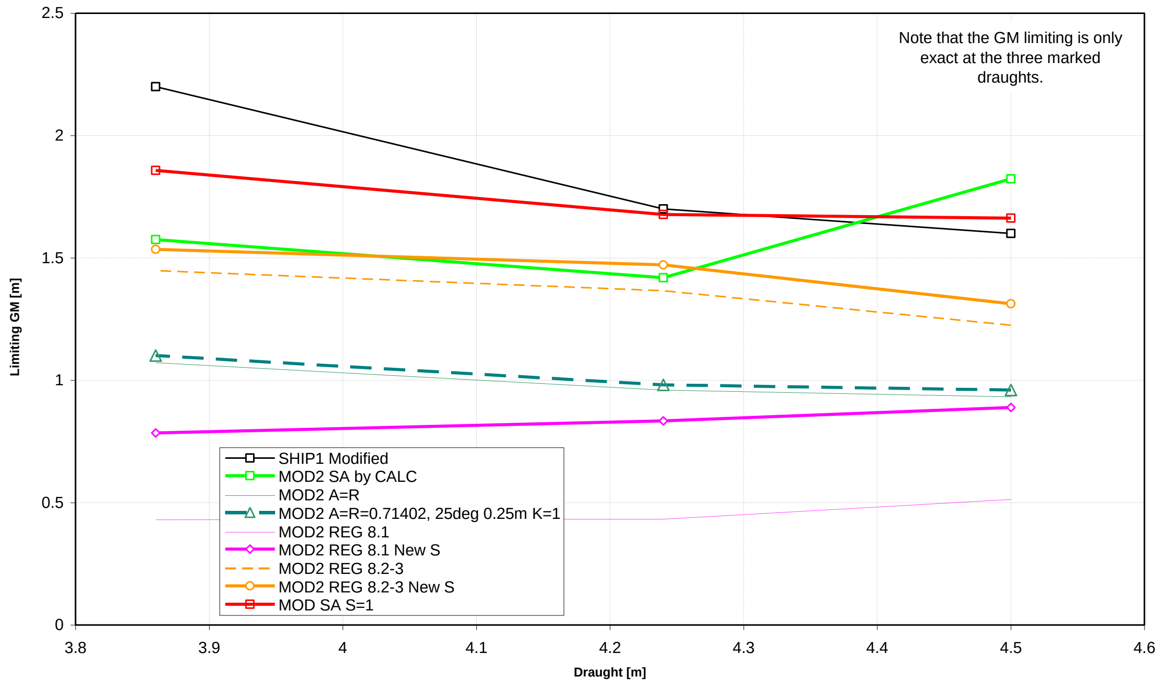


Figure 71 - Limiting GM values, SHIP 1 modified

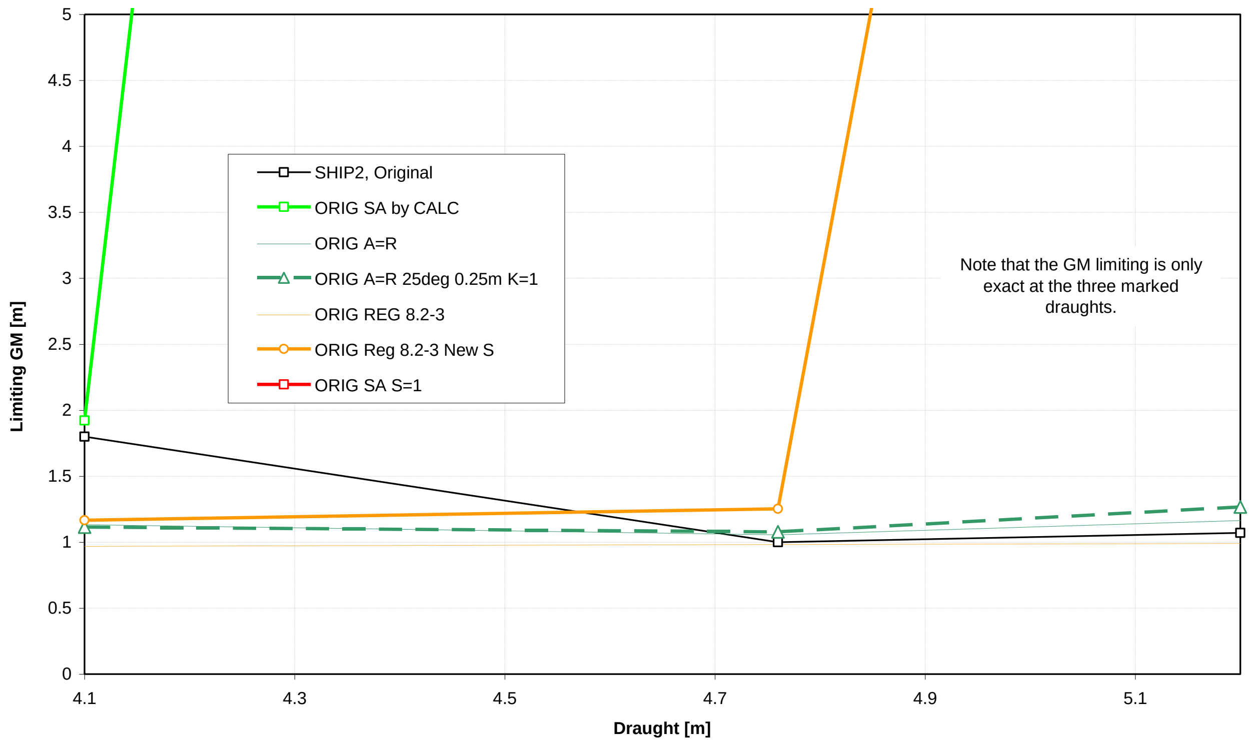


Figure 72 - Limiting GM values, SHIP 2

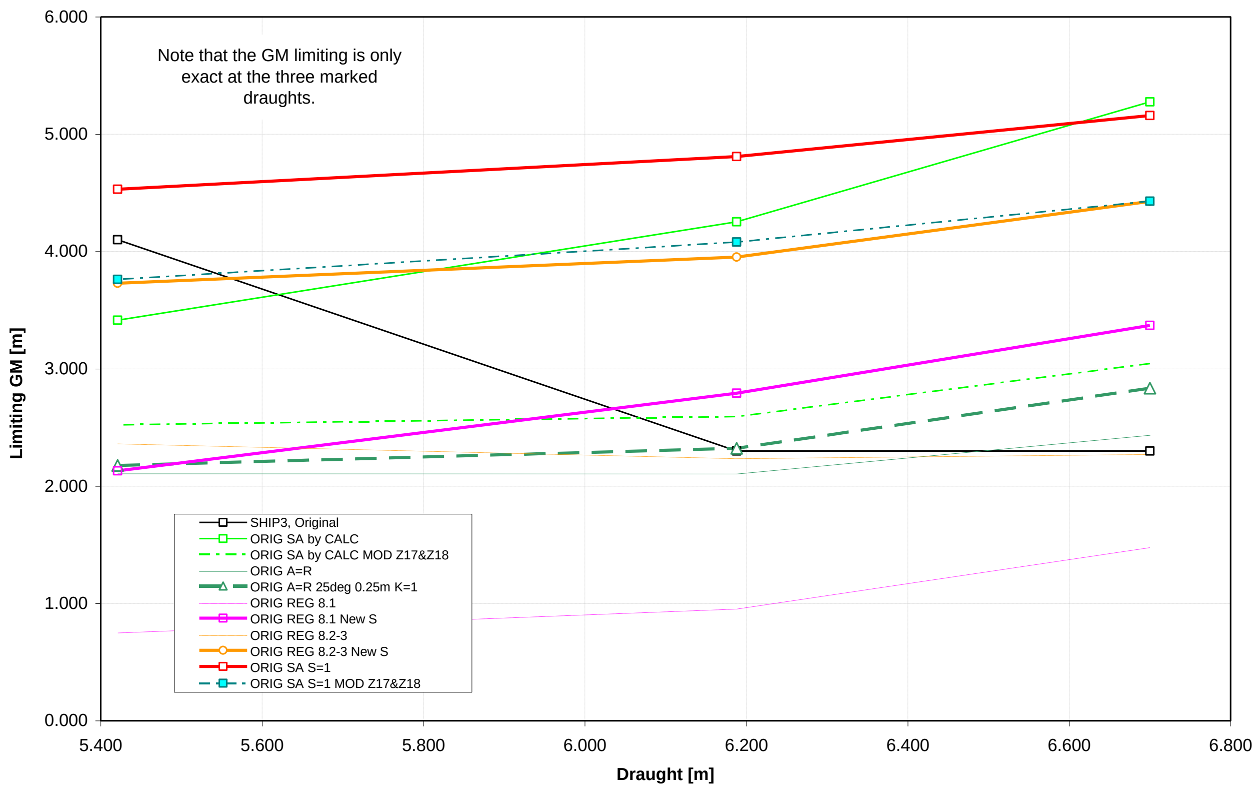


Figure 73 - Limiting GM values, SHIP 3 and SHIP 3 with a small modification to Z17 – Z18

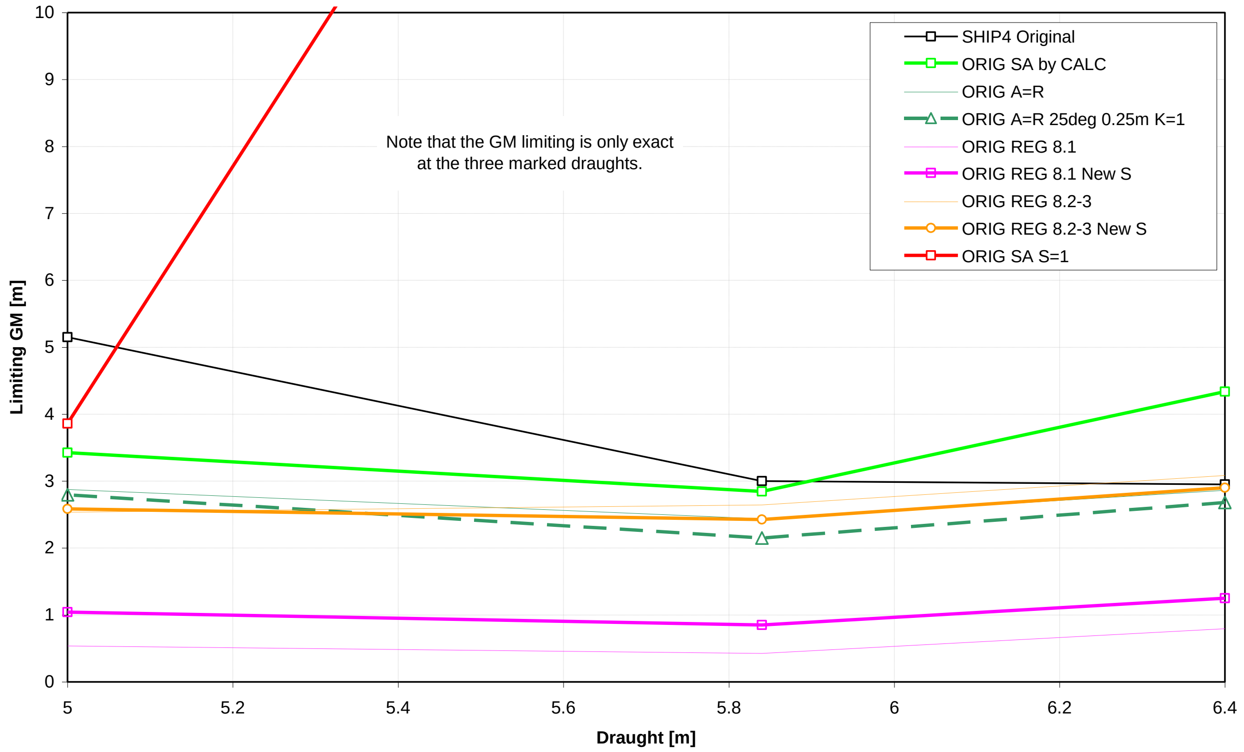


Figure 74 - Limiting GM values, SHIP 4

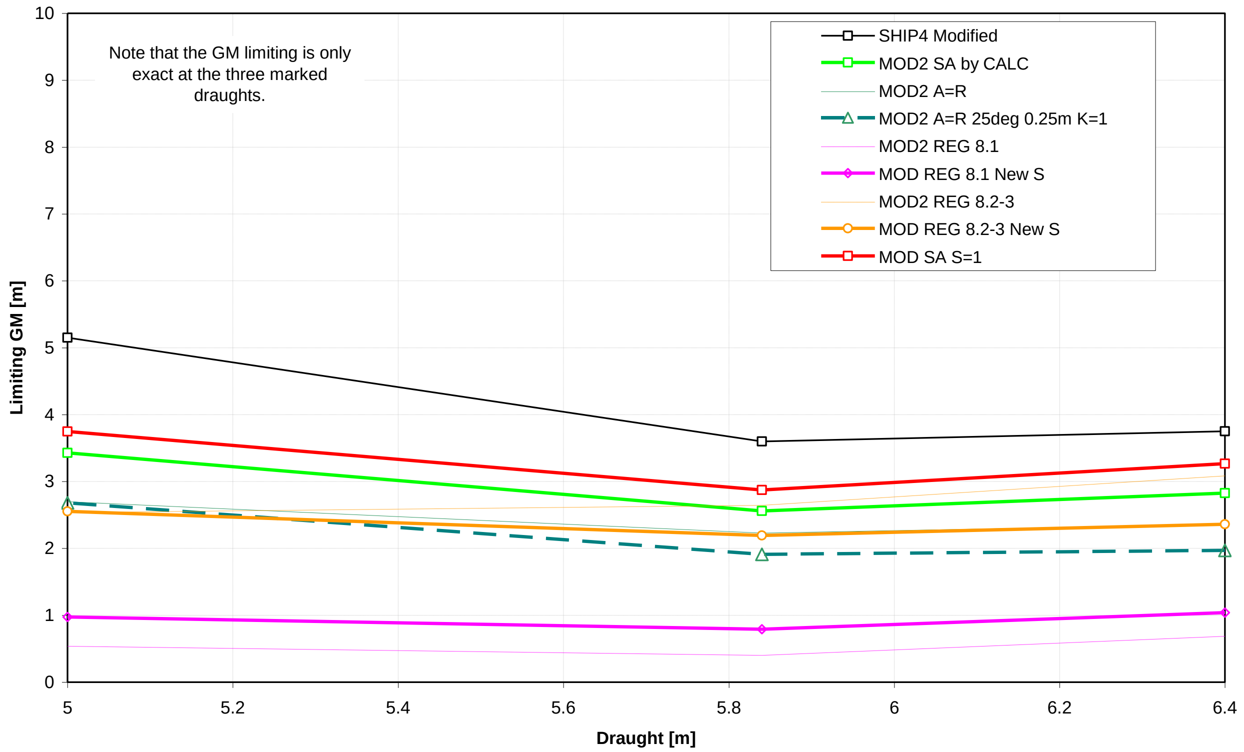


Figure 75 - Limiting GM values, SHIP 4 modified

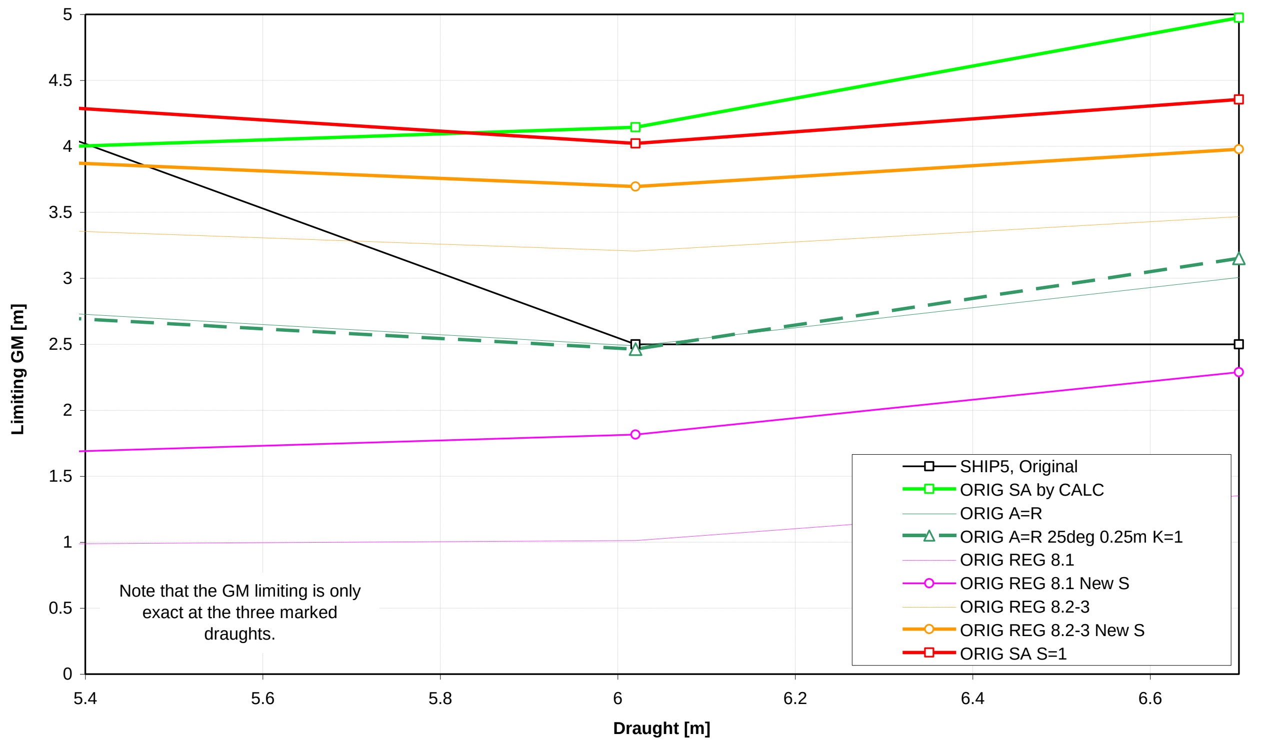


Figure 76 - Limiting GM values, SHIP 5

5.2.3. Distributions of Probability

This chapter provides a summary of statistics for the stability parameters underlying the results given in Table 14.

The following seven sets of analyses were performed for the five ship designs:

1. Alternative 1 – stability calculations based on SOLAS 2009 with the formulation of factor s for the final stages of flooding according to MSC216 (82) Reg. 7-2.3.

2. Alternative 2 - stability calculations based on SOLAS 2009 with the formulation of factor s for the final stages of flooding changed by setting GZ_{max}=0.25 and Range=25.

3. Alternative 3 – as Alternative 2, with additional removal of factor K.

4. Alternative 3b – as Alternative 3, considering only final stages of flooding and no moments due to passenger crowding and LSA launching, to demonstrate the degree of contributions of these events to the probability A.

5. Alternative 4 – stability calculations based on the assumptions of Alternative 3 and performed for studies of sensitivity of index A to variations in the metacentric height (GM) raised to meet the Stockholm Agreement (by calculation).

6. Alternative 5 - stability calculations based on the assumptions of Alternative 3 and performed for studies of sensitivity of index A to variations in the metacentric height (GM) raised to meet requirement that each of the flooding cases relevant to the Stockholm Agreement attains s=1.

7. Alternative 6 – assessment of survivability by means of numerical simulations.

Table 14 - Summary of assessed survivability in terms of index A

	Alternative1	Alternative2	Alternative3	Alternative3b	Alternative4	Alternative5	Alternative6
Gzmax	0.12	0.25	0.25	0.25	as Alternative 3 for adjusted GM to meet SA	as Alternative 3 for adjusted GM to ascertain s=1 for all SA flooding cases	Direct numerical simulation based on MC sampling
Range	16	25	25	25			
K	variable	variable	1	1			
				s_final only			

	A	A	A		A	A
Ship1	0.85697	0.83277	0.83277		x	x
Ship1 Modified	0.96230	0.95912	0.96392		0.93793	0.96124
Ship2	0.70231	0.67769	0.69312		x	x
Ship3	0.83394	0.78888	0.79280		0.94421	0.95669
Ship3 Mod Z17/Z18	0.83390	0.78884	0.79176		0.83022	0.93432
Ship4	0.85977	0.84901	0.87820		0.90343	0.97835
Ship4 Modified	0.95890	0.95766	0.98813		0.93978	0.96666
Ship5	0.80287				0.9316	0.92383

	A_{DS}	A_{DS}	A_{DS}	A_{DS} - no S_{mom}	Stockholm by calculation	Stockholm s=1	Simulation
Ship1	0.79739	0.75941	0.75941	0.79275	x	x	0.880
Ship1 Modified	0.94992	0.94589	0.95249	0.96012	0.96894	0.95762	0.934
Ship2	0.63430	0.59505	0.61342		x	x	0.778
Ship3	0.76982	0.70934	0.71175		0.94571	0.94186	0.848
Ship3 Mod Z17/Z18	0.76978	0.70929	0.71170		0.814	0.91919	
Ship4	0.78711	0.77148	0.80624	0.81983	0.92363	0.97708	0.882
Ship4 Modified	0.94912	0.94663	0.98328	0.98368	0.94572	0.97422	0.974
Ship5	0.73467				0.93111	0.91089	0.898

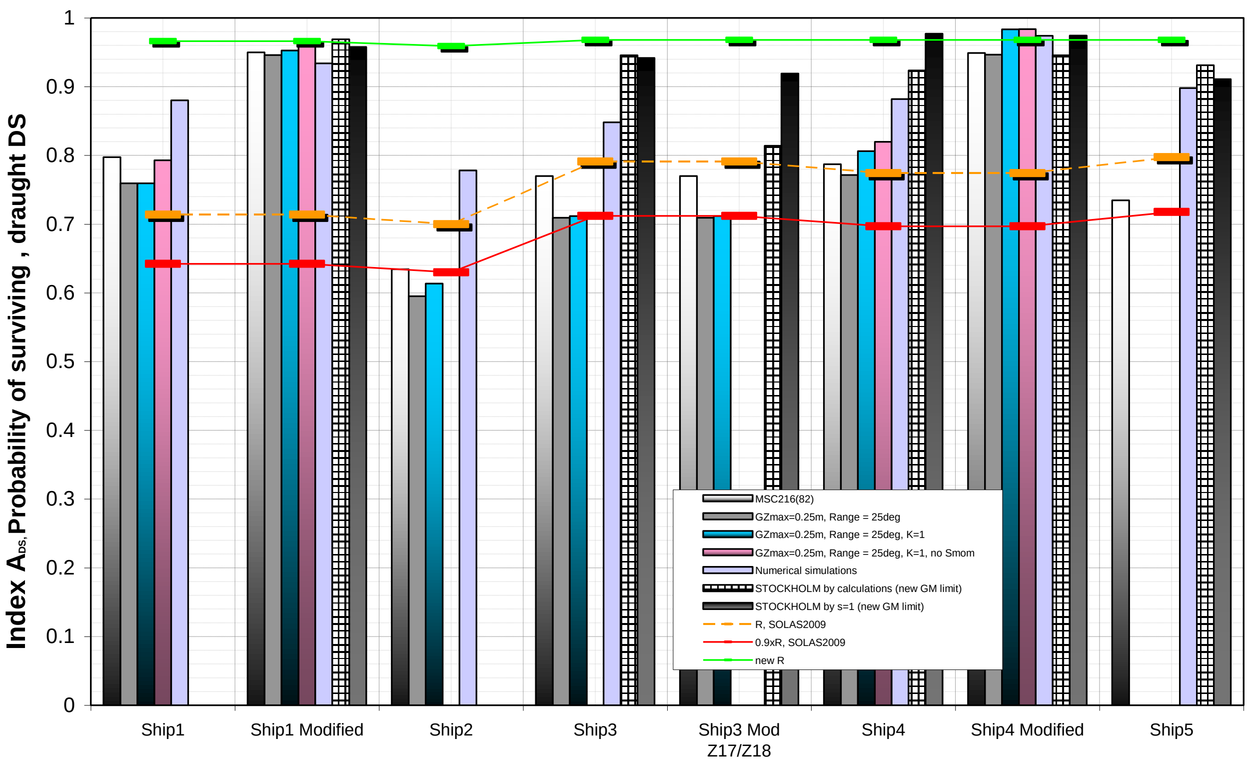


Figure 77 - Summary of assessed survivability in terms of index A

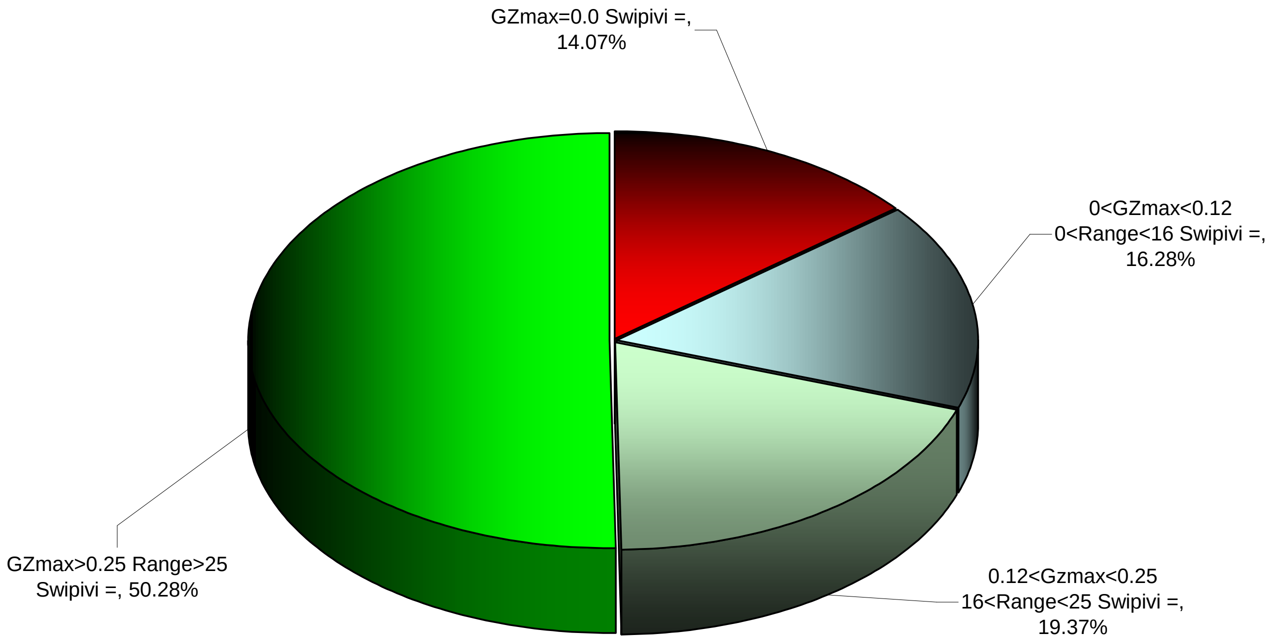


Figure 78 - Distribution of probability for GZmax, Alternative 1, SHIP 1, DS

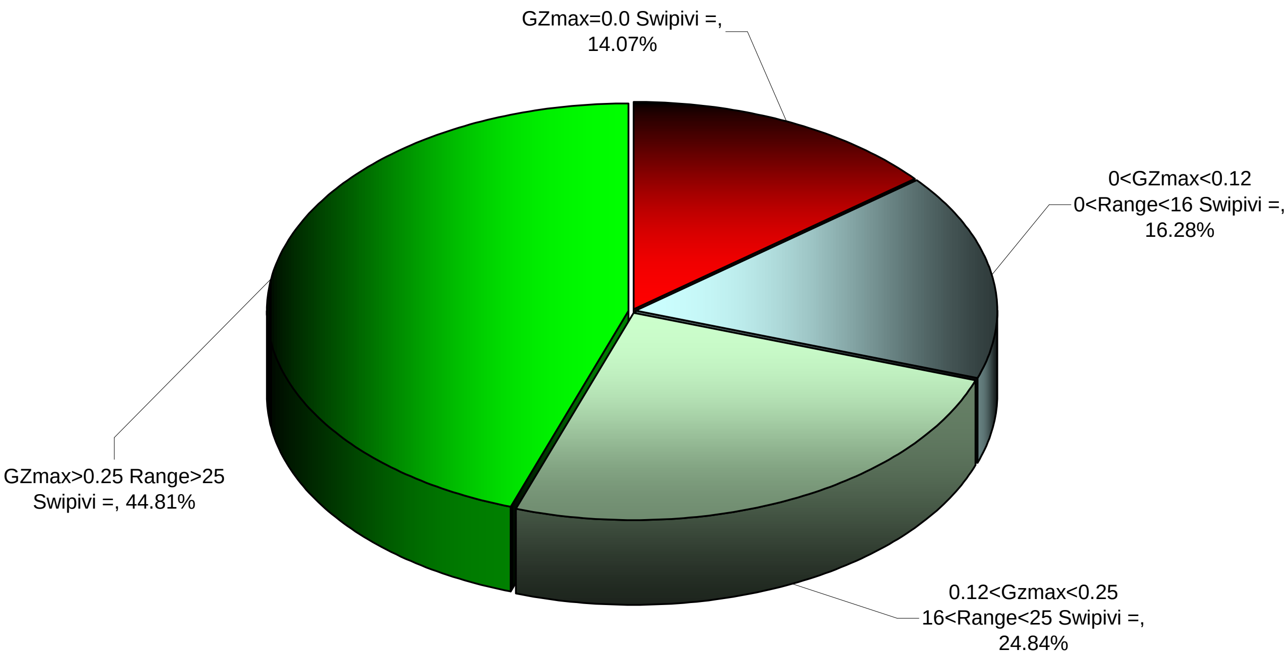


Figure 79 - Distribution of probability for GZmax, Alternative 2, SHIP 1, DS

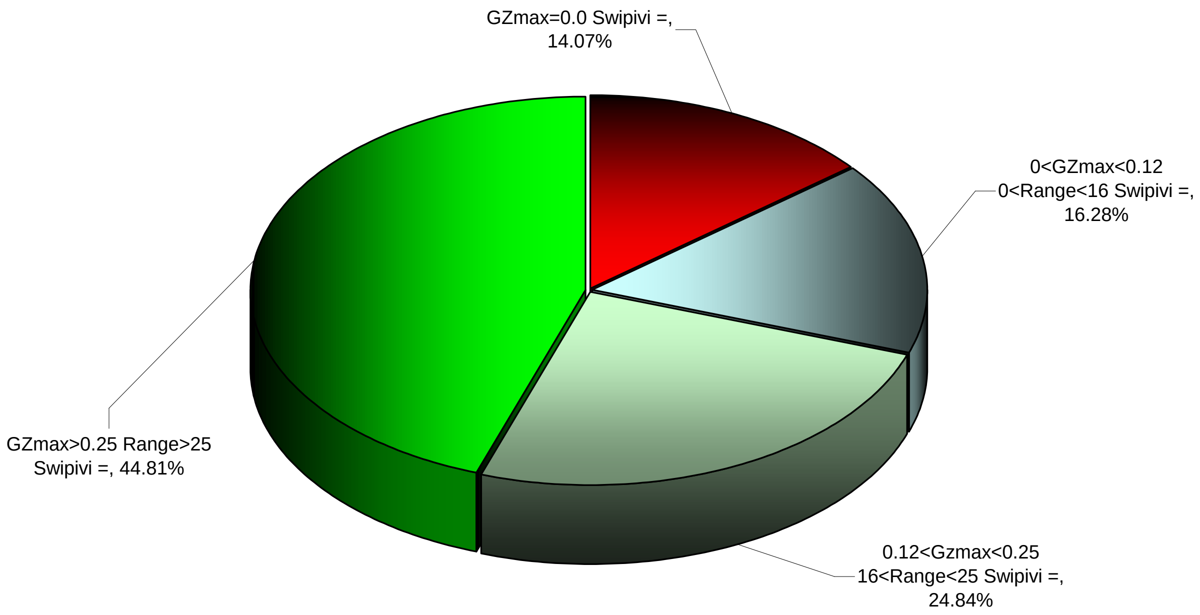


Figure 80 - Distribution of probability for GZmax, Alternative 3, SHIP 1, DS

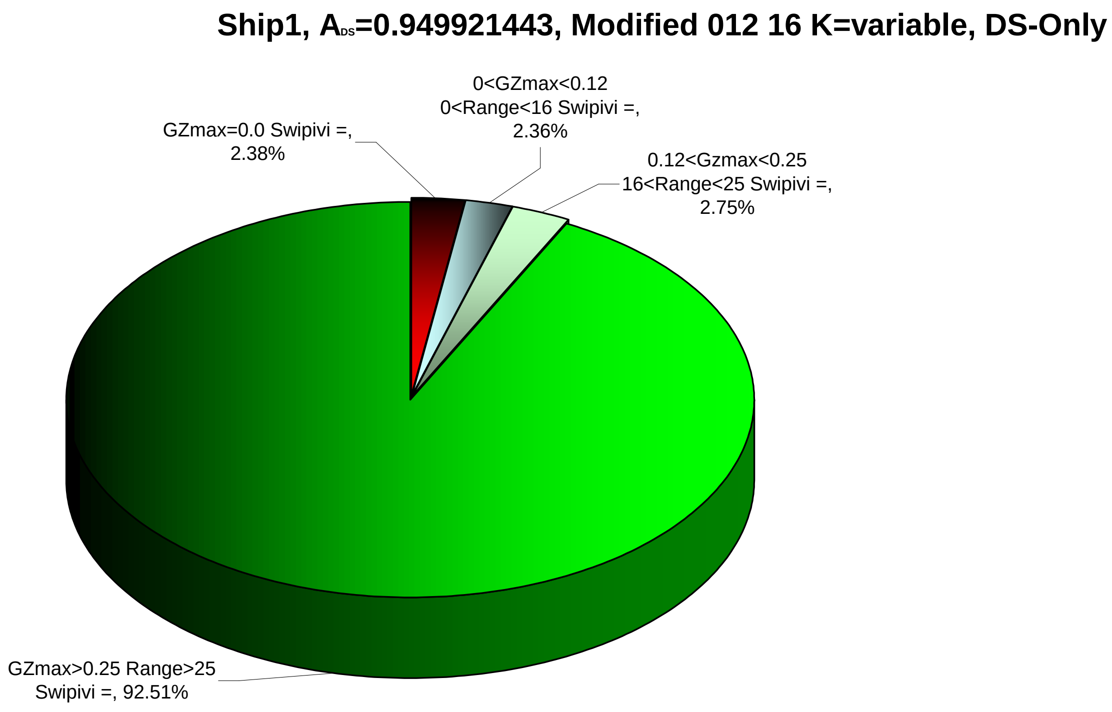


Figure 81 - Distribution of probability for GZmax, Alternative 1, SHIP 1 modified design, DS

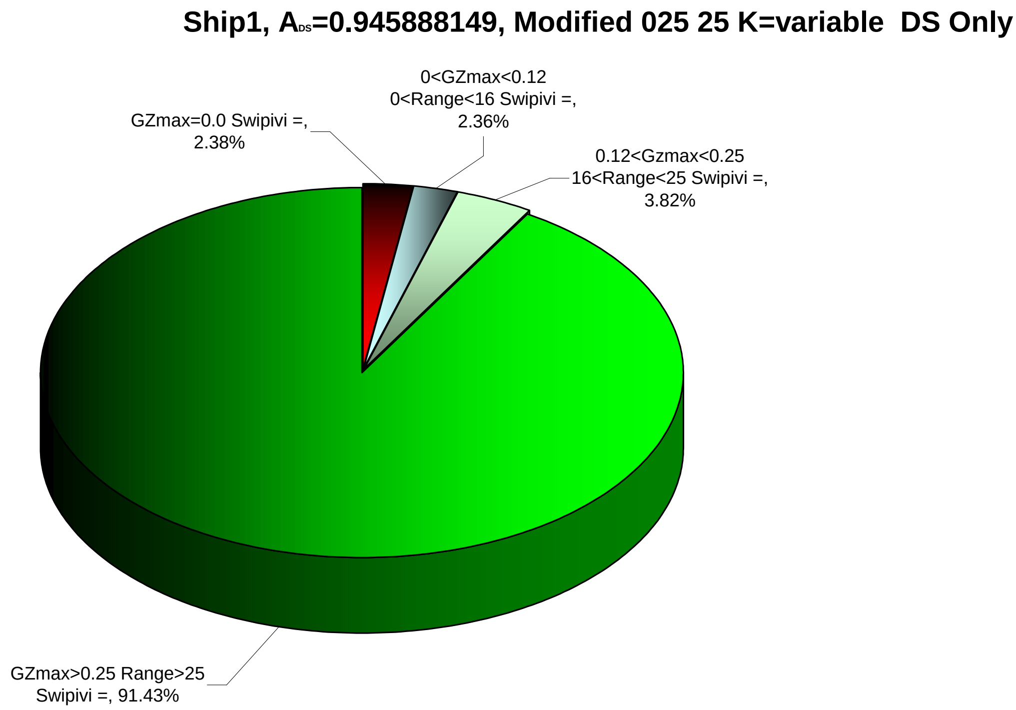


Figure 82 - Distribution of probability for GZmax, Alternative 2, SHIP 1 modified design, DS

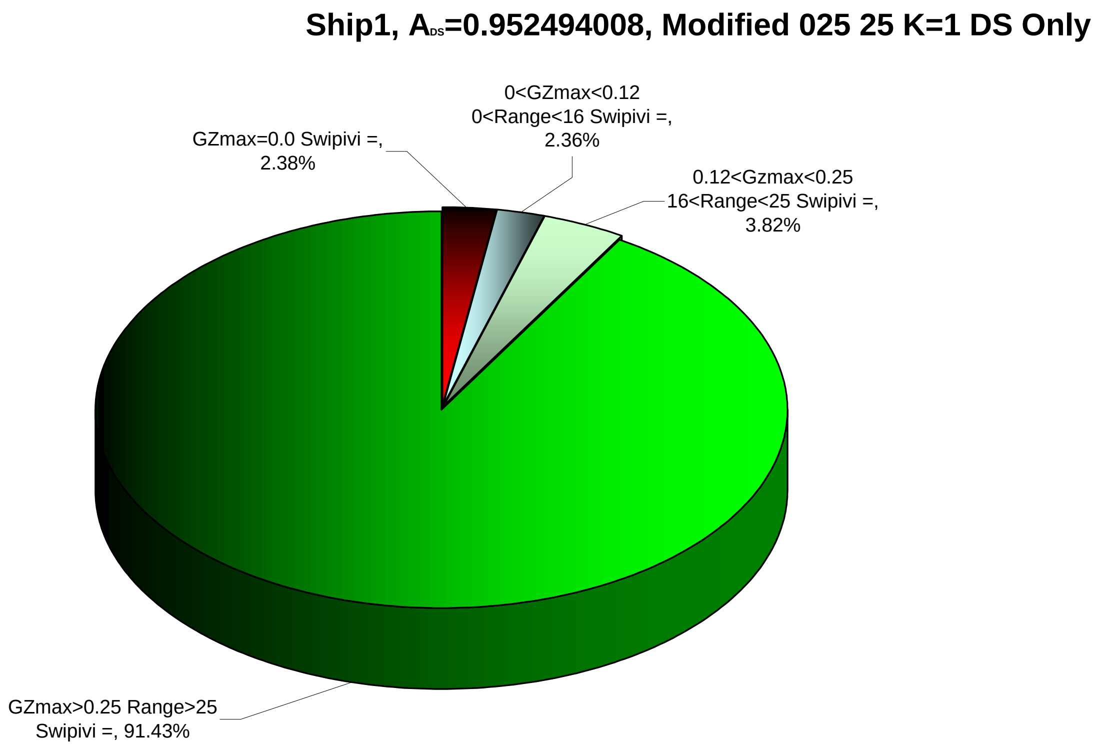


Figure 83 - Distribution of probability for GZmax, Alternative 3, SHIP 1 modified design, DS

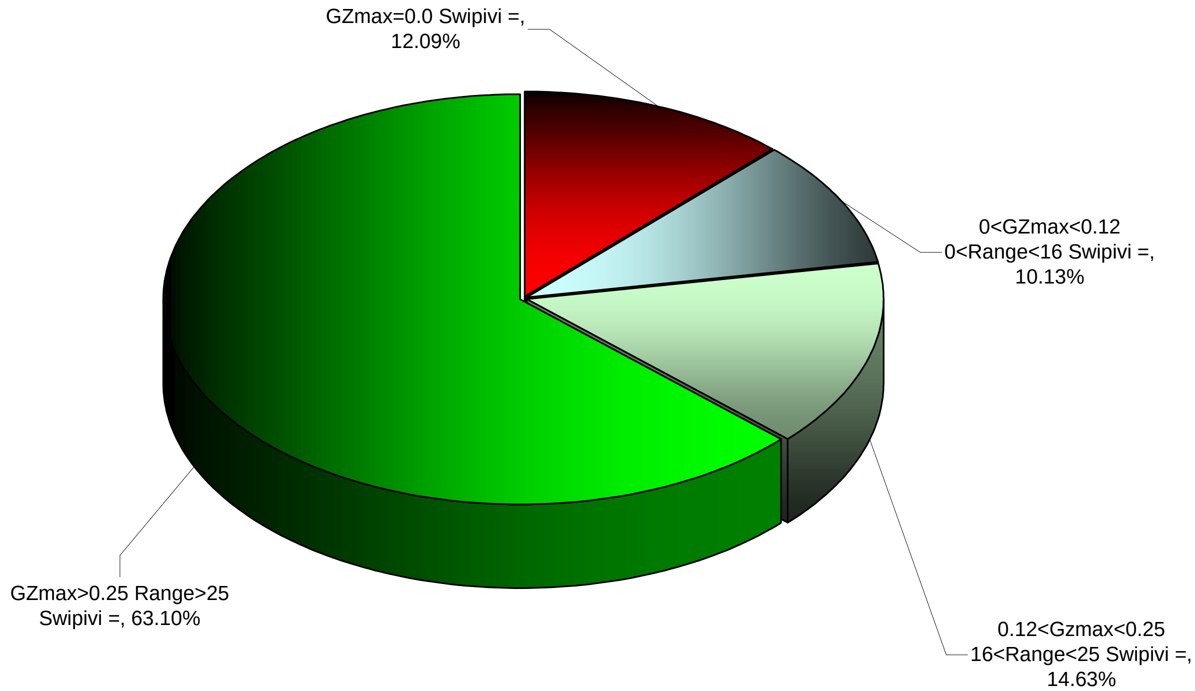


Figure 84 - Distribution of probability for GZmax, Alternative 1, SHIP 4, DS

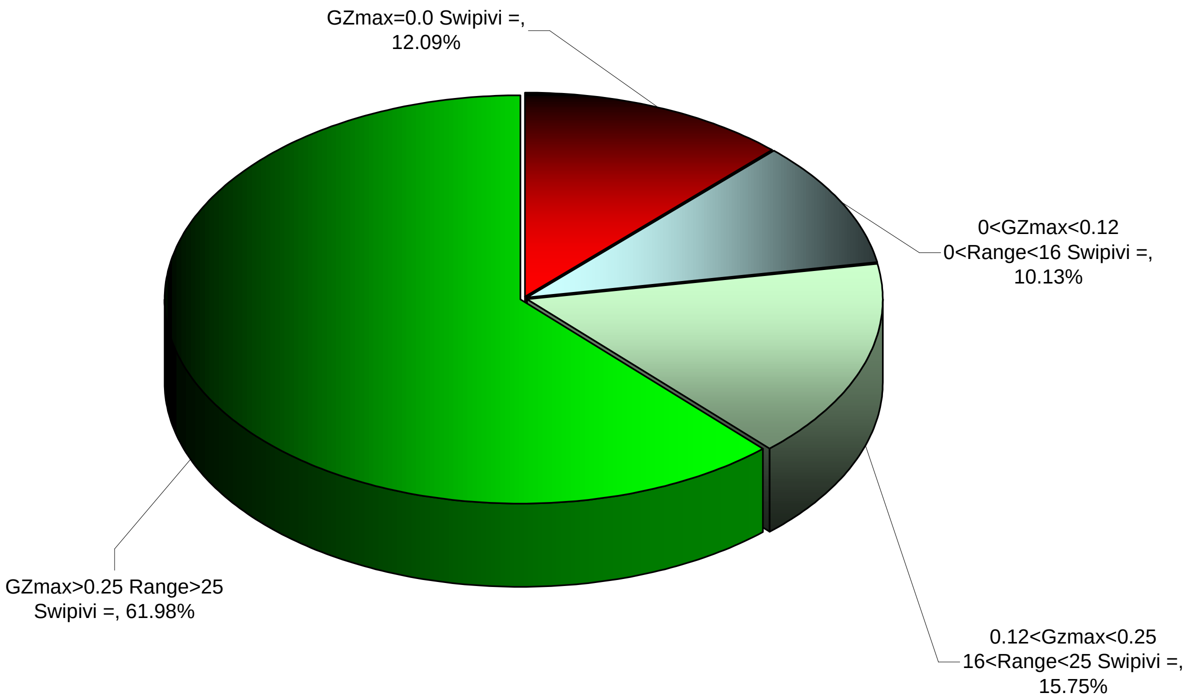


Figure 85 - Distribution of probability for GZmax, Alternative 2, SHIP 4, DS

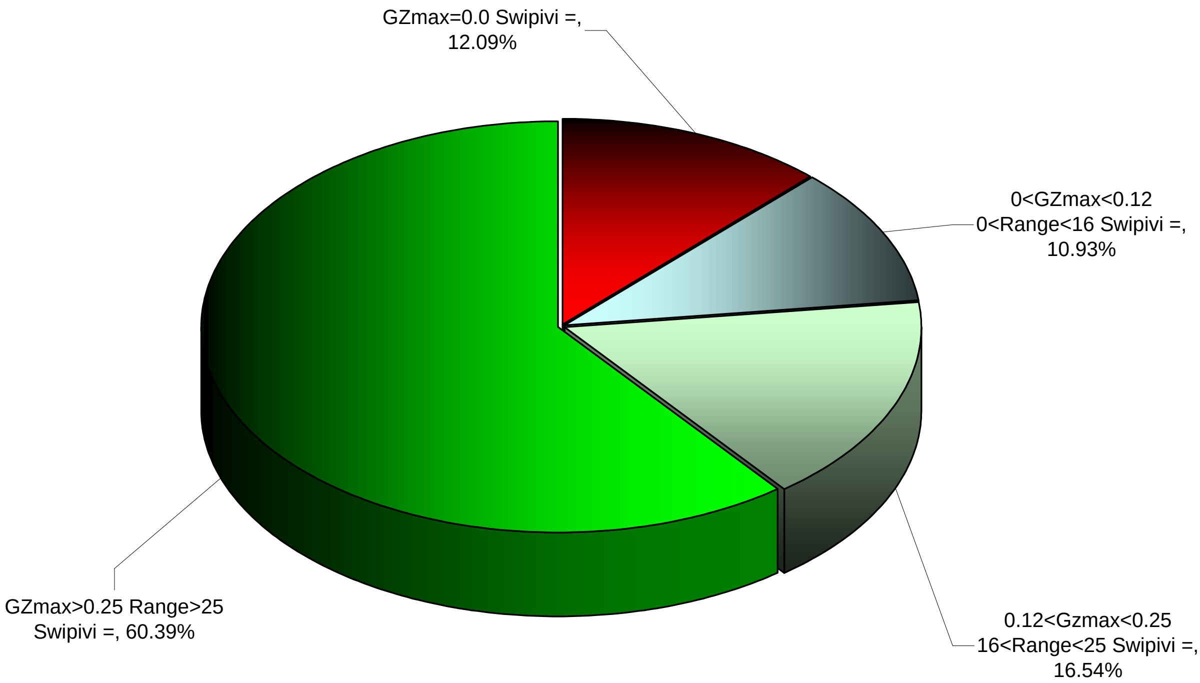


Figure 86 - Distribution of probability for GZmax, Alternative 3, SHIP 4, DS

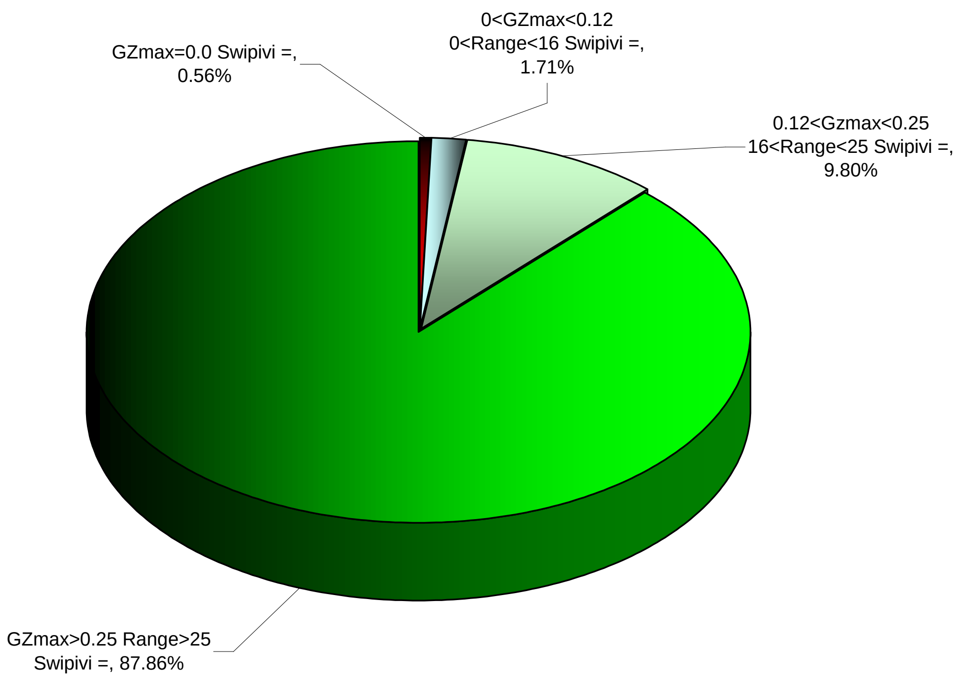


Figure 87 - Distribution of probability for GZmax, Alternative 1, SHIP 4 modified design, DS

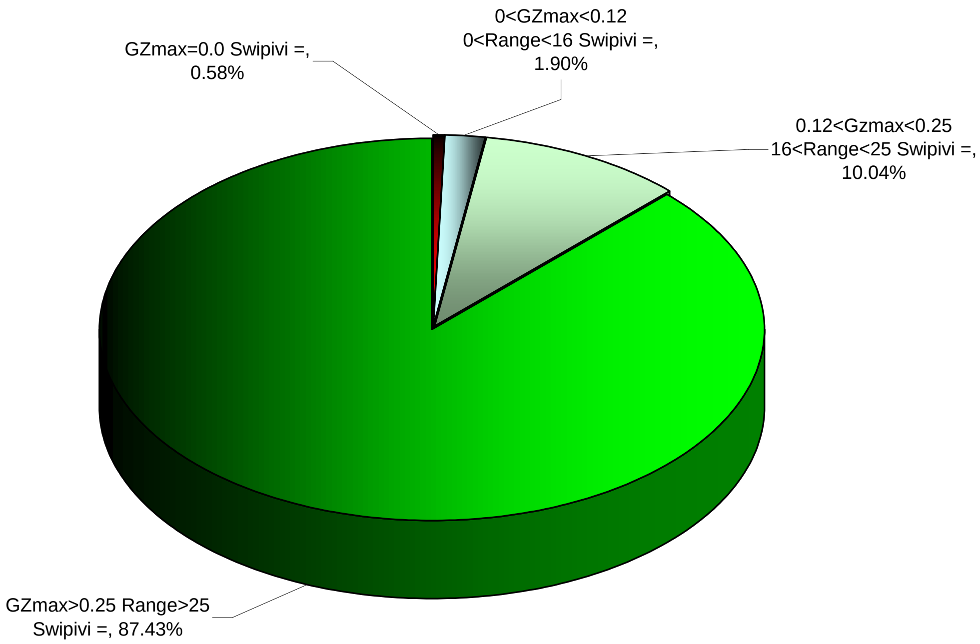


Figure 88 - Distribution of probability for GZmax, Alternative 2, SHIP 4 modified design, DS

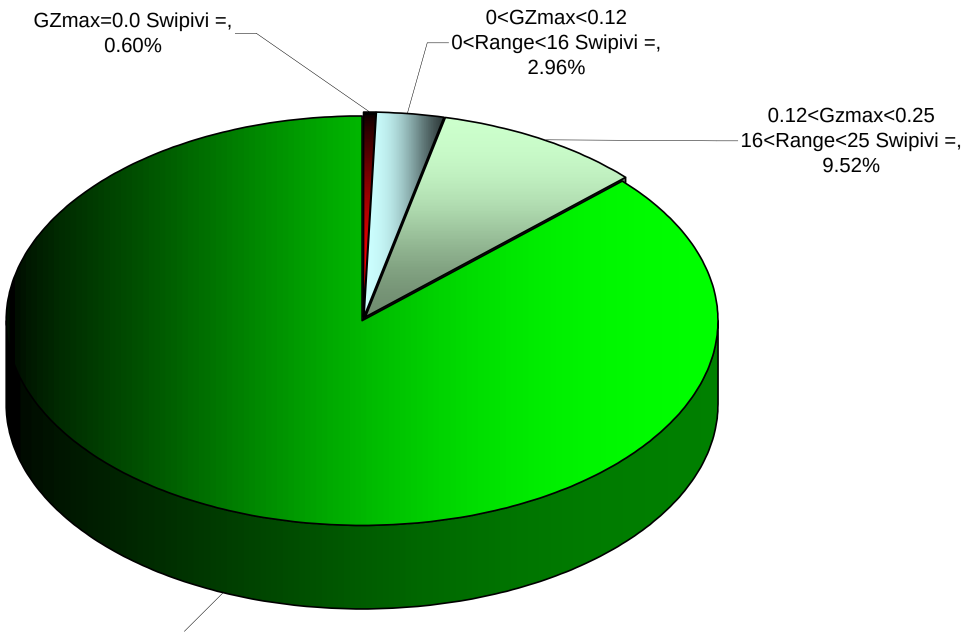


Figure 89 - Distribution of probability for GZmax, Alternative 3, SHIP 4 modified design, DS

Table 15 - Assessment of probability to survive and capsize for the five ships and their modifications

Regulation Alternative 1

Gzmax = 0.12m
Range = 16 deg
K is variable

SHIP1

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.37856	0.37846	0.00010	0.99974	0.00026
2-ZONE	0.36959	0.35456	0.01503	0.95933	0.04067
3-ZONE	0.16227	0.11027	0.05200	0.67955	0.32045
4-ZONE	0.06108	0.01280	0.04828	0.20956	0.79044
5-ZONE	0.02361	0.00089	0.02272	0.03770	0.96230
6-ZONE	0.00486	0.00000	0.00486	0.00000	1.00000
7-ZONE	0.00002	0.00000	0.00002		
	0.99999	**0.85698**	**0.14301**		

SHIP1 Modified

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.37856	0.37856	0.00000	1.00000	0.00000
2-ZONE	0.36959	0.36959	0.00000	1.00000	0.00000
3-ZONE	0.16227	0.15679	0.00548	0.96623	0.03377
4-ZONE	0.06108	0.04559	0.01549	0.74640	0.25360
5-ZONE	0.02361	0.01062	0.01299	0.44981	0.55019
6-ZONE	0.00486	0.00115	0.00371	0.23663	0.76337
7-ZONE	0.00002	0.00000	0.00002	0.00000	1.00000
	0.99999	**0.96230**	**0.03769**		

SHIP2

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.35054	0.34427	0.00627	0.98211	0.01789
2-ZONE	0.37889	0.25207	0.12682	0.66529	0.33471
3-ZONE	0.16526	0.08554	0.07972	0.51761	0.48239
4-ZONE	0.06778	0.01681	0.05097	0.24801	0.75199
5-ZONE	0.02191	0.00362	0.01829	0.16522	0.83478
6-ZONE +	0.01562	0.00000	0.01562	0.00000	1.00000
	1.00000	**0.70231**	**0.29769**		

SHIP3

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.28471	0.28320	0.00151	0.99470	0.00530
2-ZONE	0.35960	0.33748	0.02212	0.93849	0.06151
3-ZONE	0.17255	0.12221	0.05034	0.70826	0.29174
4-ZONE	0.09486	0.05673	0.03813	0.59804	0.40196
5-ZONE	0.05188	0.02578	0.02610	0.49692	0.50308
6-ZONE	0.02283	0.00661	0.01622	0.28953	0.71047
7-ZONE +	0.00951	0.00192	0.00759	0.20189	0.79811
	0.99594	**0.83393**	**0.16201**		

Regulation Alternative 2

Gzmax = 0.25m
Range = 25 deg
K is variable

SHIP1

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.37856	0.37735	0.00121	0.99680	0.00320
2-ZONE	0.36959	0.33997	0.02962	0.91986	0.08014
3-ZONE	0.16227	0.10270	0.05957	0.63290	0.36710
4-ZONE	0.06108	0.01190	0.04918	0.19483	0.80517
5-ZONE	0.02361	0.00084	0.02277	0.03558	0.96442
6-ZONE	0.00486	0.00000	0.00486	0.00000	1.00000
7-ZONE	0.00002	0.00000	0.00002		
	0.99999	**0.83276**	**0.16723**		

SHIP1 Modified

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.37856	0.37856	0.00000	1.00000	0.00000
2-ZONE	0.36959	0.36925	0.00034	0.99908	0.00092
3-ZONE	0.16227	0.15493	0.00734	0.95477	0.04523
4-ZONE	0.06108	0.04493	0.01615	0.73559	0.26441
5-ZONE	0.02361	0.01032	0.01329	0.43710	0.56290
6-ZONE	0.00486	0.00112	0.00374	0.23045	0.76955
7-ZONE	0.00002	0.00000	0.00002	0.00000	1.00000
	0.99999	**0.95911**	**0.04088**		

Regulation Alternative 3

Gzmax = 0.25m
Range = 25 deg
K = 1

SHIP1

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.37856	0.37735	0.00121	0.99680	0.00320
2-ZONE	0.36959	0.33997	0.02962	0.91986	0.08014
3-ZONE	0.16227	0.10270	0.05957	0.63290	0.36710
4-ZONE	0.06108	0.01190	0.04918	0.19483	0.80517
5-ZONE	0.02361	0.00084	0.02277	0.03558	0.96442
6-ZONE	0.00486	0.00000	0.00486	0.00000	1.00000
7-ZONE	0.00002	0.00000	0.00002		
	0.99999	**0.83276**	**0.16723**		

SHIP1 Modified

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.37856	0.37856	0.00000	1.00000	0.00000
2-ZONE	0.36959	0.36925	0.00034	0.99908	0.00092
3-ZONE	0.16227	0.15527	0.00700	0.95686	0.04314
4-ZONE	0.06108	0.04838	0.01270	0.79208	0.20792
5-ZONE	0.02361	0.01132	0.01229	0.47946	0.52054
6-ZONE	0.00486	0.00114	0.00372	0.23457	0.76543
7-ZONE	0.00002	0.00000	0.00002	0.00000	1.00000
	0.99999	**0.96392**	**0.03607**		

Regulation Alternative 1

Gzmax = 0.12m
Range = 16 deg
K is variable

SHIP4

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.35107	0.35050	0.00057	0.99838	0.00162
2-ZONE	0.38742	0.33653	0.05089	0.86864	0.13136
3-ZONE	0.17370	0.12723	0.04647	0.73247	0.26753
4-ZONE	0.06025	0.03427	0.02598	0.56880	0.43120
5-ZONE	0.02054	0.00908	0.01146	0.44206	0.55794
6-ZONE	0.00572	0.00195	0.00377	0.34091	0.65909
7-ZONE +	0.00053	0.00022	0.00031	0.41509	0.58491
	0.99923	**0.85978**	**0.13945**		

SHIP4 Modified

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.35107	0.35107	0.00000	1.00000	0.00000
2-ZONE	0.38742	0.38008	0.00734	0.98105	0.01895
3-ZONE	0.17370	0.15998	0.01372	0.92101	0.07899
4-ZONE	0.06025	0.04959	0.01066	0.82307	0.17693
5-ZONE	0.02054	0.01452	0.00602	0.70691	0.29309
6-ZONE	0.00572	0.00335	0.00237	0.58566	0.41434
7-ZONE +	0.00053	0.00031	0.00022	0.58491	0.41509
	0.99923	**0.95890**	**0.04033**		

SHIP5

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.31593	0.31593	0.00000	1.00000	0.00000
2-ZONE	0.33608	0.31208	0.02400	0.92859	0.07141
3-ZONE	0.15854	0.11383	0.04471	0.71799	0.28201
4-ZONE	0.07726	0.03689	0.04037	0.47748	0.52252
5-ZONE	0.04322	0.01777	0.02545	0.41115	0.58885
6-ZONE	0.02259	0.00638	0.01621	0.28243	0.71757
7-ZONE +	0.04638	0.00000	0.04638	0.00000	1.00000
	1.00000	**0.80288**	**0.19712**		

Regulation Alternative 2

Gzmax = 0.25m
Range = 25 deg
K is variable

SHIP4

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.35107	0.34861	0.00246	0.99299	0.00701
2-ZONE	0.38740	0.33038	0.05702	0.85281	0.14719
3-ZONE	0.17370	0.12551	0.04819	0.72257	0.27743
4-ZONE	0.06025	0.03345	0.02680	0.55519	0.44481
5-ZONE	0.02054	0.00891	0.01163	0.43379	0.56621
6-ZONE	0.00591	0.00193	0.00398	0.32657	0.67343
7-ZONE +	0.00067	0.00023	0.00044	0.34328	0.65672
	0.99954	**0.84902**	**0.15052**		

SHIP4 Modified

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.35107	0.35107	0.00000	1.00000	0.00000
2-ZONE	0.38740	0.37952	0.00788	0.97966	0.02034
3-ZONE	0.17370	0.15965	0.01405	0.91911	0.08089
4-ZONE	0.06025	0.04934	0.01091	0.81892	0.18108
5-ZONE	0.02054	0.01440	0.00614	0.70107	0.29893
6-ZONE	0.00591	0.00337	0.00254	0.57022	0.42978
7-ZONE +	0.00067	0.00031	0.00036	0.46269	0.53731
	0.99954	**0.95766**	**0.04188**		

Regulation Alternative 3

Gzmax = 0.25m
Range = 25 deg
K = 1

SHIP4

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.35107	0.34863	0.00244	0.99305	0.00695
2-ZONE	0.38740	0.34019	0.04721	0.87814	0.12186
3-ZONE	0.17370	0.13654	0.03716	0.78607	0.21393
4-ZONE	0.06025	0.03924	0.02101	0.65129	0.34871
5-ZONE	0.02054	0.01085	0.00969	0.52824	0.47176
6-ZONE	0.00591	0.00252	0.00339	0.42640	0.57360
7-ZONE +	0.00067	0.00024	0.00043	0.35821	0.64179
	0.99954	**0.87821**	**0.12133**		

SHIP4 Modified

	p(di)	p(di & N=0)	p(di & N=all)	p(N=0 | di)	p(N=all | di)
1-ZONE	0.35107	0.35107	0.00000	1.00000	0.00000
2-ZONE	0.38740	0.38626	0.00114	0.99706	0.00294
3-ZONE	0.17370	0.17156	0.00214	0.98768	0.01232
4-ZONE	0.06025	0.05667	0.00358	0.94058	0.05942
5-ZONE	0.02054	0.01773	0.00281	0.86319	0.13681
6-ZONE	0.00591	0.00448	0.00143	0.75804	0.24196
7-ZONE +	0.00067	0.00037	0.00030	0.55224	0.44776
	0.99954	**0.98814**	**0.01140**		

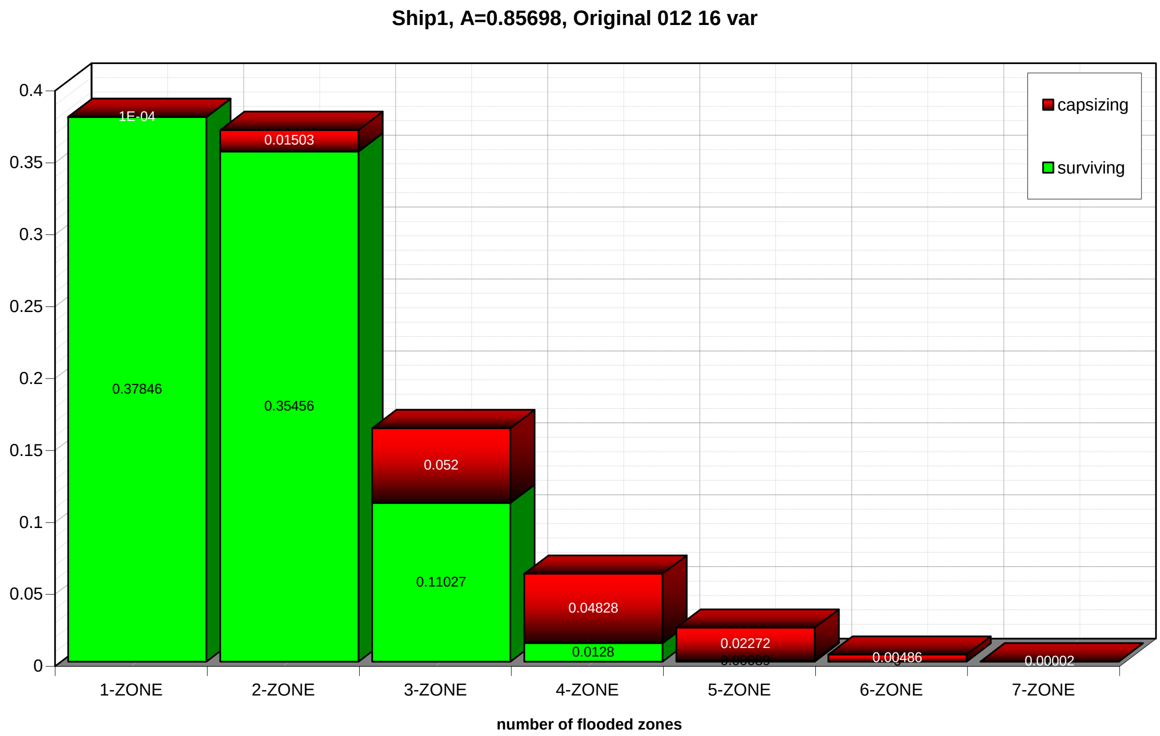


Figure 90 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 1, SHIP 1

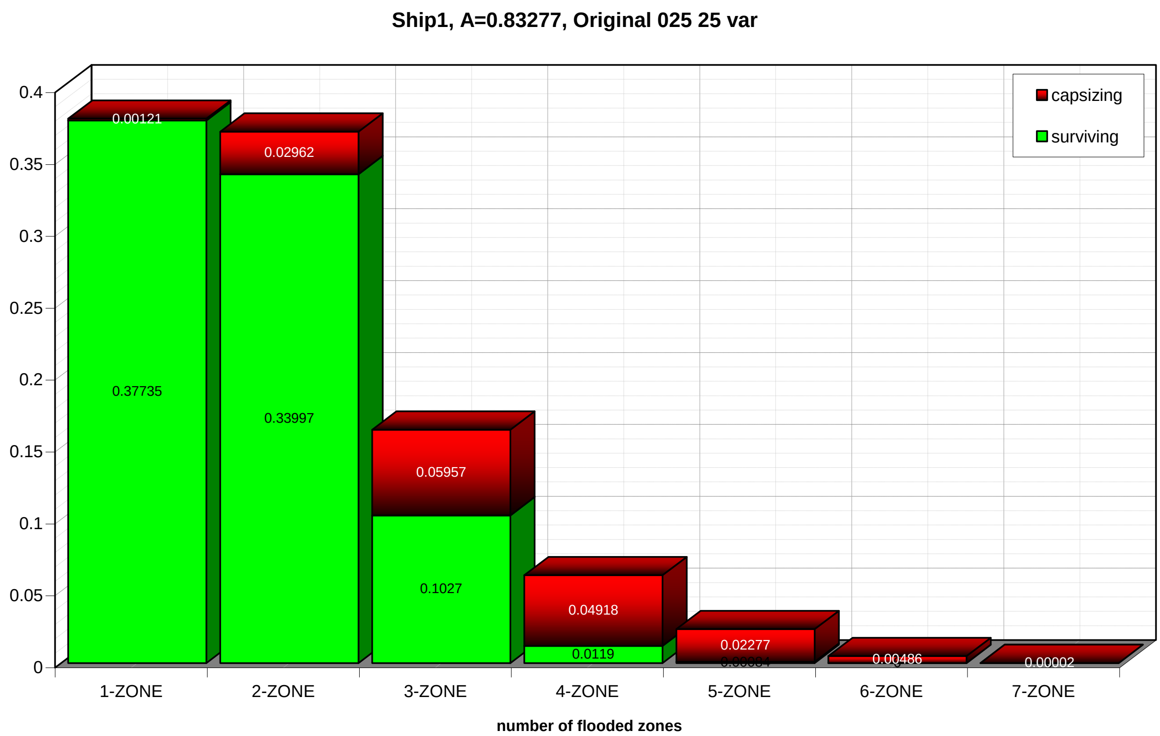


Figure 91 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 2, SHIP 1

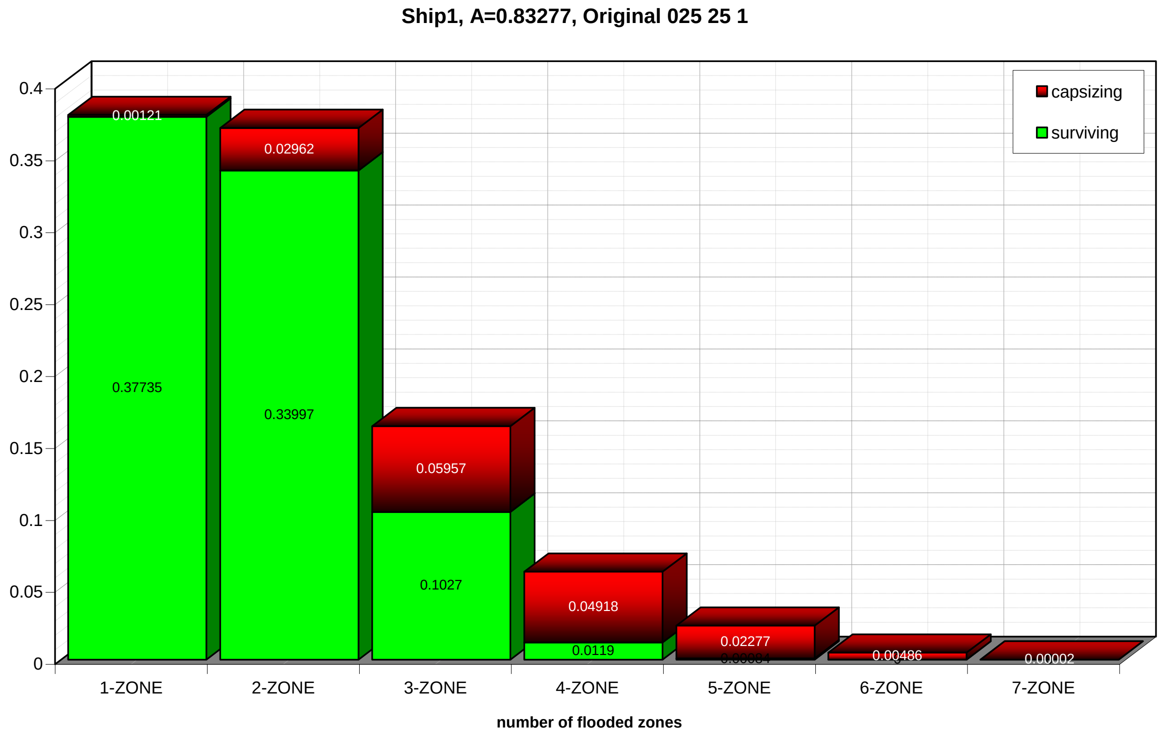


Figure 92 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 3, SHIP 1

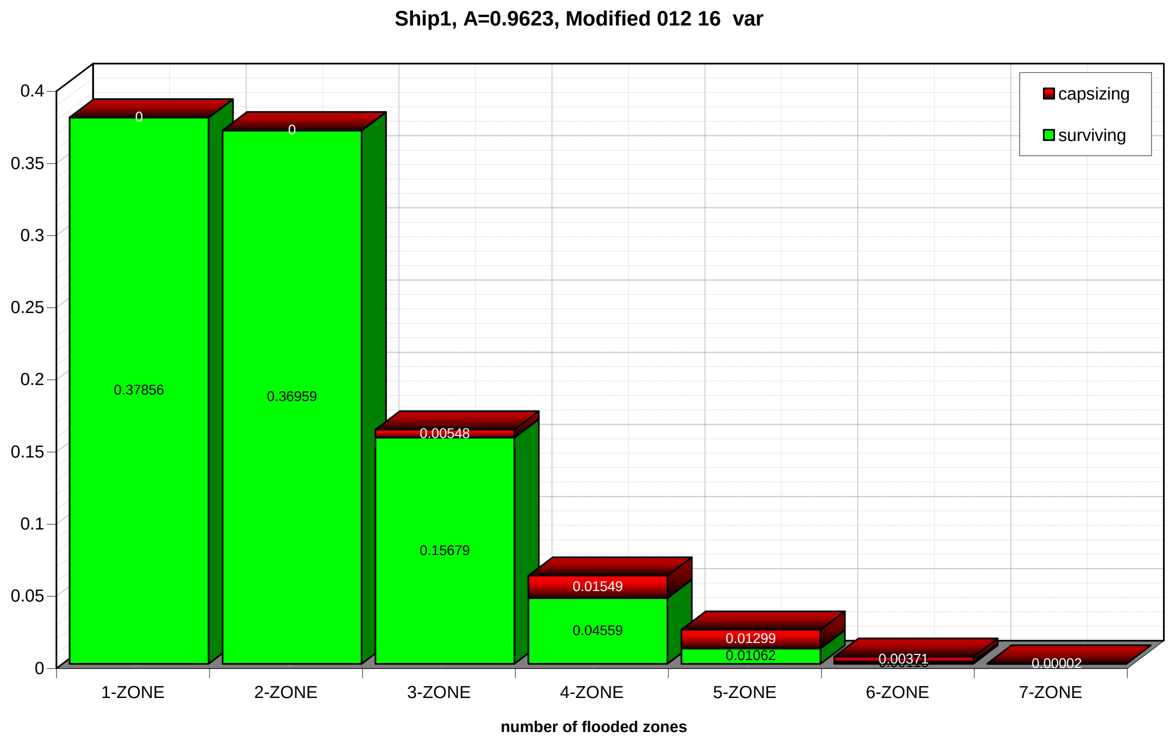


Figure 93 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 1, SHIP 1 modified design

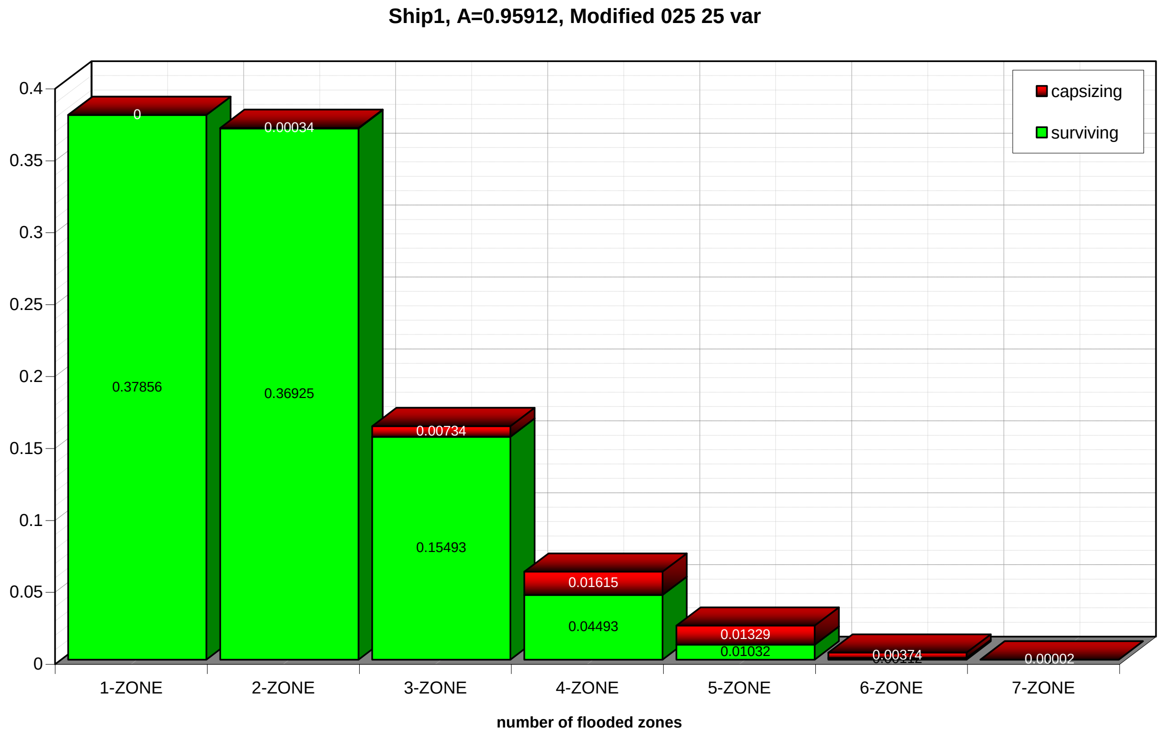


Figure 94 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 2, SHIP 1 modified design

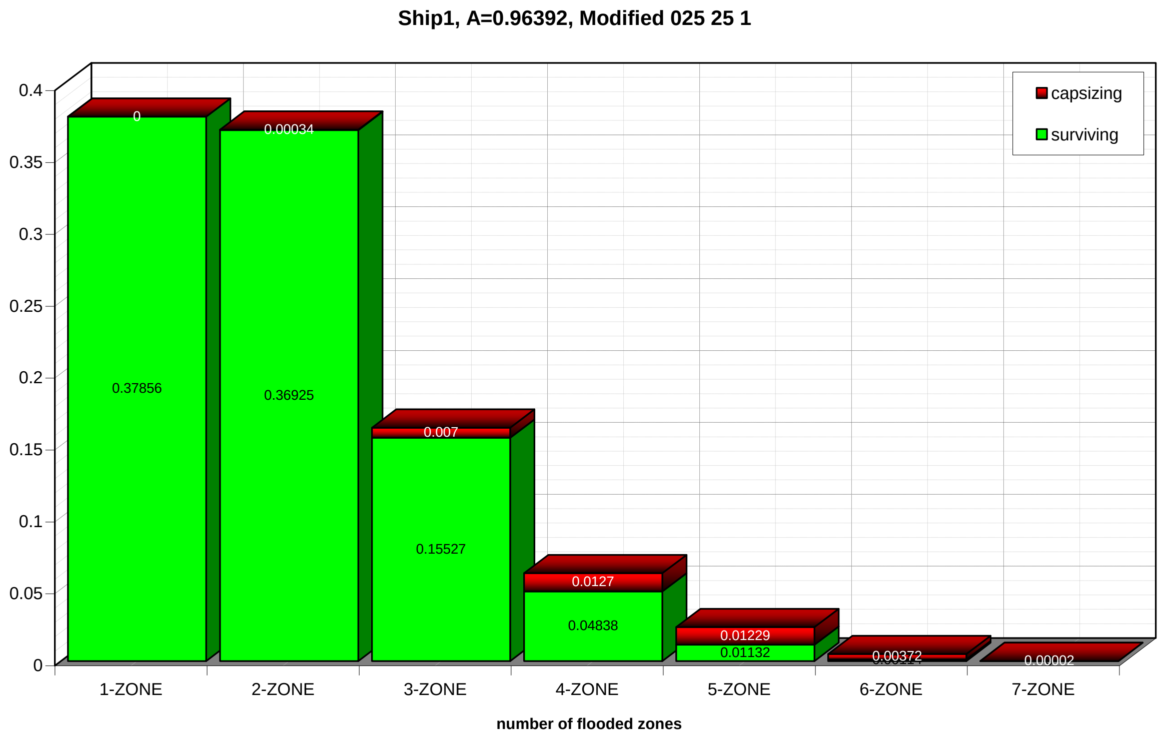


Figure 95 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 3, SHIP 1 modified design

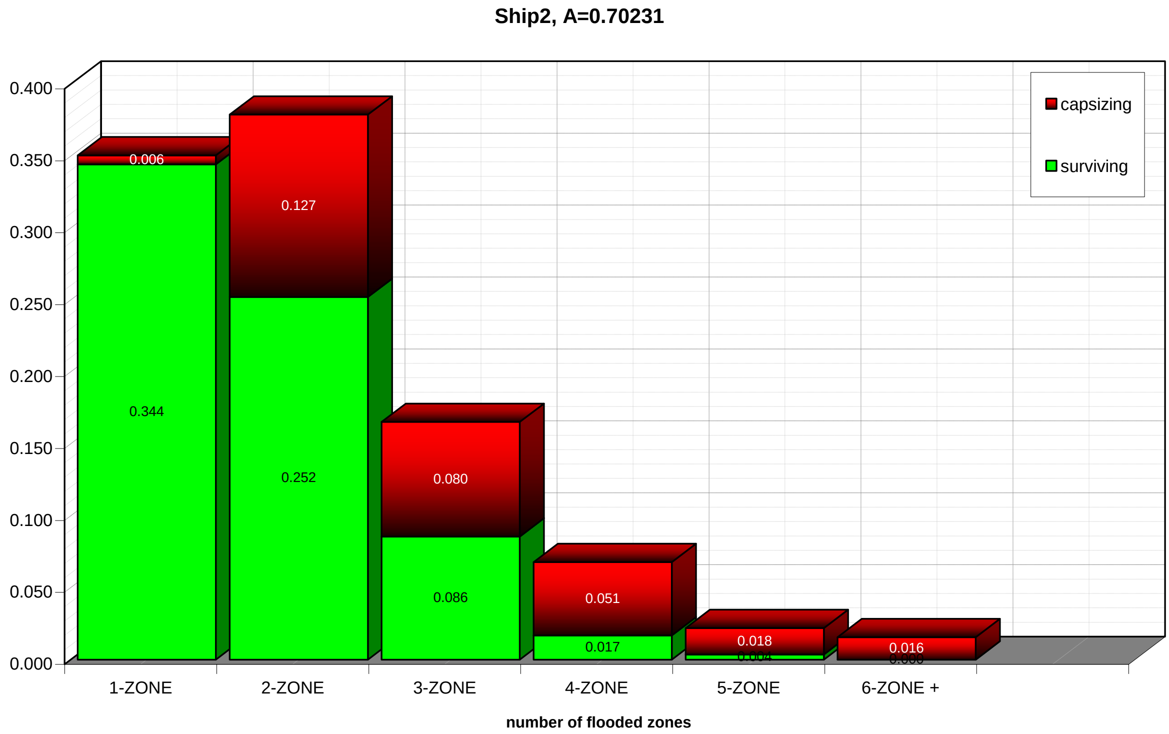


Figure 96 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 1, SHIP 2

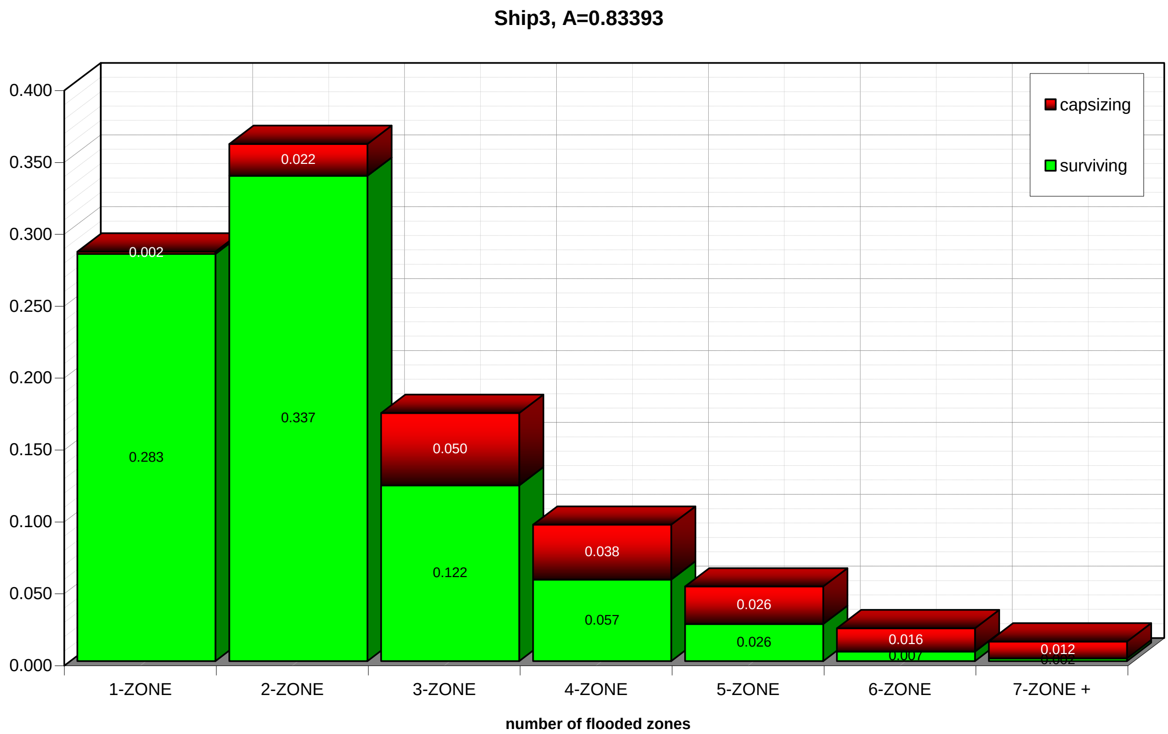


Figure 97 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 1, SHIP 3

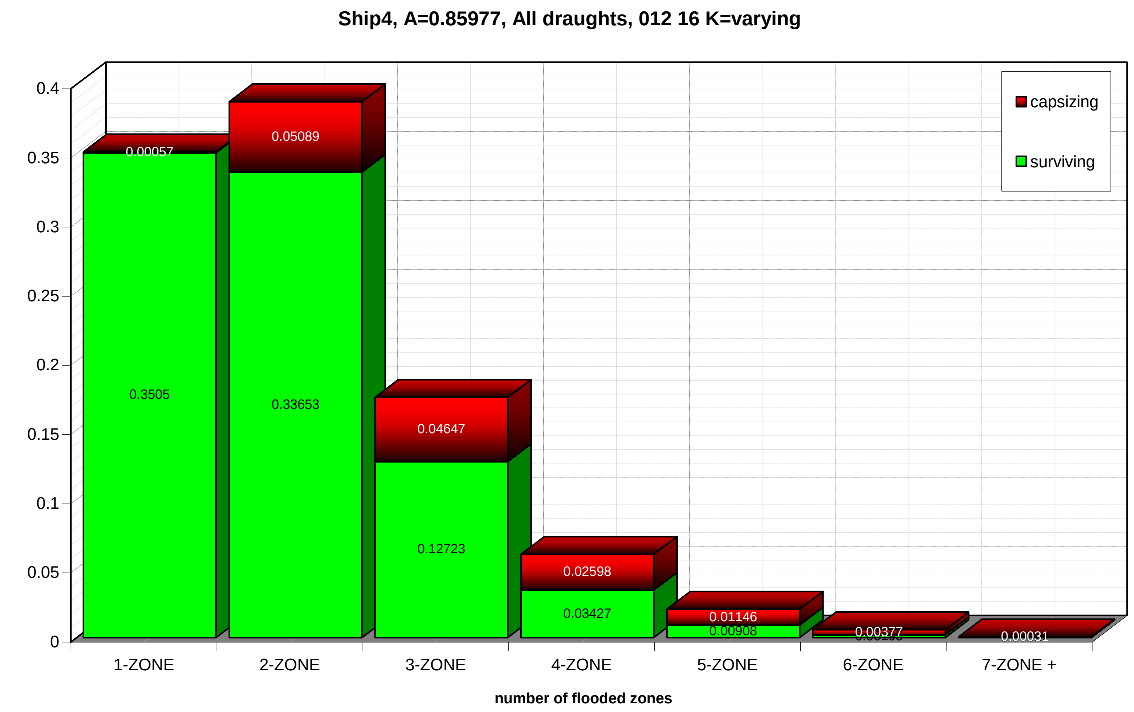


Figure 98 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 1, SHIP 4

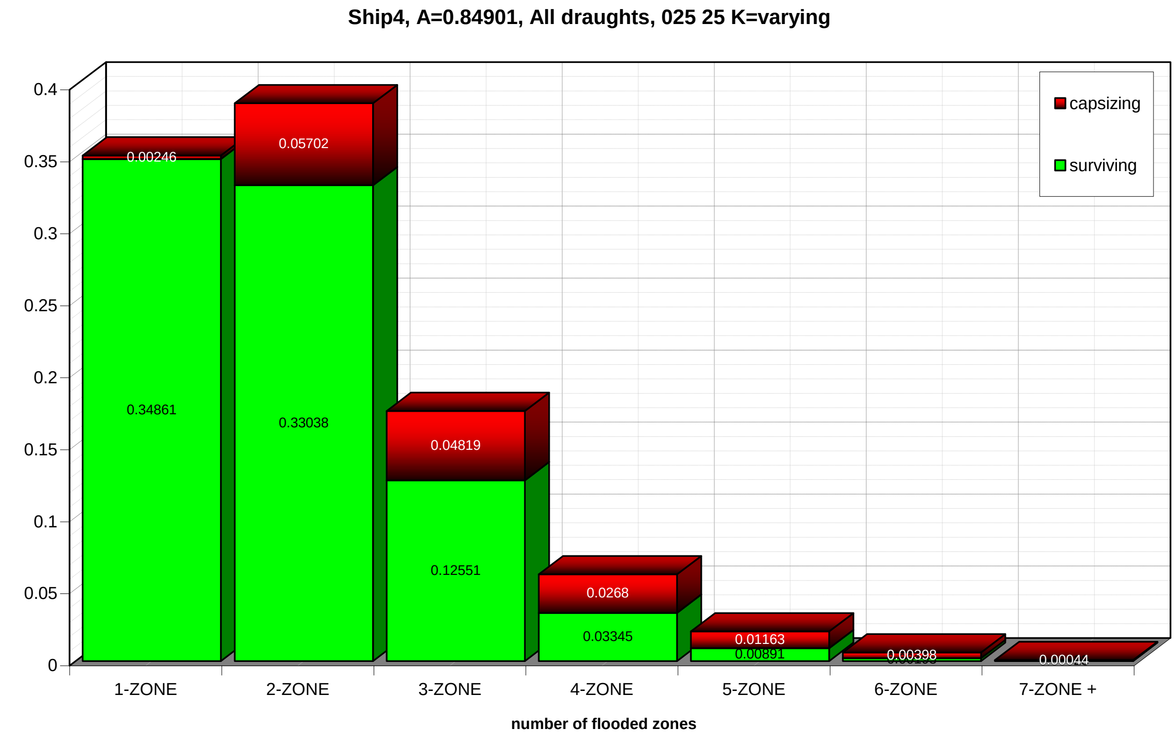


Figure 99 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 2, SHIP 4

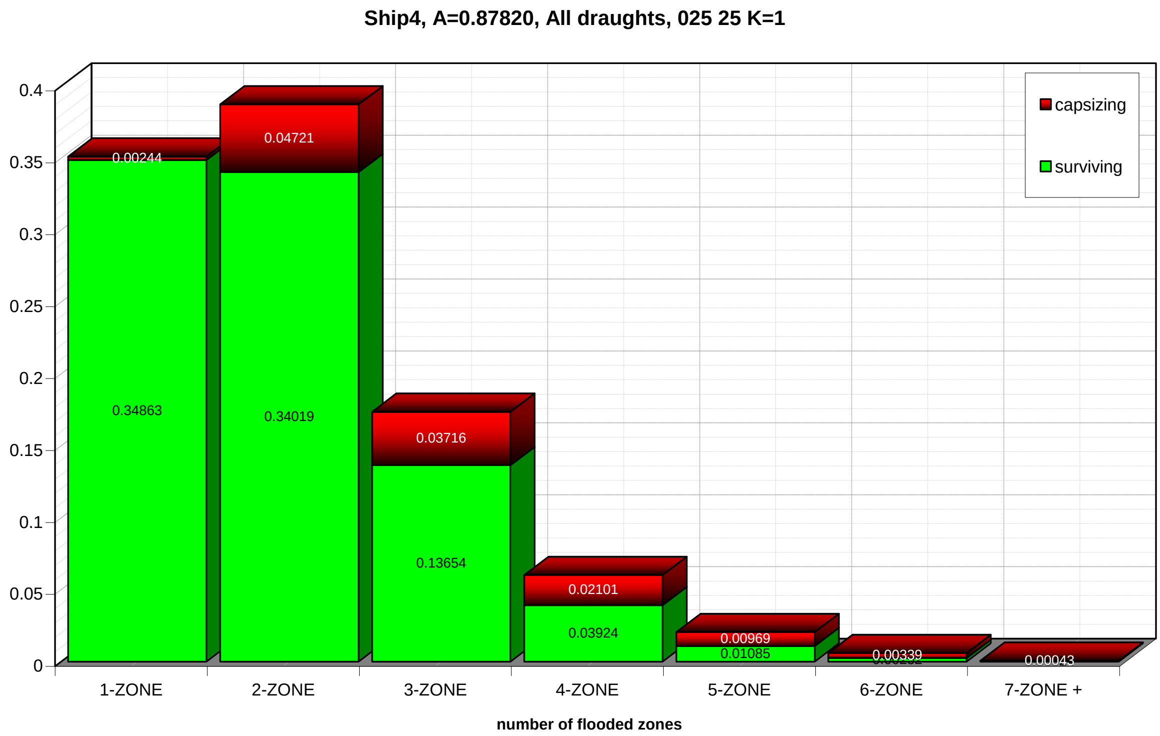


Figure 100 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 3, SHIP 4

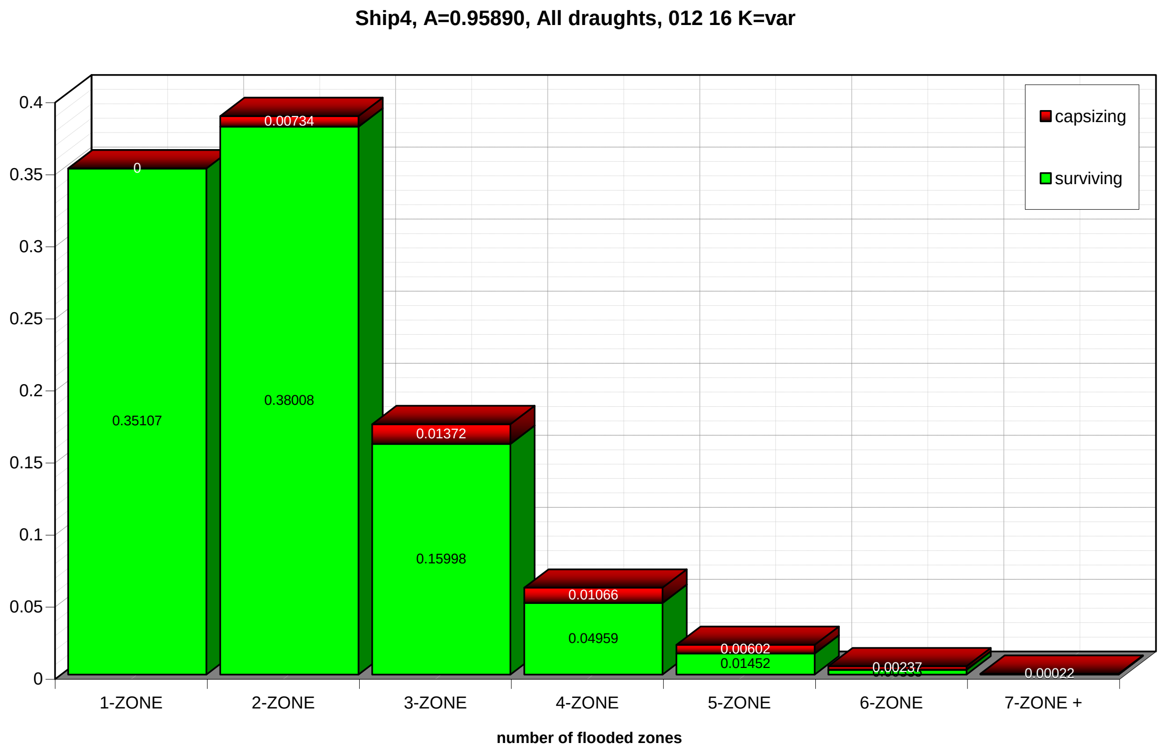


Figure 101 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 1, SHIP 4 modified design

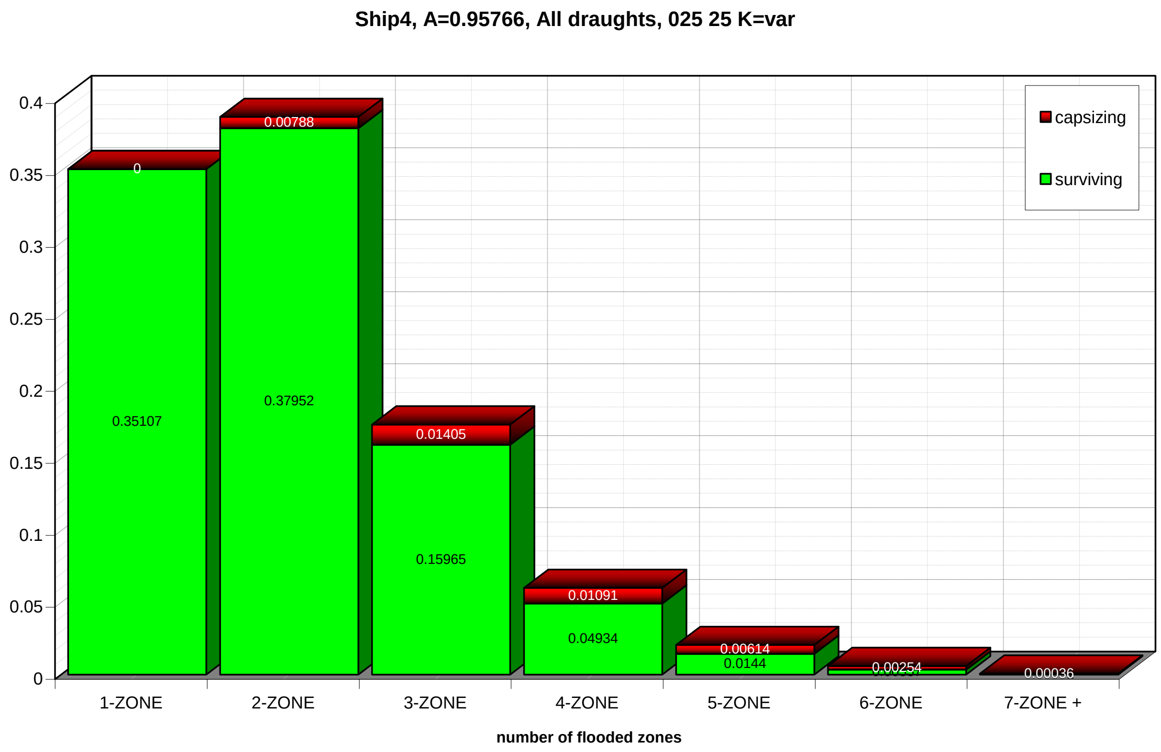


Figure 102 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 2, SHIP 4 modified design

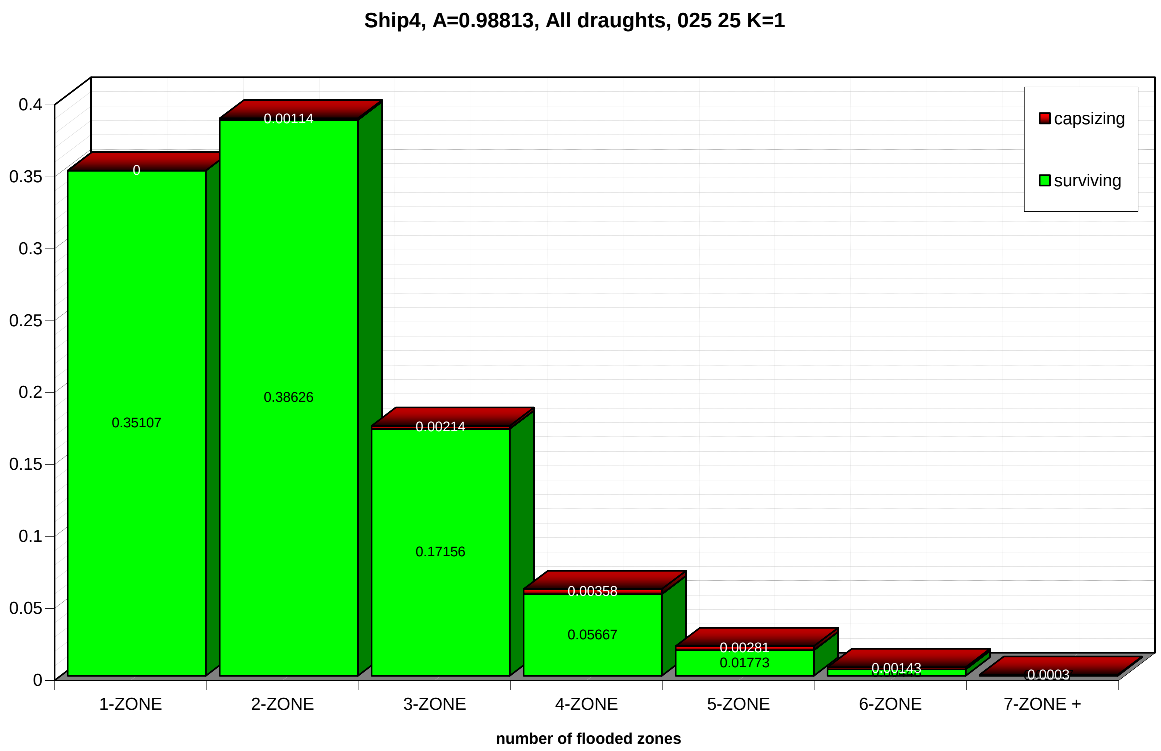


Figure 103 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 3, SHIP 4 modified design

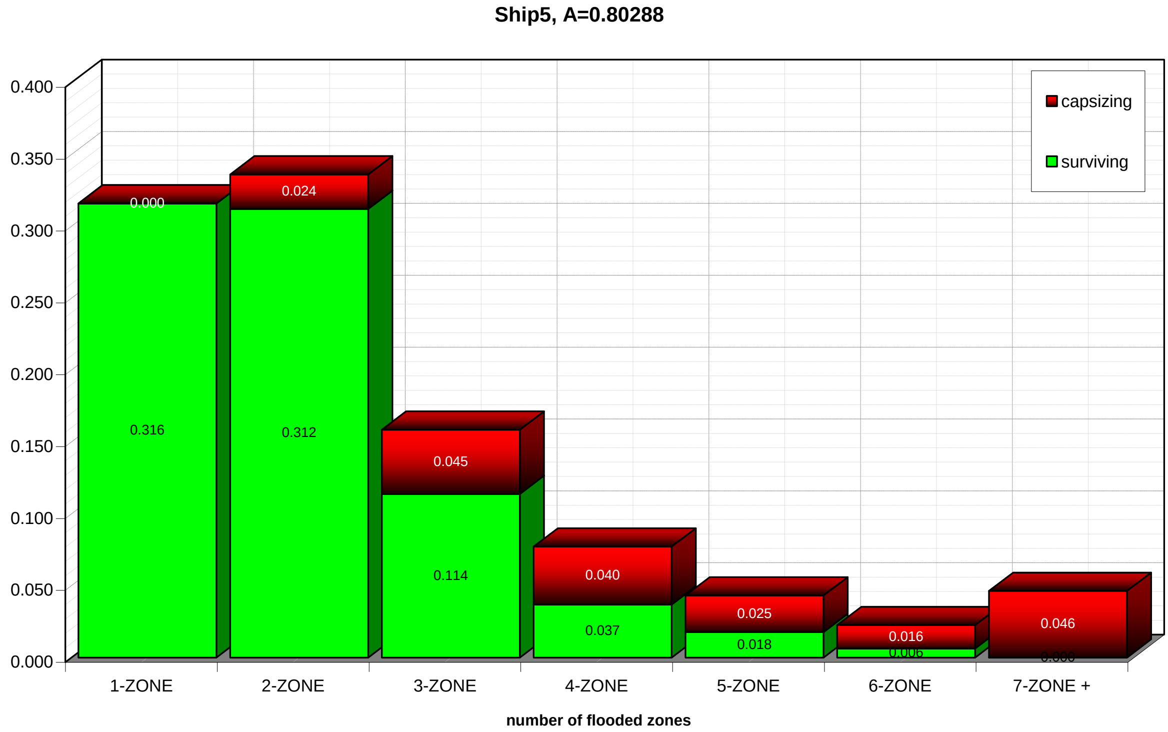


Figure 104 - Distribution of probability for surviving and capsizing within 30 minutes, Alternative 1, SHIP 5

5.2.4. Physical Model Experiments

The tank testing programme (see Annex 3) comprised tests on three ships in the first phase (Ships 1, 3 and 4) and two ships in the second phase (Ship 1 and Ship 4 after design modifications to raise their survivability).

The purpose of these tests was to validate the ability of modified criteria to address problems of stability of RoPax ships with water on the vehicle deck.

The key result to be validated by physical testing was the sea state that results in ship capsize. Information on critical sea states then allows probability s to be assigned. It is proposed that, if the formulation for s proves accurate, it can be used to supplement or replace requirements of the Stockholm Agreement, which aims to ensure survivability at a given level.

Note that further arguments must be considered regarding the fact that the Stockholm Agreement only targets a small but specific set of possible flooding cases (<B/5, 2-comp) to be made completely survivable, whilst in contrast, SOLAS 2009 addresses all feasible cases, a proportion of which (approximate ~R) are to be rendered survivable by designers. However, these explanations can only be performed theoretically and do not form part of physical testing.

Detailed summary tank testing data is given in three reports in Annex 3. Table 16 to Table 21, with supplementary figures provide summaries of all tests performed in all project phases. Figure 40 to Figure 42 summarise tests performed in the context of theoretical predictions, as well as all other available data on survivability.

SHIP 1

An initial plan for tests for a modified version of Ship 1 involved a case that was extremely marginal from a stability point of view. The plan was to demonstrate that even a marginal amount of stability would result in a given level of predictable survivability of H_{crit} = 2.58m, as shown in Table 21.

Instead, however, the tests demonstrated how sensitive assumptions for calculations are. Namely, as is also mentioned in Annex 4, an assumption on 90% permeability of vehicle deck might not reflect reality. Although the overall space might be filled, the area of relevance to stability (normally up to 0.3 – 0.5m off the deck's surface) is only covered with vehicle wheels. This assumption, and possibly many others, could prove detrimental to survivability. As was experienced during test preparations, a physical model built within tolerances seems to have shown that real life stability might not exist as assumed. Although the exact cause has proven difficult to establish, it transpires that vehicle deck permeability bears significant impact on stability.

Subsequently, a test case selected aimed at the demonstration of survivability increased for modified ships to at least 4m, which was validated.

SHIP 4

A 2-zone case was selected for test, DS/REG7_P7-8.3.0.

(a) The case was completely non-survivable for a design compliant with current standards.

(b) The case would not be survivable under the Stockholm Agreement (i.e. implying failure). However, since the Stockholm Agreement is limited in scope (e.g. B/5), the ship would not even be checked for this scenario, and given other limited scope scenarios were compliant, the ship would have been approved, despite the scenario being un-survivable.

These sets of tests demonstrate perhaps some difficulty implicit in verifying the level of survivability by model experiments. The case of Ship 1 at higher angles of heel puts into question the various assumptions made in analyses. Comparisons of results from this project add to the great spread in relationship between ship stability parameters and the survivability derived by model experiments (see Figure 40 to Figure 42).

However, it must be stressed that these uncertainties are only relevant for the proportion of flooding cases where the probability of survival is less than one, or more than zero. As shown in Annex 2, these cases, marked in "grey" colour, only comprise some 10-15% of all cases. Conservative adjustment for the formulation based on stability parameters would ascertain that predictions always account for water accumulation and ensure survival in given sea states is realistic (see Figure 42). Such adjustment results in reduction in probability A of the order of 1-2% (see Table 14), and therefore seems justifiable to be implemented.

For flooding cases where the s=0 (red cases), the ship would capsize very rapidly even in calm seas.

For flooding cases where the s=1 (green cases), the ship will survive in seas of at least 4m.

It could be suggested at this stage that the requirement of the Stockholm Agreement for Hs = 4m could be verified based on factor s=1 for specific flooding cases considered under the Stockholm Agreement (<B/5 and 2-comp).

Table 16 - Summary results of physical model experiments for SHIP 1 case R7_S6-7.4.0

Damage R7_P6-7.4.0
TOTAL RUNS 43
Survival Boundary 3.6m

Hs	Runs	Capsizes	pf = No of capsizes / No or runs
4.25	5	0	0
4	10	1	0.1
3.75	10	7	0.7
3.5	5	2	0.4
3.25	5	2	0.4
3	1	1	
2.5	5	0	0

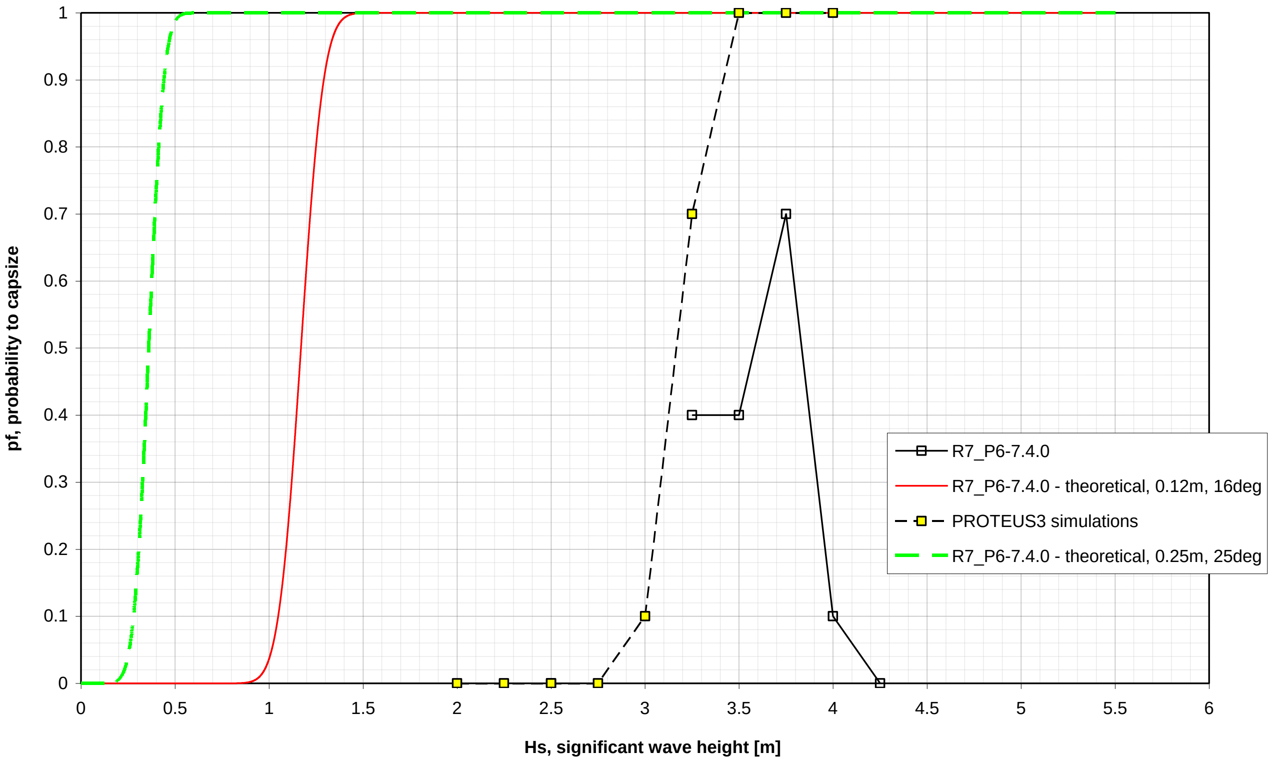


Table 17 - Summary results of physical model experiments for SHIP 1 case R7_S7-9.1.0-1

Damage R7_S7-9.1.0-1
TOTAL RUNS 85
Survival Boundary 4m

Hs	Runs	Capsizes	pf
4.25	10	4	0.4
4	10	7	0.7
3.9	10	0	0
3.75	10	0	0
3.5	20	3	0.15
3.35	10	0	0
3.25	10	0	0
3	5	0	0

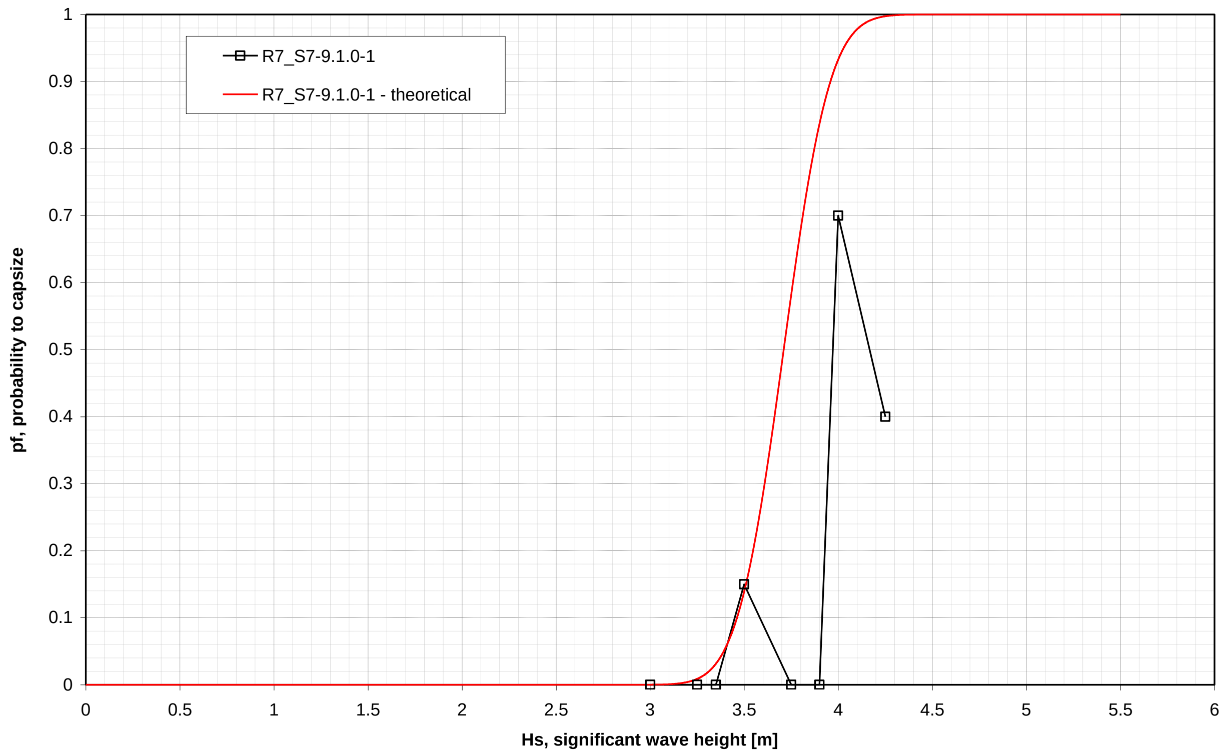


Table 18 - Summary results of physical model experiments for SHIP 3

Damage R7P15-16.2.0-1
TOTAL RUNS 146
Survival Boundary 3.55m

	Hs	Runs	Capsizes	pf
2	**2m**	10	0	0
2.5	**2.5m**	5	0	0
3	**3m**	10	0	0
3.25	**3.25m**	20	5	0.25
3.5	**3.5m**	60	27	0.45
3.75	**3.75m**	31	24	0.774193548
4	**4m**	10	10	1

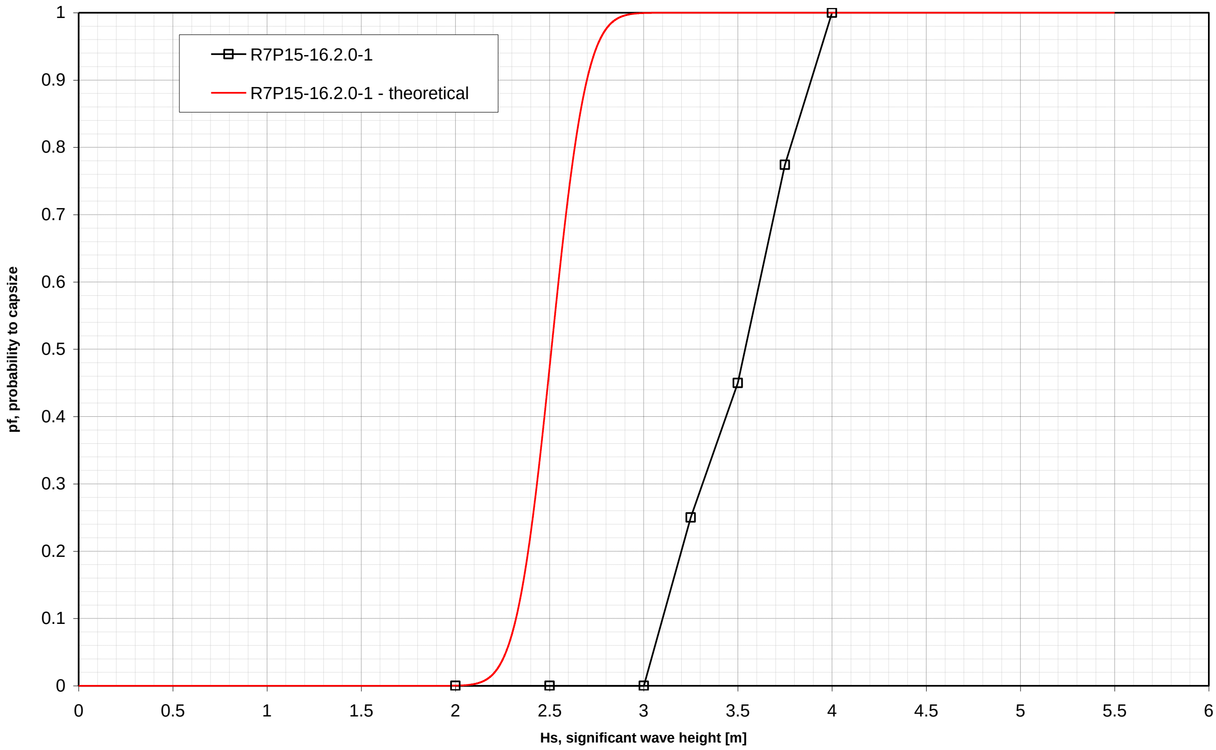


Table 19 - Summary results of physical model experiments for SHIP 4

Damage R7_P8-9.3.0
TOTAL RUNS 93
Survival Boundary 2.75m

Hs	Runs	Capsizes	pf
1.5m	5	2	0.4
1.75m	5	0	0
2m	5	2	0.4
2.25m	10	3	0.3
2.5m	5	0	0
2.75m	15	2	0.133333333
2.9m	23	11	0.47826087
3m	15	15	1
3.5m	5	5	1
4m	5	5	1

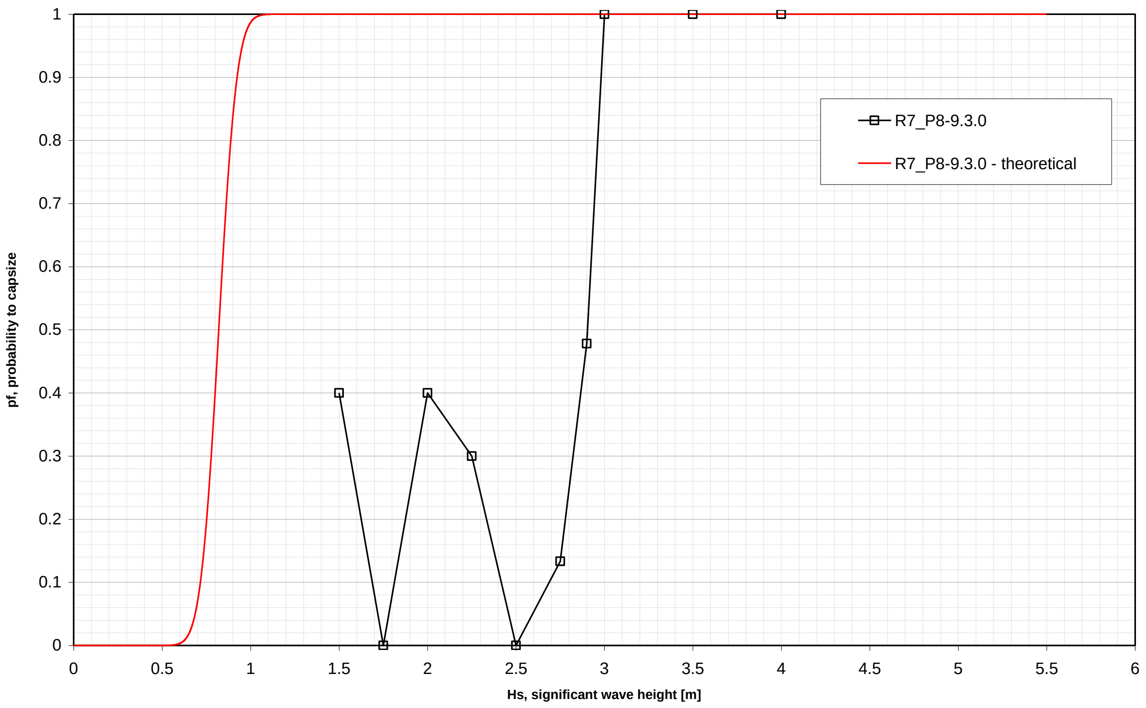


Table 20 - Summary results of physical model experiments for SHIP 4 modified

Ship 4

Damage R7M4_P7-8.3.0

Run	Wave Height Target	Wave Height Measured	Result	Time to capsize	Comment	SVA RUN NUMBER	Date
1	4.0m	4.0800m	Survive	N/A		2461A-29965-01	08/02/2011
2	4.0m	4.0523m	Survive	N/A		2461A-29965-02	08/02/2011
3	4.0m	4.0542m	Survive	N/A		2461A-29965-03	08/02/2011
4	4.0m	4.0557m	Survive	N/A		2461A-29965-04	08/02/2011
5	4.0m	4.0326m	Survive	N/A		2461A-29965-05	08/02/2011
6	4.0m	4.0495m	Survive	N/A		2461A-29965-06	08/02/2011
7	4.0m	4.0490m	Survive	N/A		2461A-29965-07	08/02/2011
8	4.0m	4.0371m	Survive	N/A		2461A-29965-08	08/02/2011
9	4.0m	4.0500m	Survive	N/A		2461A-29965-09	08/02/2011
10	4.0m	4.0523m	Survive	N/A		2461A-29965-10	08/02/2011

Damage R7M4_P7-8.3.0
TOTAL RUNS 10
Survival Boundary >4.0m

Table 21 - Summary results of physical model experiments for all ships tested

Phase 1 2010

	DAM	SIDE	T	TR	HEEL	GZMAXR	RANGEF	AGZR	RESMRG	XRESMRG	K	si (no K factor)	K*s	Htheo, 0.12m, 16deg	Htheo, 0.25m, 25deg	Hcrit
SHIP1	R7_P6-7.4.0	PS	5.545	1.054	-1.3	0.072	7.79	0.00669	0.513	-2.1	1	0.7352	0.7352	1.17	0.36	**3.6**
SHIP1	R7_S7-9.1.0-1	SB	5.123	-0.201	0.9	0.093	19.14	0.01925	1.517	78.61	1	0.9383	0.9383	3.71	1.14	**4**
											1					
SHIP3	R7P15-16.1.0	PS	7.282	1.111	3.2	0.154	11.36	0.01855	-	-	1	0.9179	0.9179	3.64	1.12	No capsize
SHIP3	R7P15-16.1.0	PS				0.12	10.025	0.013			1	0.8897	0.8897	2.51	0.77	**3.55**
											1					
SHIP4	R7_P8-9.3.0	PS	8.289	1.413	7.8	0.046	8.52	0.00433	-	-	0.948683298	0.6722	0.6377	0.82	0.25	**2.9**

Phase 2 2011

Ship1	R7M2_P5-7.4.0-1	PS	5.261	2.931	-24.721	0.066568	18.635326				0	0.8630	0.0000	2.58	0.79	no stable position
Ship1	R7M2_P4-6.1.0-1	SB	5.128	1.571	0	0.282816	50.000038				1	1.0000	1.0000	29.46	9.05	**over 4m**
Ship4	REG7_P7-8.3.0	PS	8.248	0.185	8.85357	0.853803	20.915009				0.876529449	1.0000	0.8765	37.20	11.43	**over 4m**

5.2.5. Numerical Simulations

An extensive series of numerical simulations were performed, to provide additional evidence on the expected behaviour of ships in a flooding accident.

The key technique employed was that of solving the numerical problem of ship stability in waves using the Monte-Carlo simulation, whereby a set of key random variables describing accidents characteristics, are sampled from respective probability distributions, see Figure 104, and the requisite response is simulated in a time domain, aiming to construct the statistic given by model (28) and given below for reference:

$$A|T = \int_{\Omega} \int_{Hs=0}^{\infty} d\Omega \cdot dHs \cdot f_{Hs|coll}(Hs) \cdot f_{\lambda}(\lambda) \cdot f_{X|\lambda}(x|\lambda) \cdot f_{B|x}(b|x) \cdot f_H(h) \cdot F_D(t_0|x,\lambda,b,h,T,Hs) \quad (65)$$

The overall results are summarised in Table 14 and Figure 77. The simulations are typically performed for a 30-minute duration.

It transpires from these results that the overall impression of survivability is confirmed. The proportion of dangerous flooding cases that can occur, as is internationally agreed, since the requisite probability assigned to them is greater than zero, is of the order of (1-A) x 100%, and which typically reaches the order of 10%-30% in absolute magnitude.

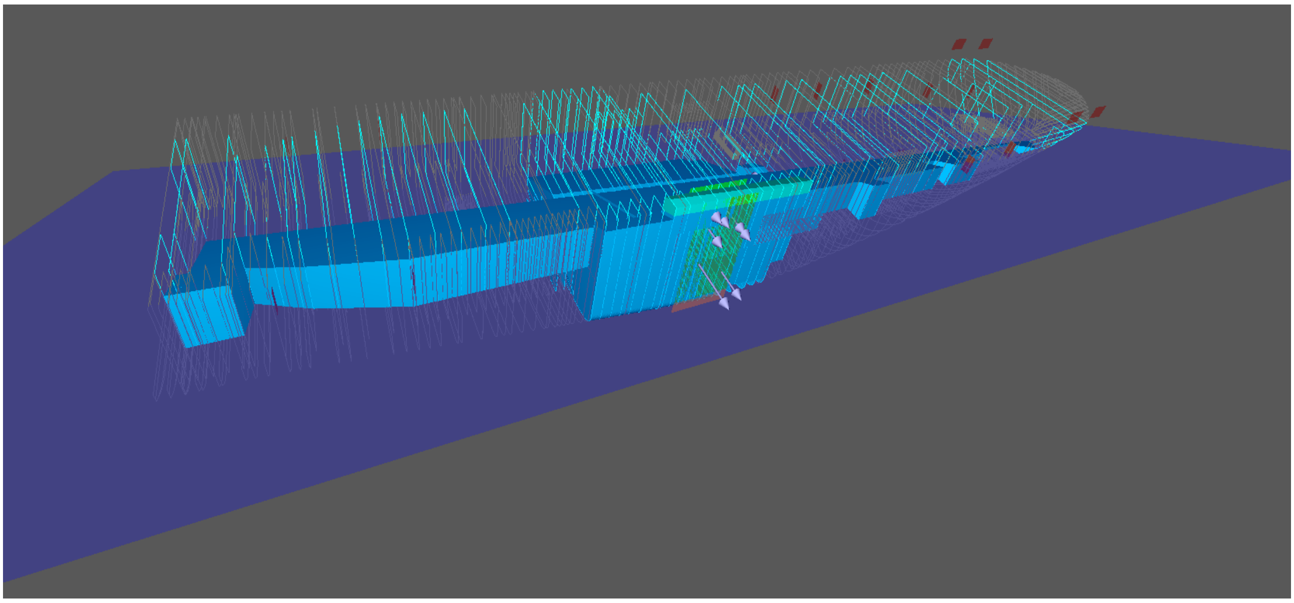


Figure 105 - Sample animation of simulation results for SHIP 1, case DS/R7_P6-7.4.0

Table 22 - Summary results of survivability assessed for single flooding case for SHIP 1, case DS/R7_P6-7.4.0

Hs	No. of Sims	Capsizes	(pf)DS
2.00	10	0	0
2.25	10	0	0
2.50	10	0	0
2.75	10	0	0
3.00	10	1	0.100
3.25	10	7	0.700
3.50	10	10	1
3.75	10	10	1
4.00	10	10	1

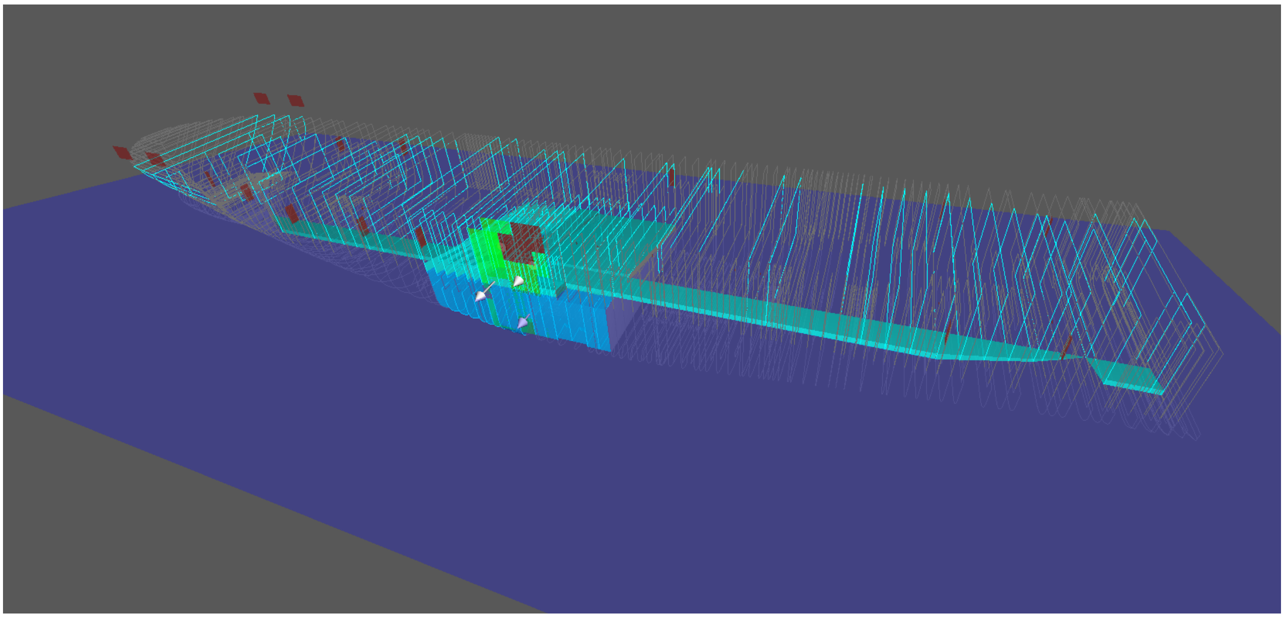
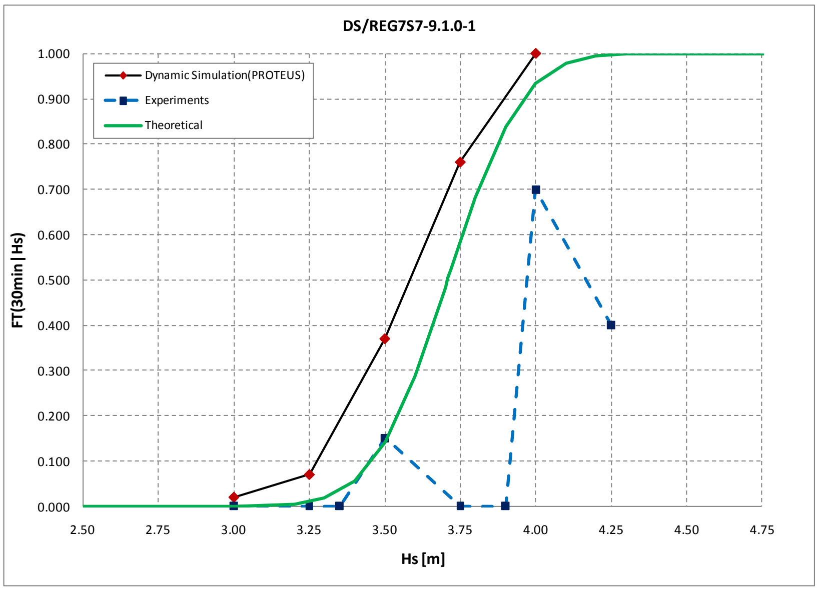


Figure 106 - Sample animation of simulation results for SHIP 1, case DS/R7_S7-9.1.0-1

Table 23 - Summary results of survivability assessed for single flooding case for SHIP 1, case DS/R7_S7-9.1.0-1

Hs	No. of Sims	Capsizes	(pf)DS
3.00	100	2	0.020
3.25	100	7	0.070
3.50	100	37	0.370
3.75	100	76	0.760
4.00	100	100	1.000



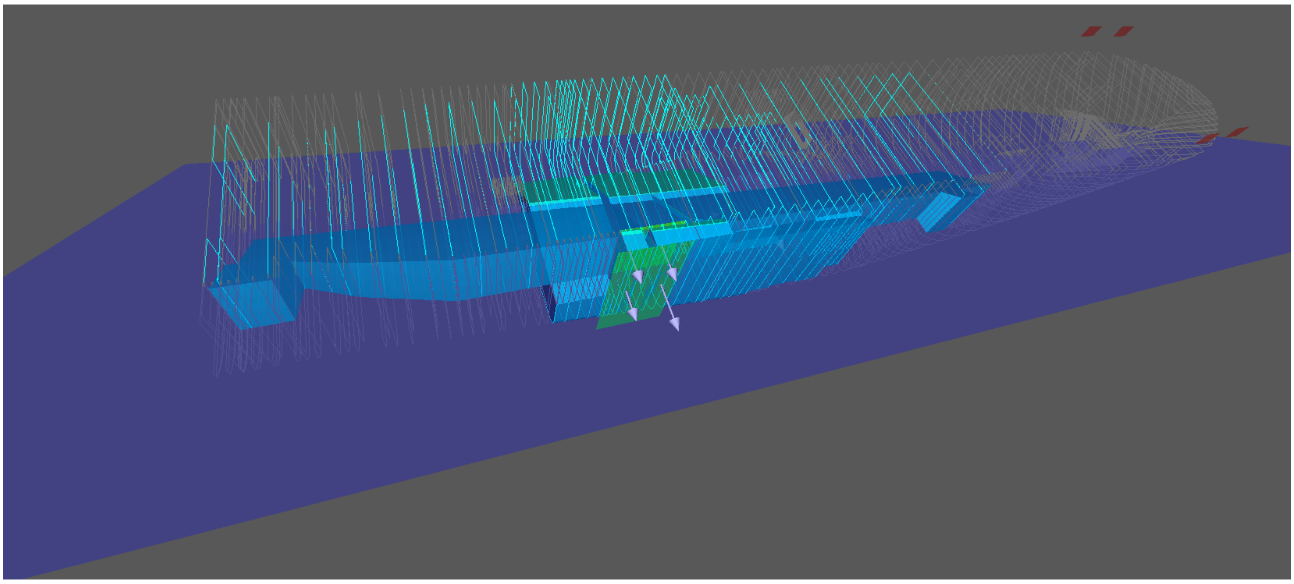


Figure 107 - Sample animation of simulation results for SHIP 1 modified, case DS/R7MOD2_P5-7.4.0-1

Table 24 - Summary results of survivability assessed for single flooding case for SHIP 1 modified, case DS/R7MOD2_P5-7.4.0-1

Case No.	Hs	No. of Sims	Capsizes	(pf)DS
1	3.50	10	10	1
2	3.75	10	10	1
3	4.00	10	10	1
4	4.25	10	10	1

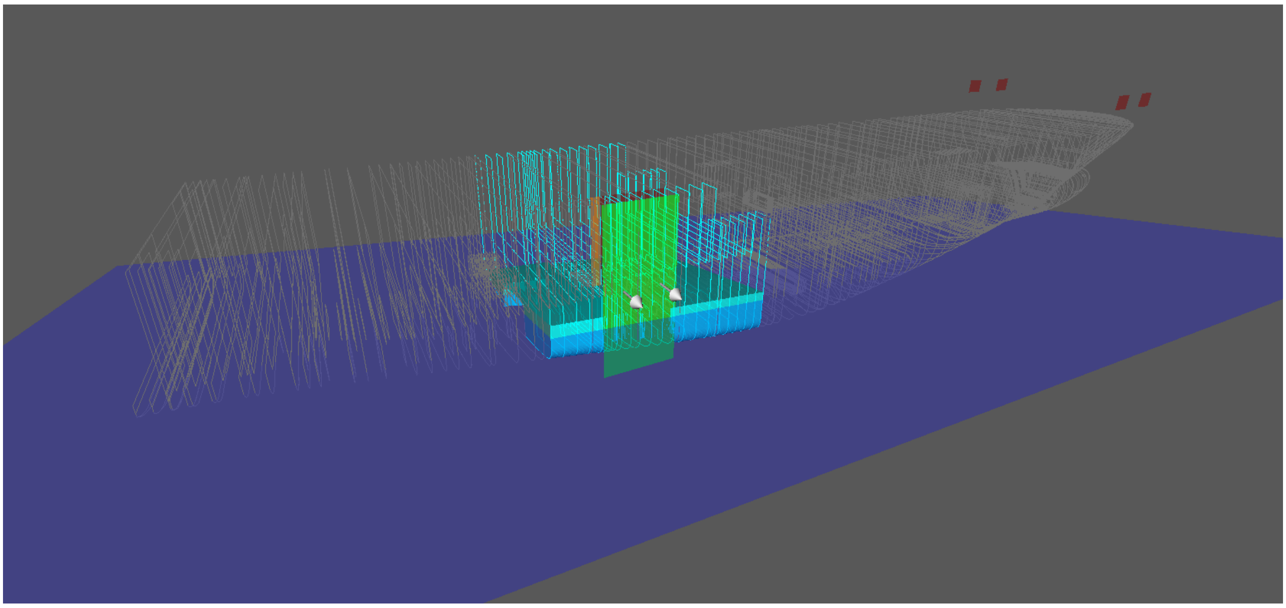


Figure 108 - Sample animation of simulation results for SHIP 1 modified, case DS/R7MOD2_P4-6.1.0-1

Table 25 - Summary results of survivability assessed for single flooding case for SHIP 1 modified, case DS/R7MOD2_P4-6.1.0-1

Hs	No. of Sims	Capsizes	(pf)DS
3.50	20	0	0.000
3.75	20	0	0.000
4.00	20	0	0.000
4.25	20	0	0.000
4.50	20	0	0.000

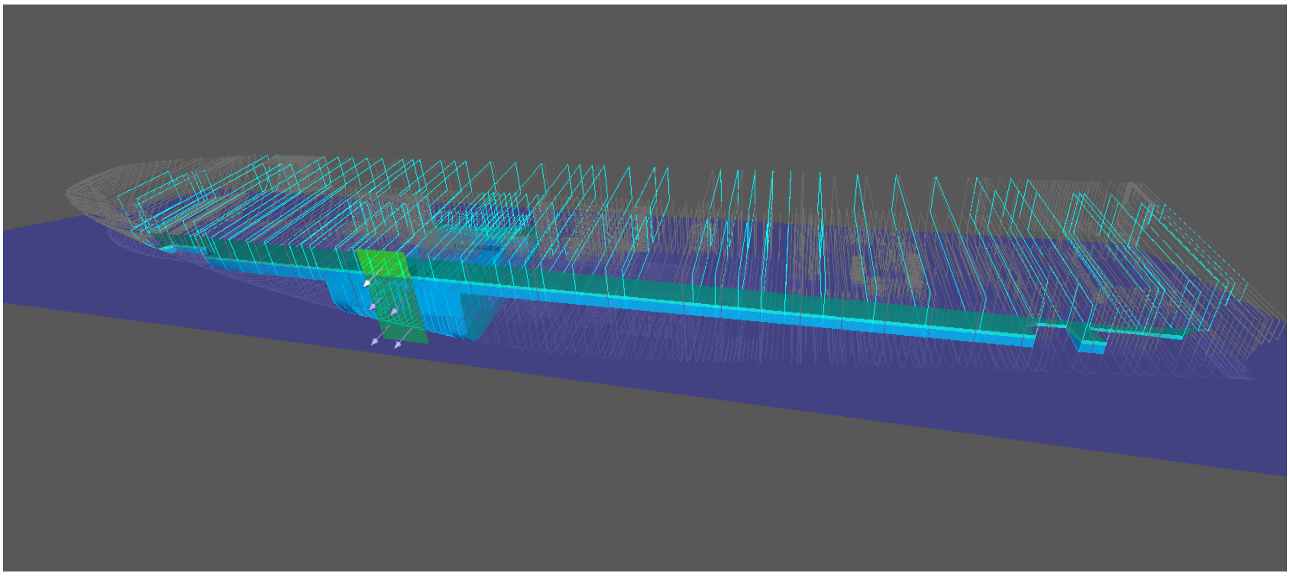
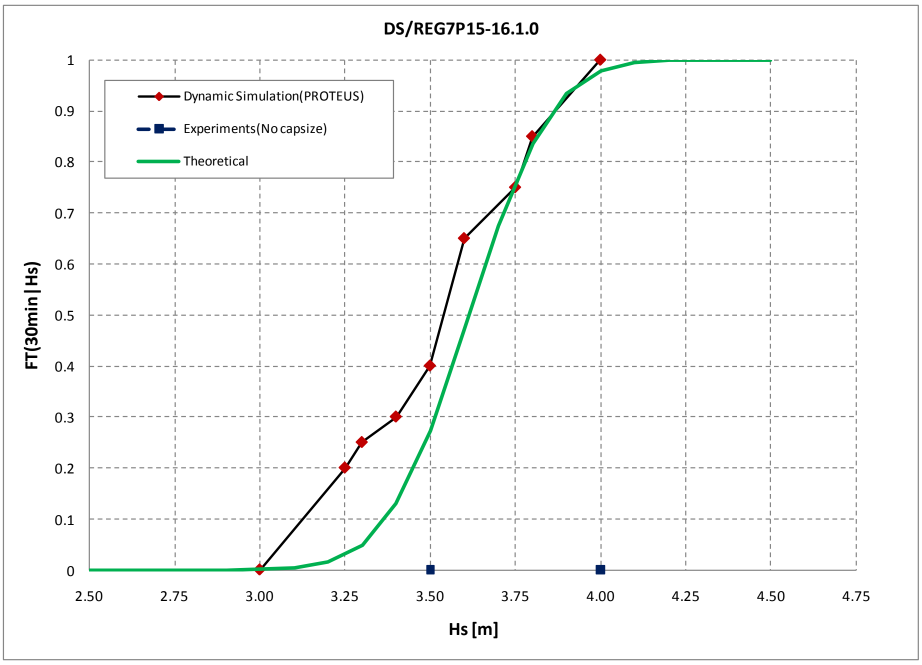


Figure 109 - Sample animation of simulation results for SHIP 3, case DS/R7_P15-16.1.0

Table 26 - Summary results of survivability assessed for single flooding case for SHIP 3, case DS/R7_P15-16.1.0

Hs	No. of Sims	Capsizes	(pf)DS
3.00	20	0	0
3.25	20	4	0.20
3.3	20	5	0.25
3.40	20	6	0.30
3.50	20	8	0.40
3.60	20	13	0.65
3.75	20	15	0.75
3.80	20	17	0.85
4.00	20	20	1



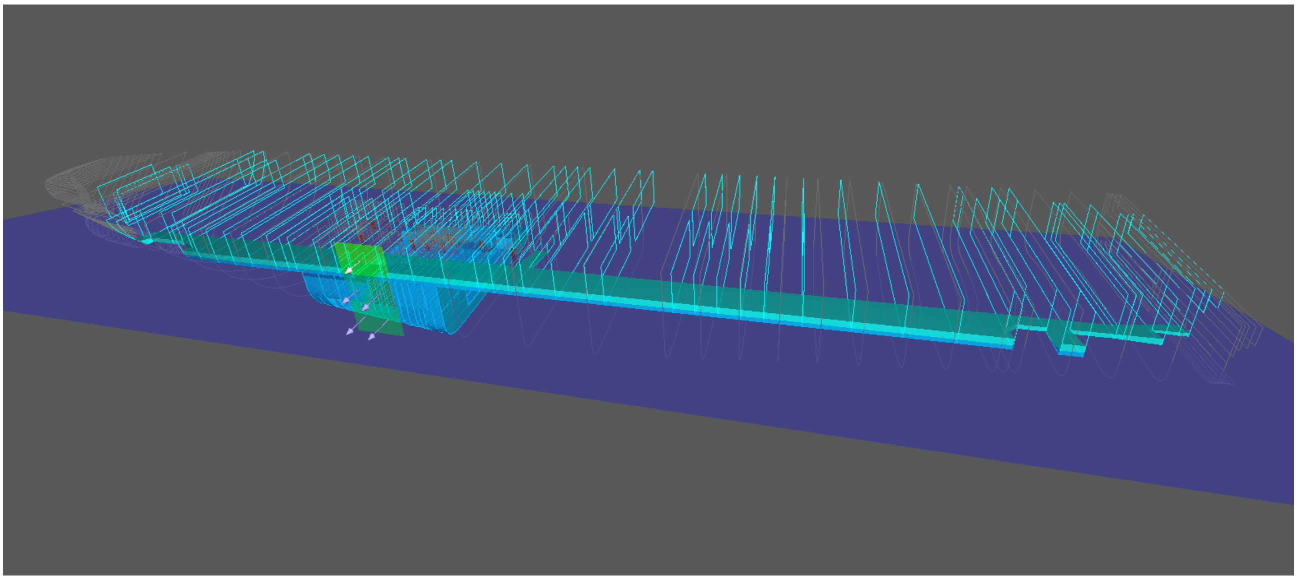
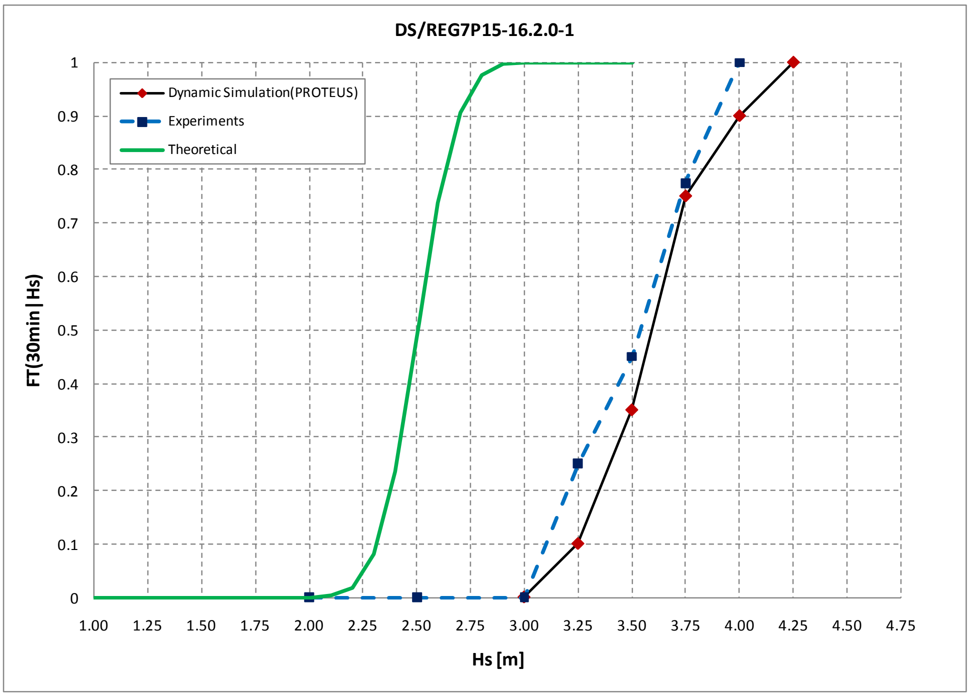


Figure 110 - Sample animation of simulation results for SHIP 3, case DS/R7_P15-16.2.0-1

Table 27 - Summary results of survivability assessed for single flooding case for SHIP 3, case DS/R7_P15-16.2.0-1

Hs	No. of Sims	Capsizes	(pf)DS
3.00	20	0	0
3.25	20	2	0.1
3.50	20	7	0.35
3.75	20	15	0.75
4.00	20	18	0.9
4.25	20	20	1



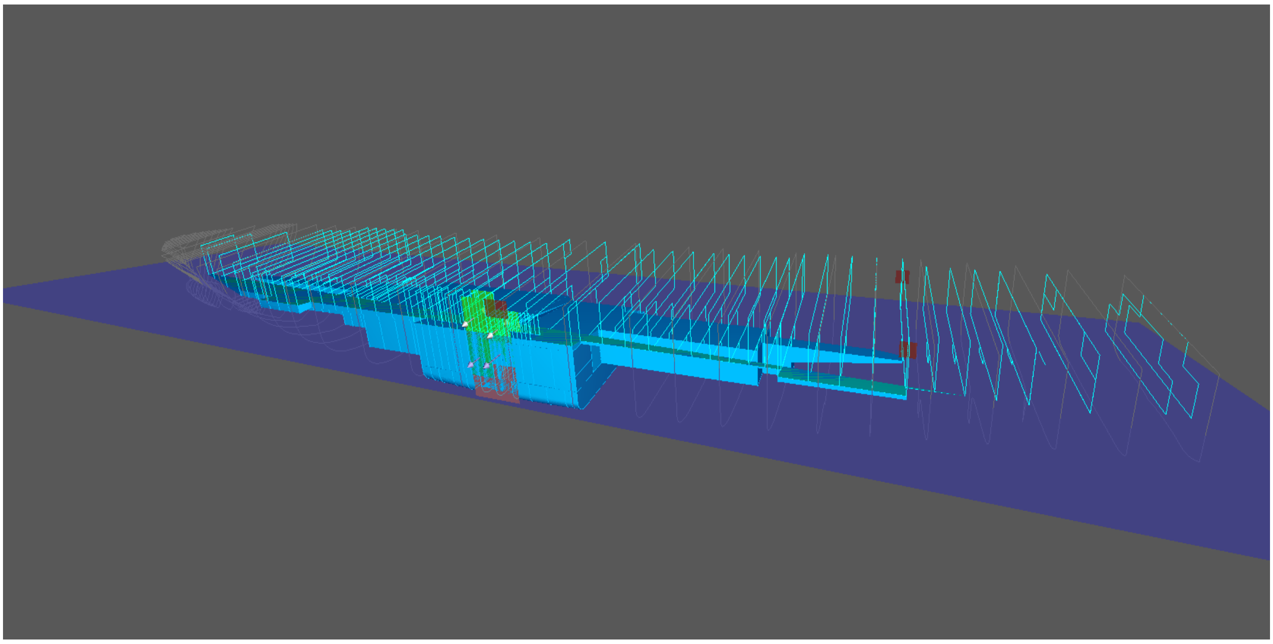
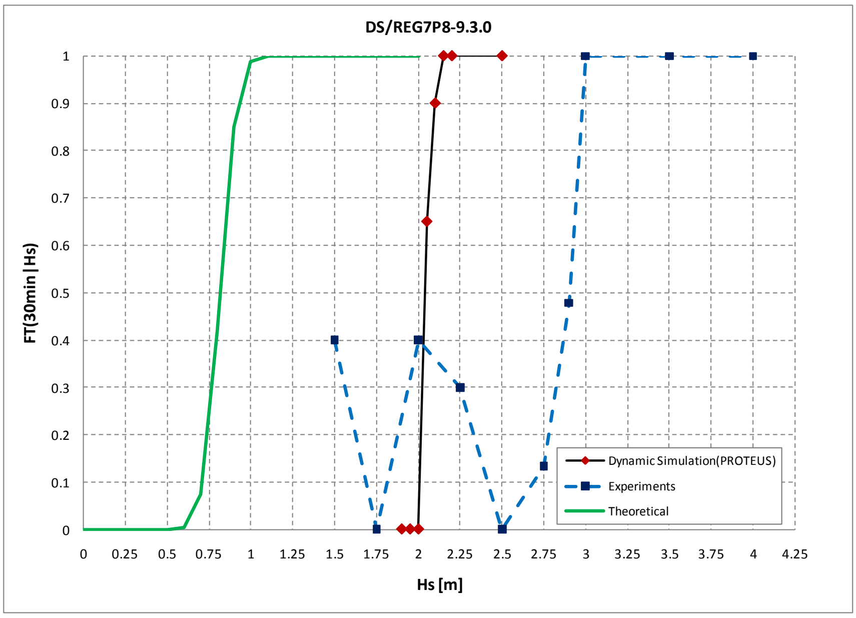


Figure 111 - Sample animation of simulation results for SHIP 4, case DS/R7_P8-9.3.0

Table 28 - Summary results of survivability assessed for single flooding case for SHIP 4, case DS/R7_P8-9.3.0

Hs	No. of Sims	Capsizes	(pf)DS
1.9	20	0	0
1.95	20	0	0
2	20	0	0
2.05	20	13	0.65
2.10	20	18	0.9
2.15	20	20	1
2.20	20	20	1
2.50	20	20	1



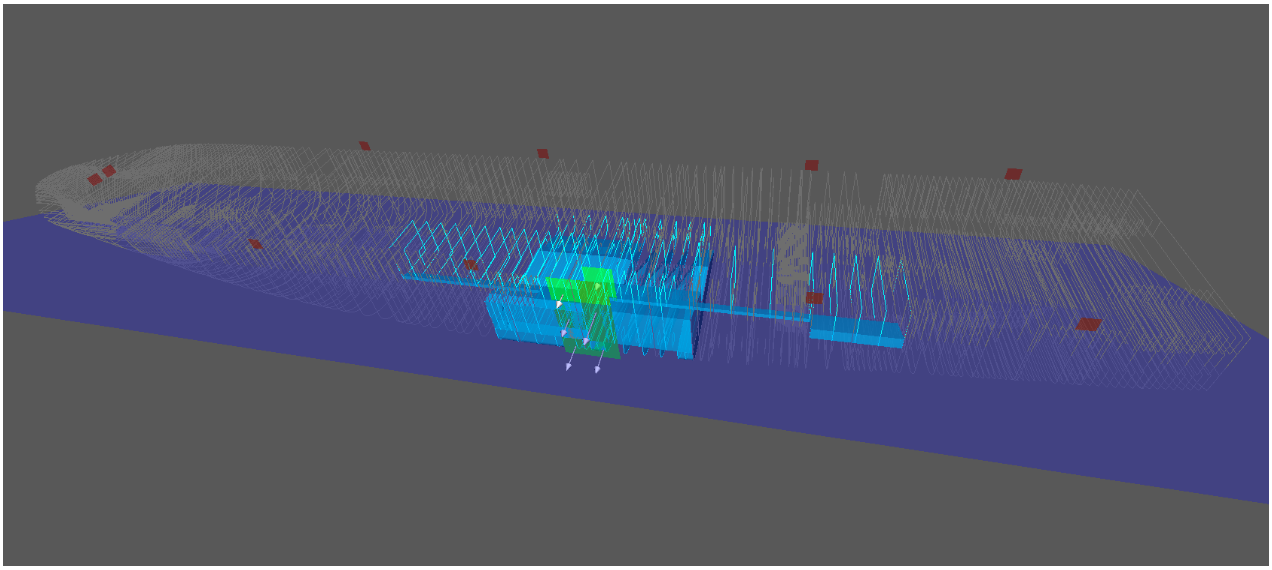


Figure 112 - Sample animation of simulation results for SHIP 4 modified, case DS/R7MOD4_P7-8.3.0

Table 29 - Summary results of survivability assessed for single flooding case for SHIP 4 modified, case DS/R7MOD4_P7-8.3.0

Hs	No. of Sims	Capsizes	(pf)DS
3.75	10	0	0.000
4.00	10	0	0.000
4.25	10	0	0.000
4.50	10	0	0.000

Table 30 - Summary results of assessed "global" survivability from Monte Carlo (MC) simulations

Design No.	No. of Simulation	$(1\text{-}pf)_{DS}$	$(1\text{-}pf0.005)_{DS}$	$(1\text{-}pf0.995)_{DS}$
	Hs=Random	Hs=Random	Hs=Random	Hs=Random
SHIP 1	500	0.880	0.916	0.841
SHIP 1 (MOD)	500	0.934	0.955	0.909
SHIP 2	500	0.778	0.822	0.732
SHIP 3	500	0.848	0.882	0.811
SHIP 4	500	0.882	0.914	0.847
SHIP 4 (MOD)	500	0.974	0.980	0.964
SHIP 5	500	0.898	0.931	0.862

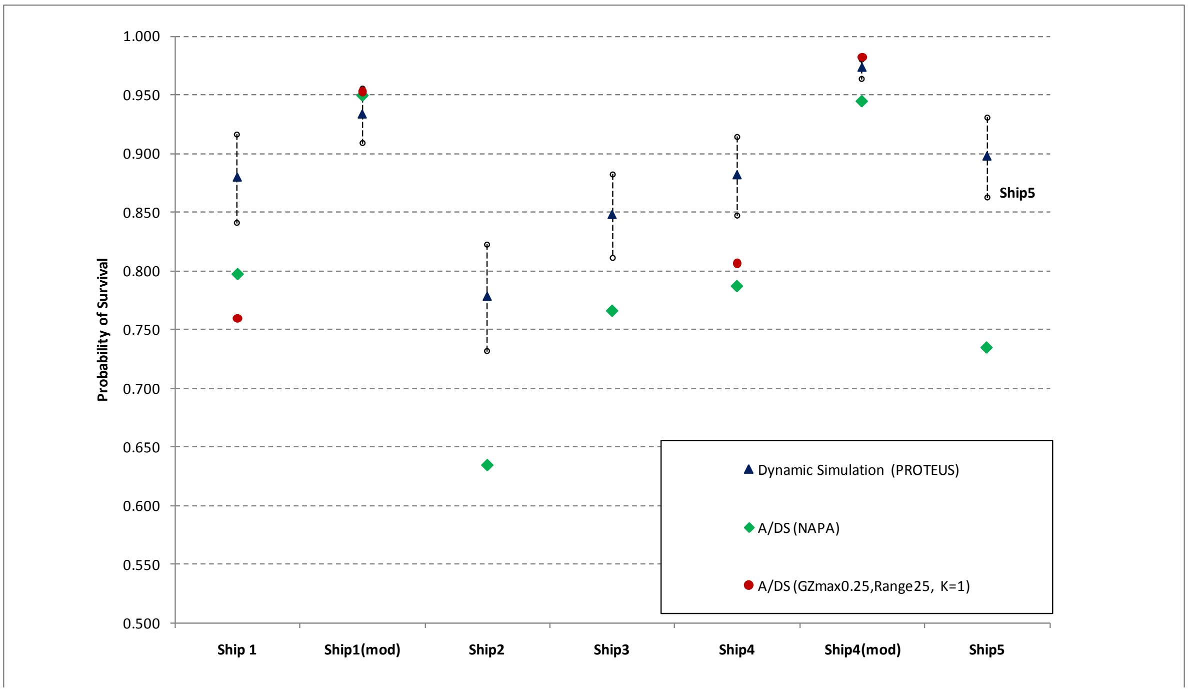


Figure 113 - Global survivability statistics from MC simulations, given in Table1

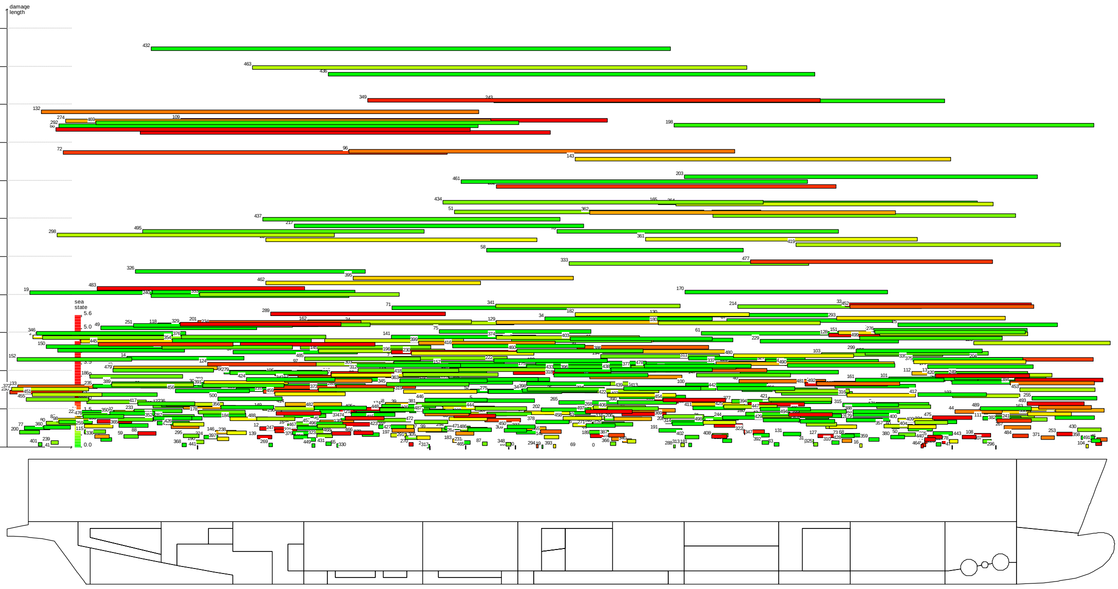


Figure 114 - Monte Carlo Simulated 500 damage cases for SHIP 1, original design

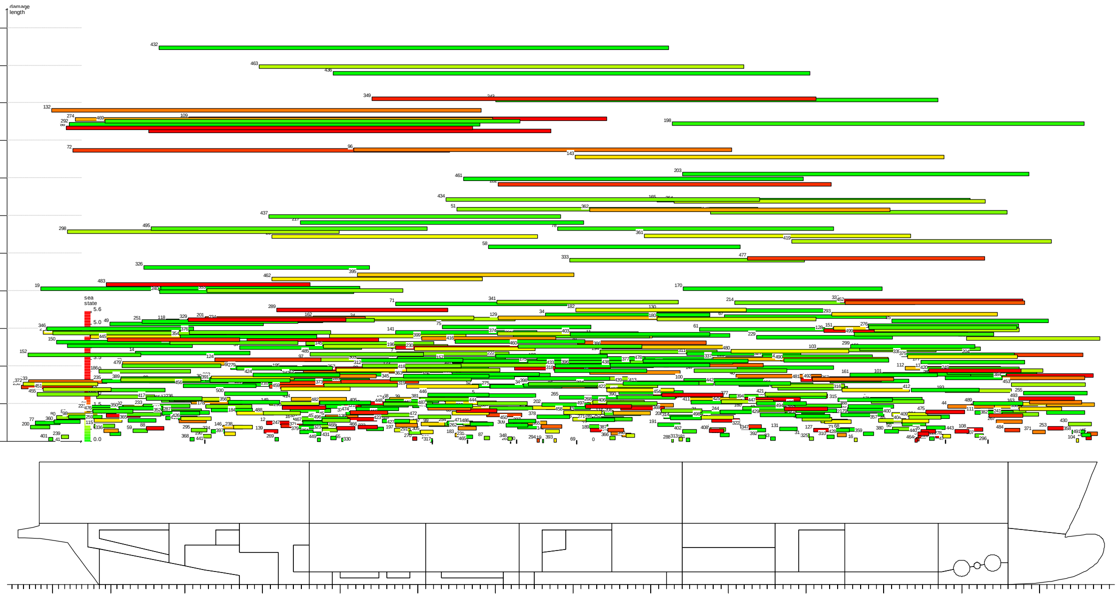


Figure 115 - Monte Carlo Simulated 500 damage cases for SHIP 1, modified design

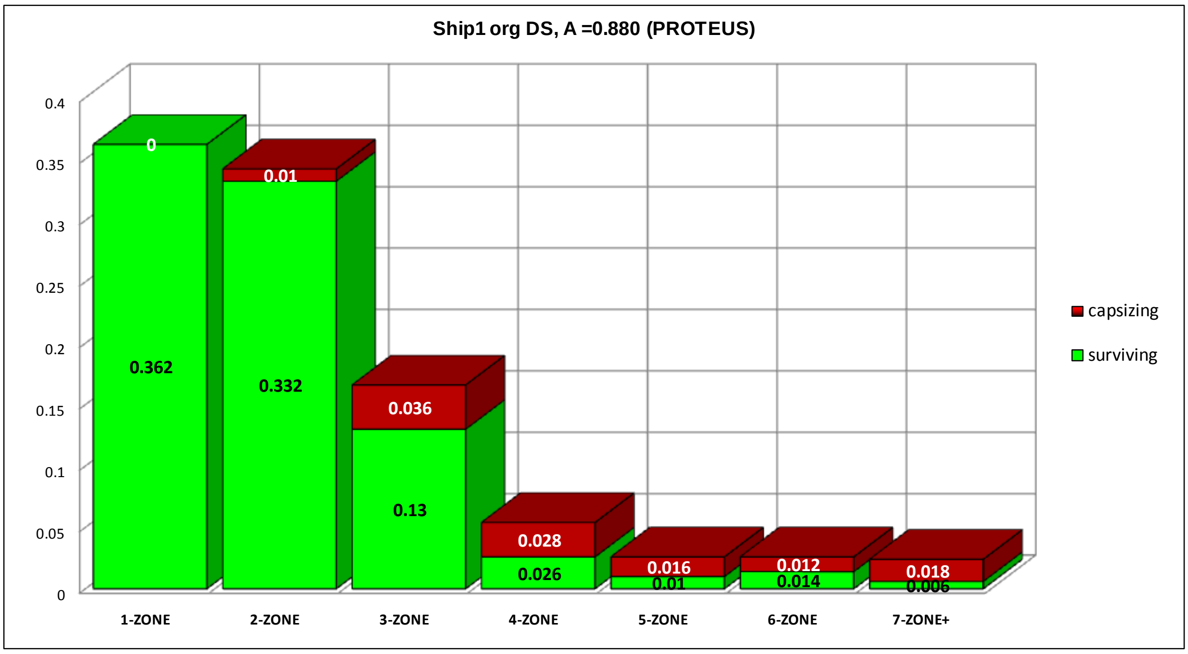


Figure 116 - Distribution of probability for surviving and capsizing (MC simulation for SHIP 1)

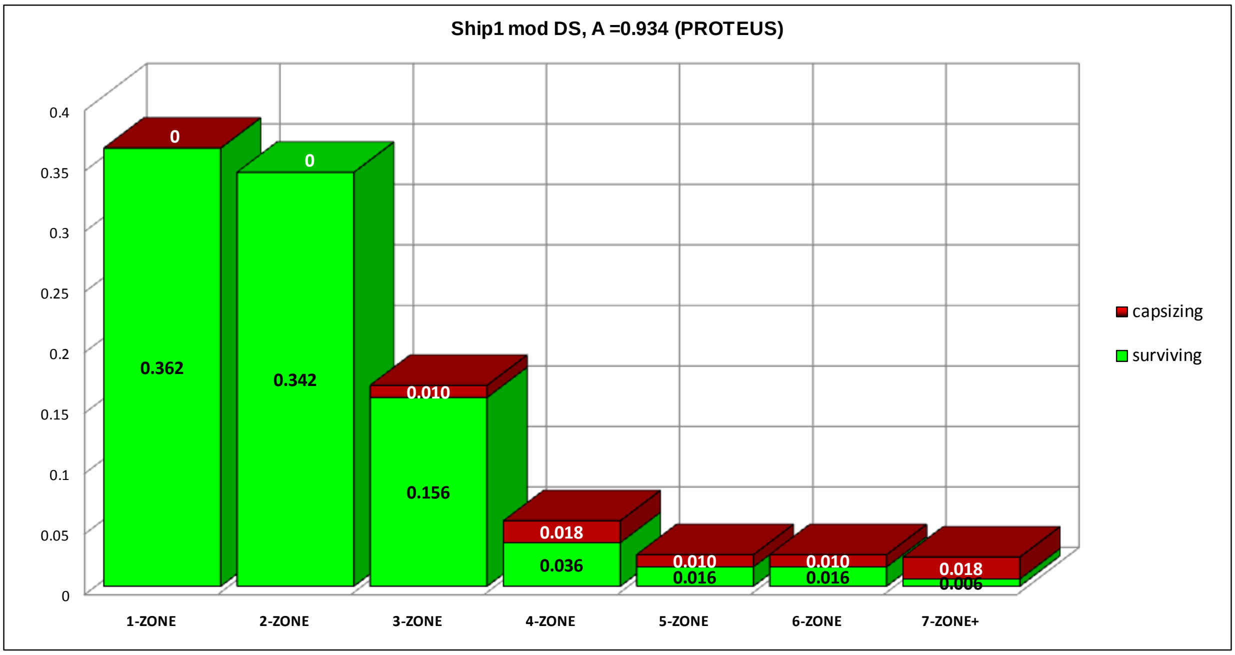


Figure 117 - Distribution of probability for surviving and capsizing (MC simulation for SHIP 1 modified)

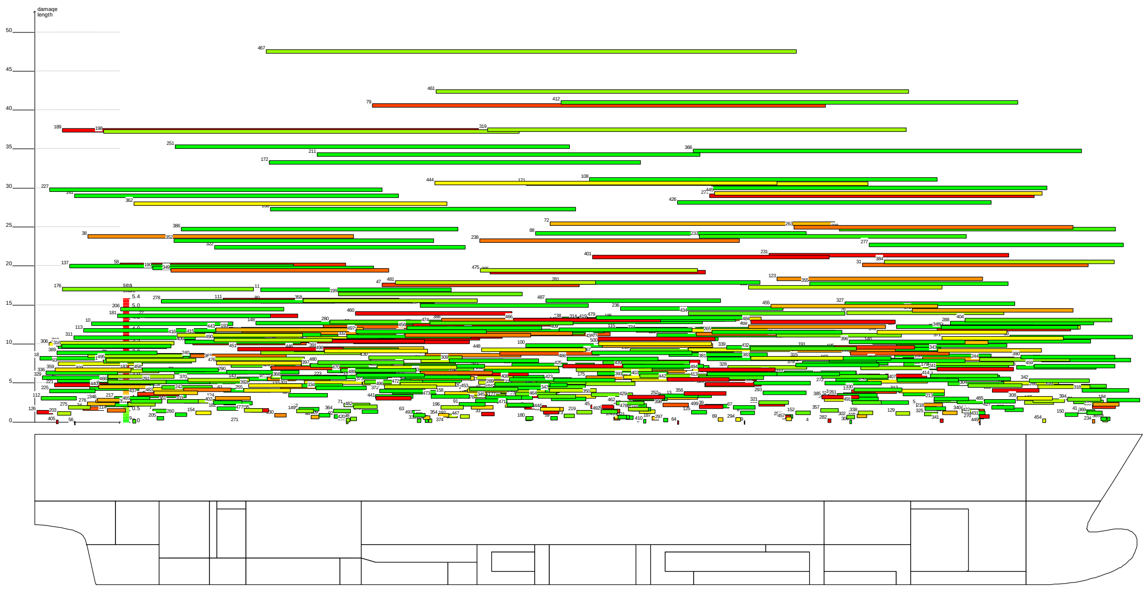


Figure 118 - Monte Carlo Simulated 500 damage cases for SHIP 2

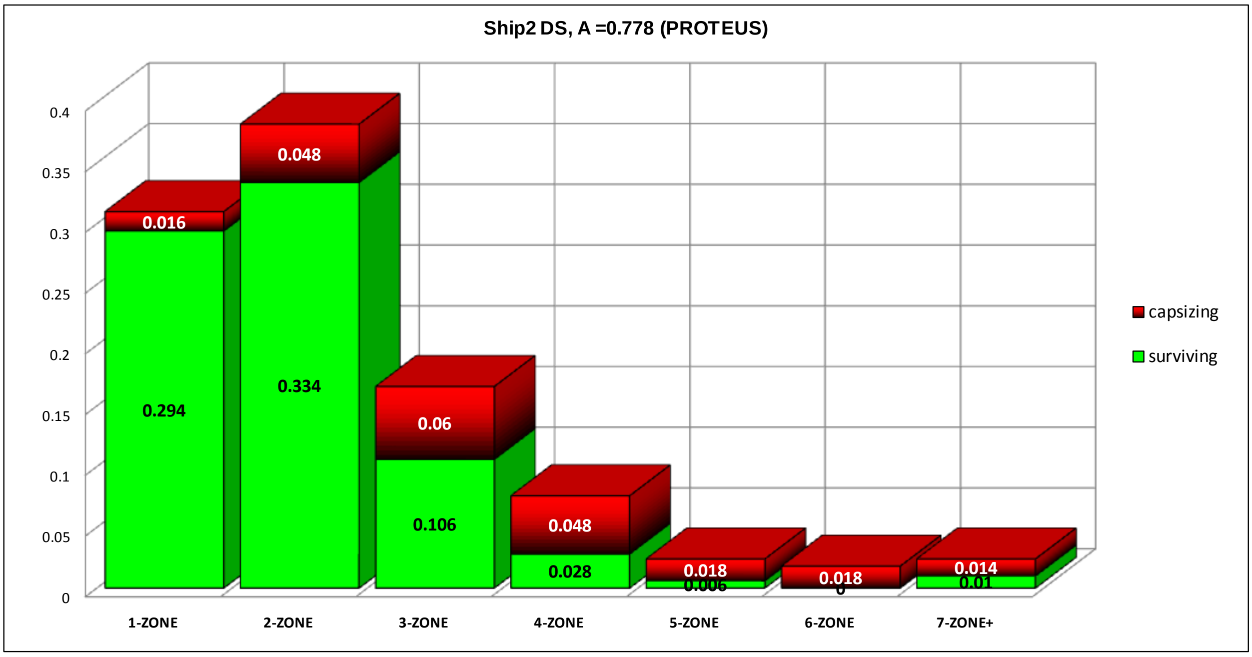


Figure 119 - Distribution of probability for surviving and capsizing (MC simulation for SHIP 2)

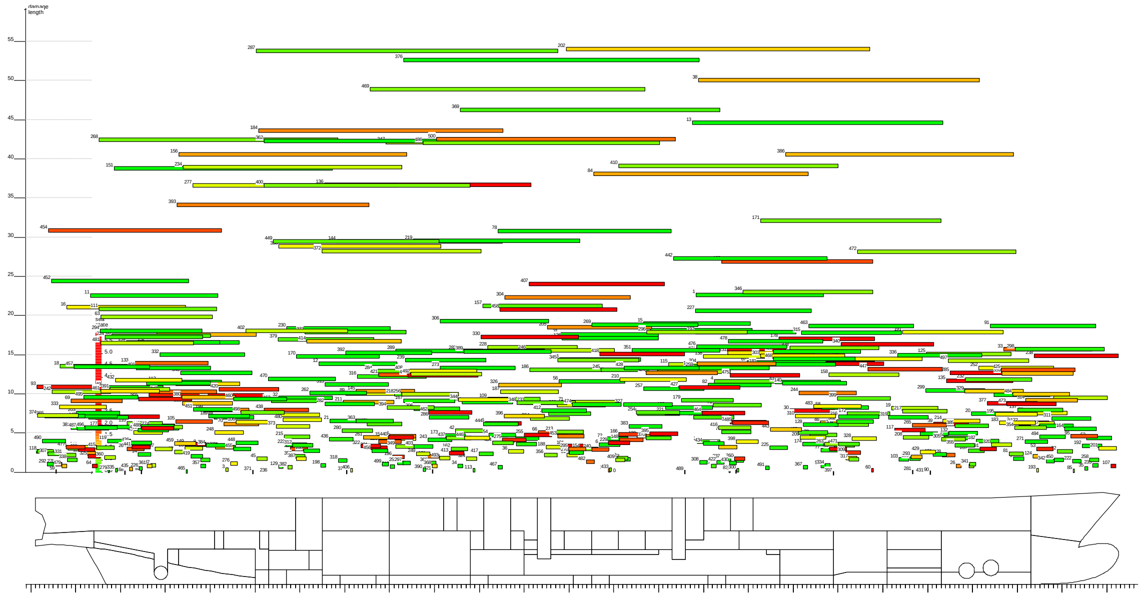


Figure 120 - Monte Carlo Simulated 500 damage cases for SHIP 3

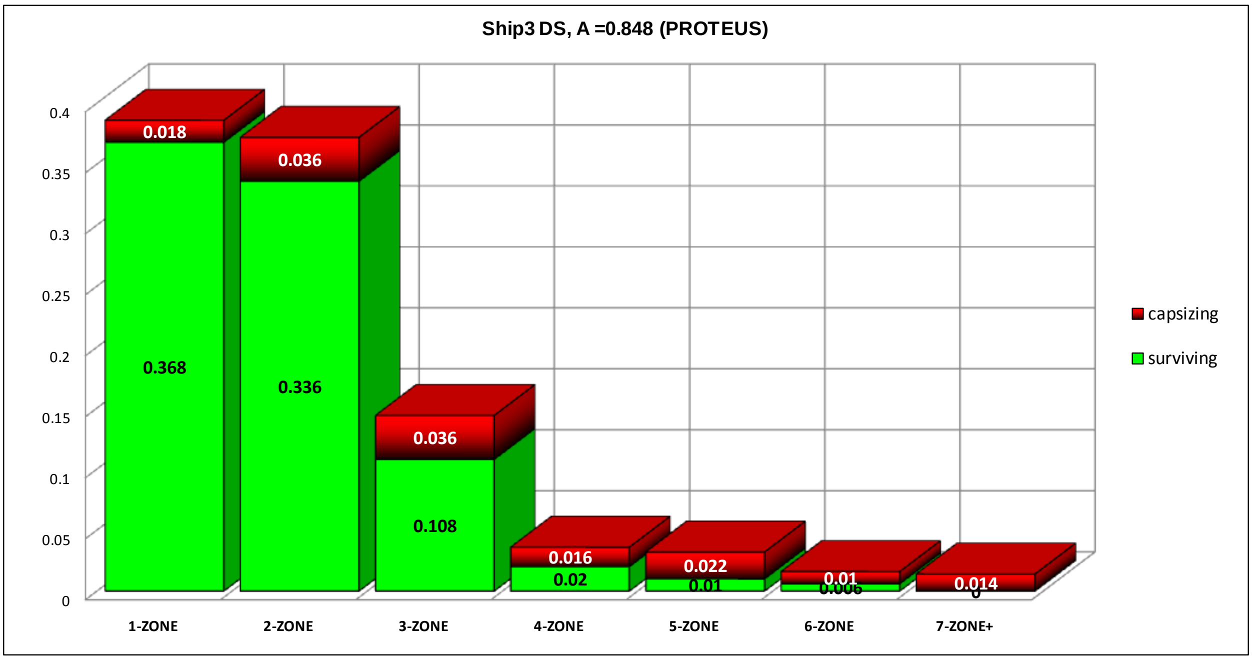


Figure 121 - Distribution of probability for surviving and capsizing (MC simulation for SHIP 3)

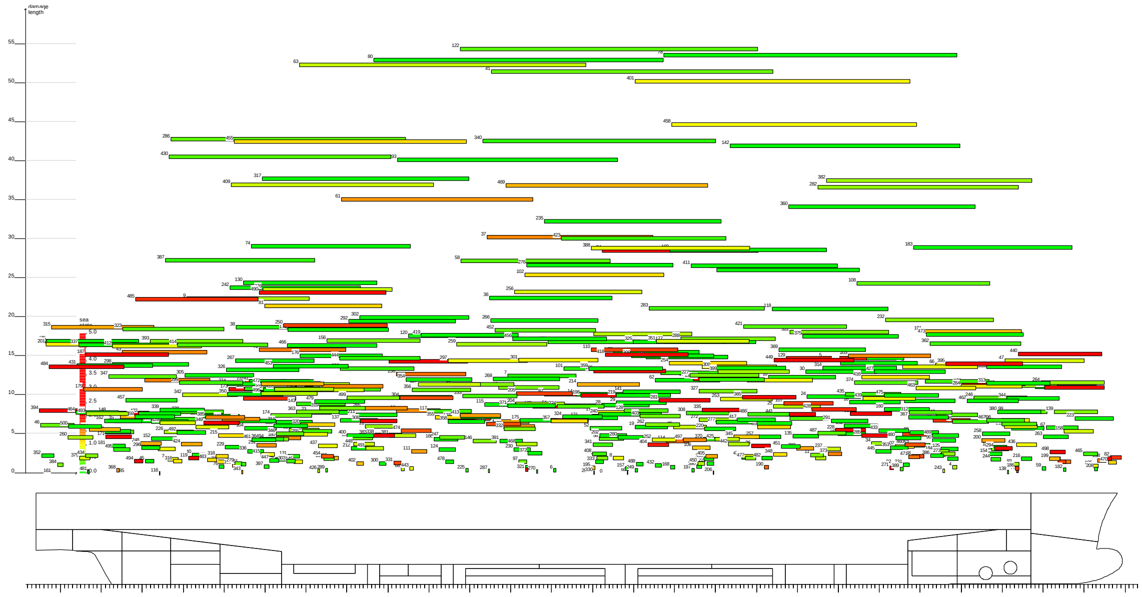


Figure 122 - Monte Carlo Simulated 500 damage cases for SHIP 4, original design

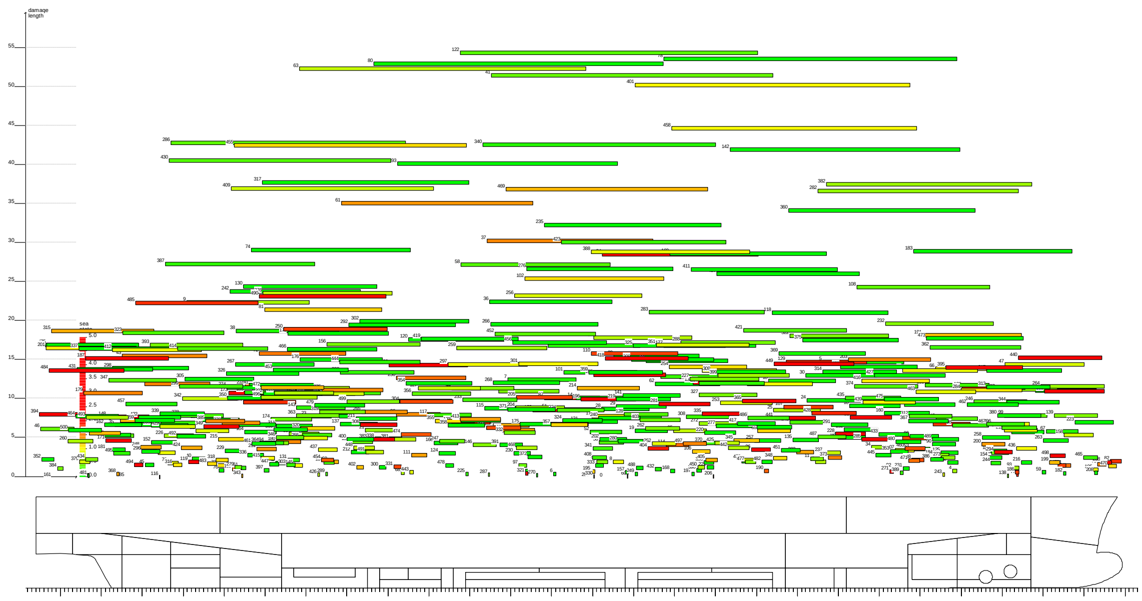


Figure 123 - Monte Carlo Simulated 500 damage cases for SHIP 4, modified design

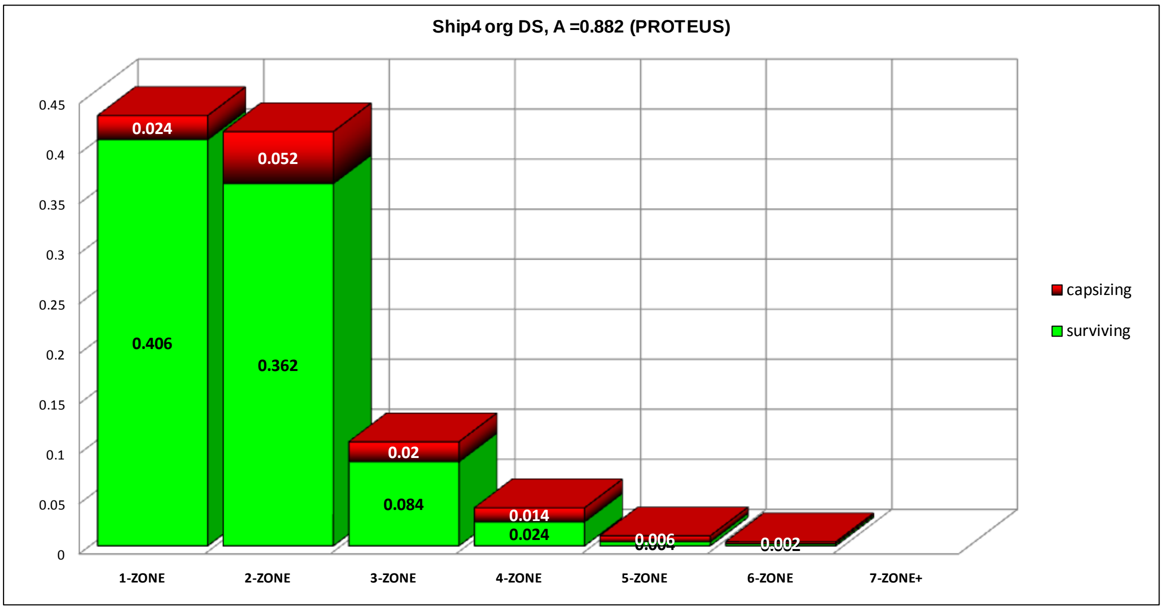


Figure 124 - Distribution of probability for surviving and capsizing (MC simulation for SHIP 4)

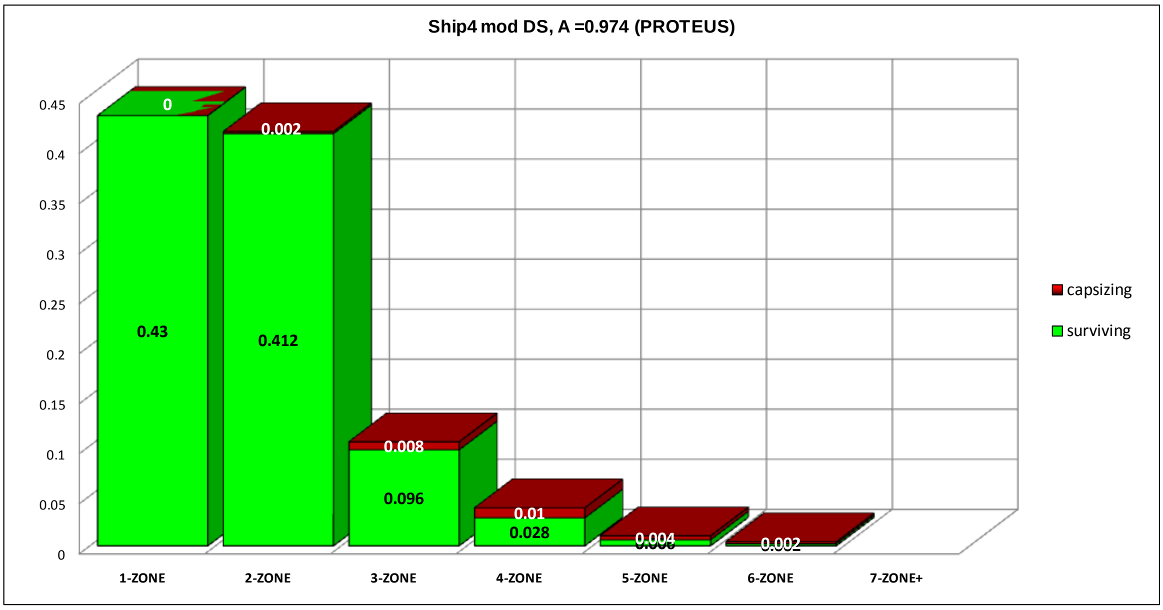


Figure 125 - Distribution of probability for surviving and capsizing (MC simulation for SHIP 1 modified)

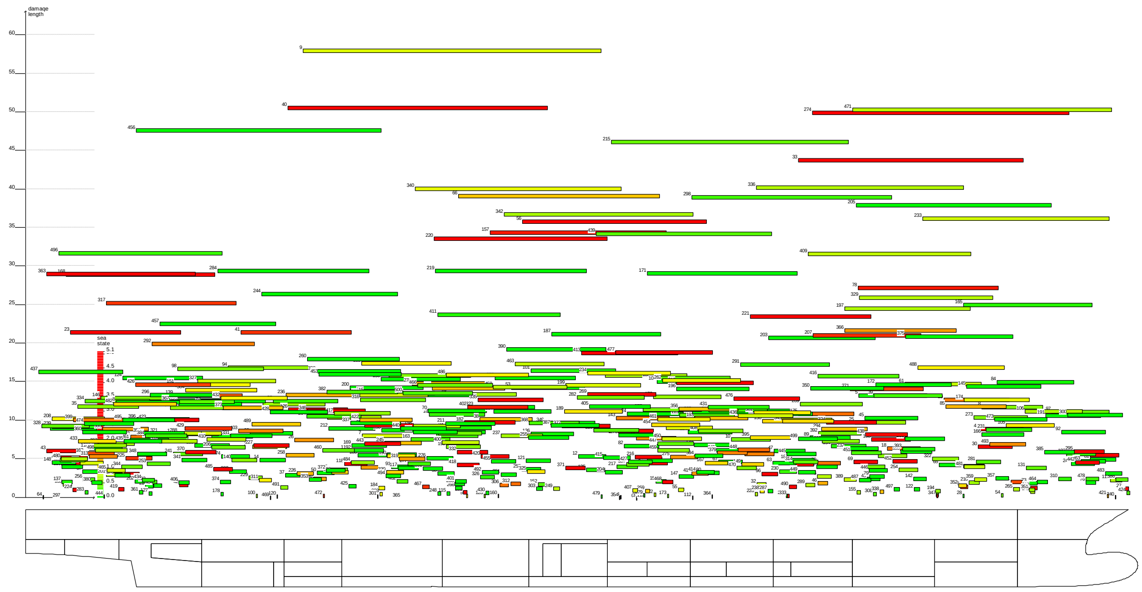


Figure 126 - Monte Carlo Simulated 500 damage cases for SHIP 5

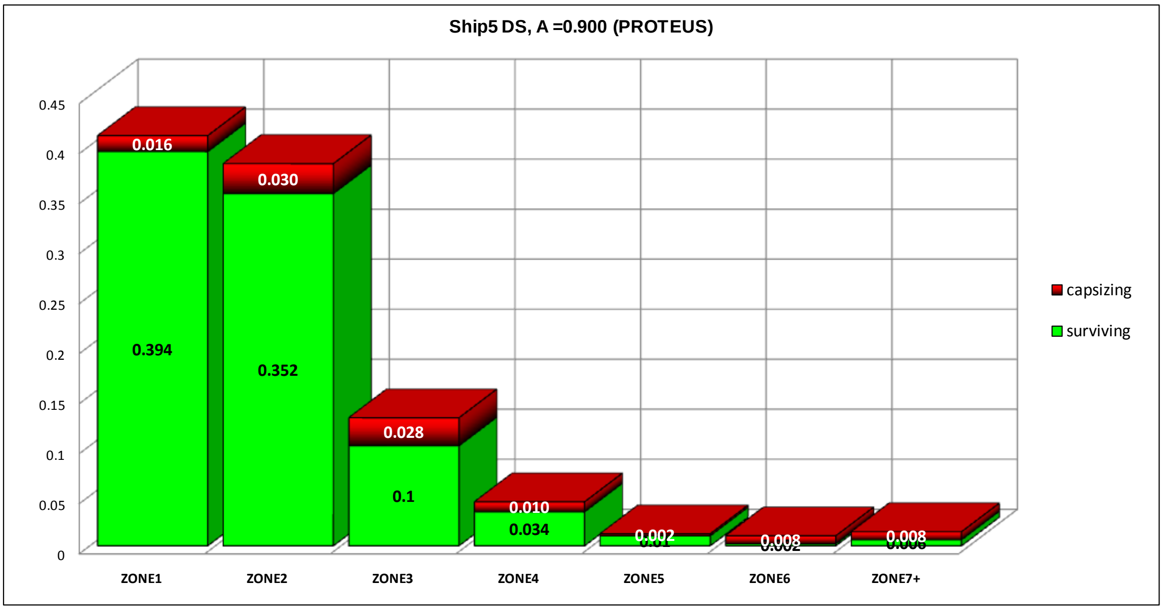


Figure 127 - Distribution of probability for surviving and capsizing (MC simulation for SHIP 5)

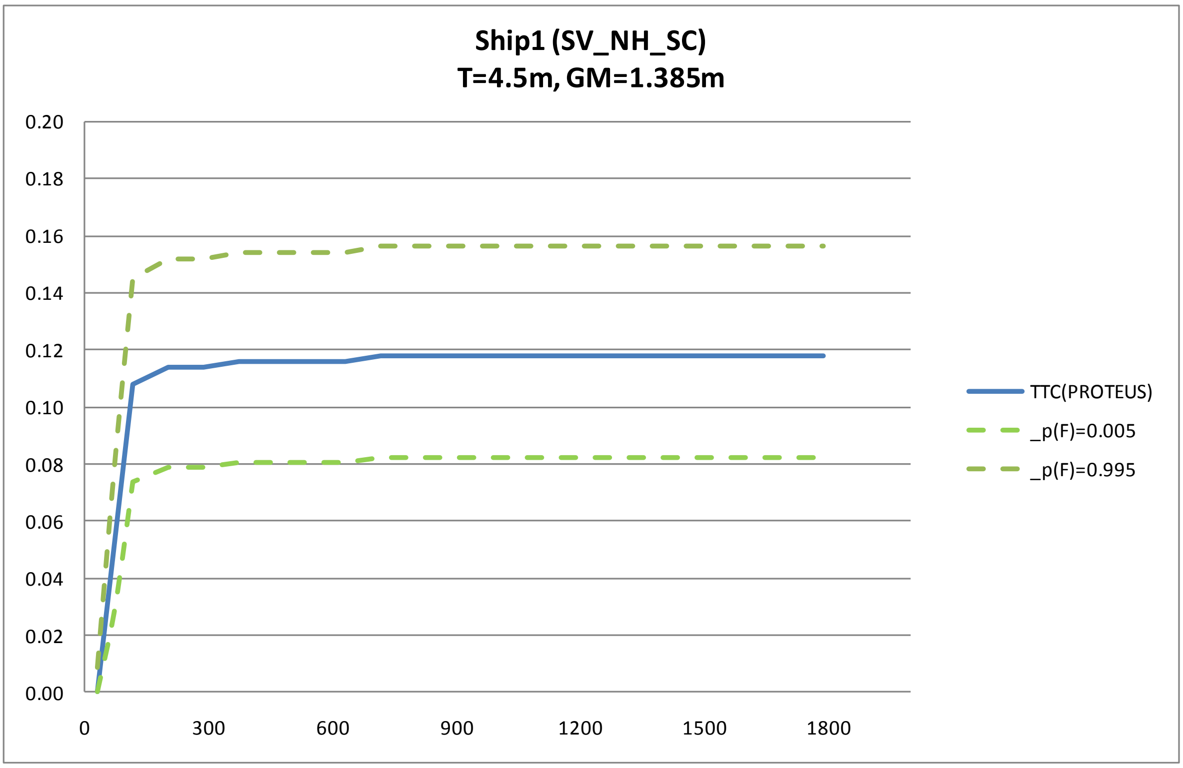


Figure 128 - Monte Carlo simulation results for SHIP 1

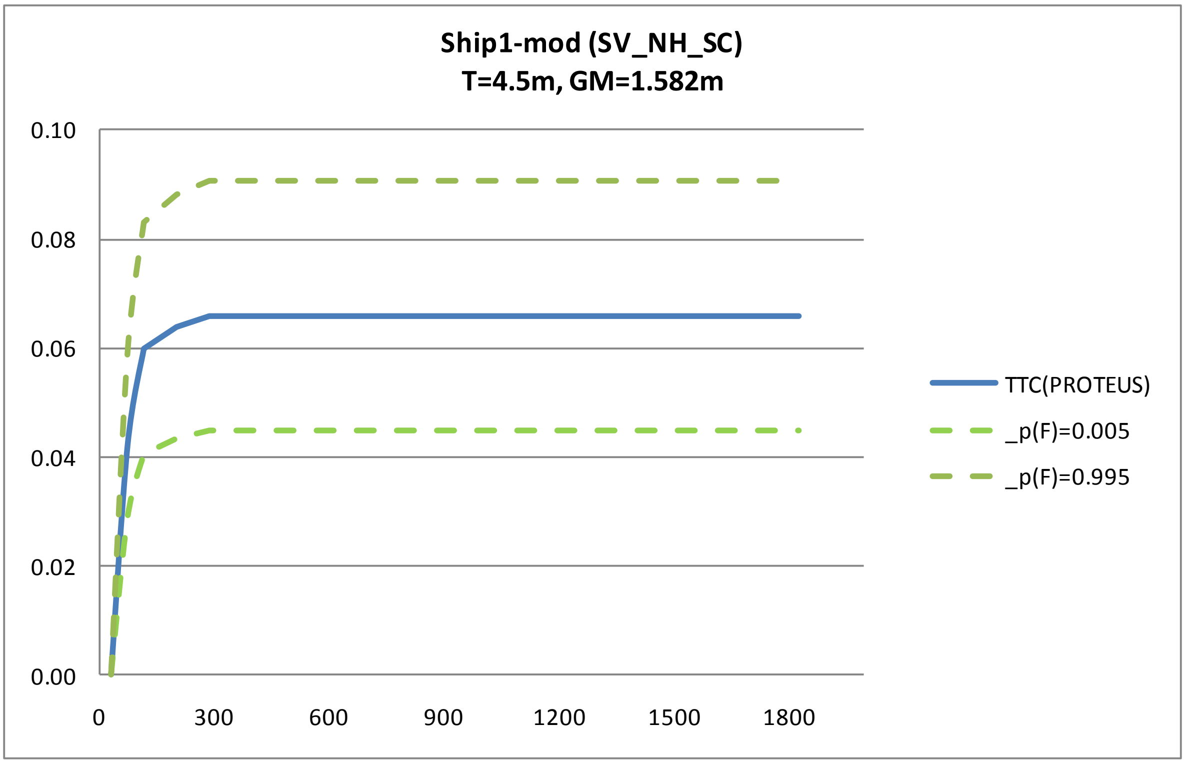


Figure 129 - Monte Carlo simulation results for SHIP 1 modified

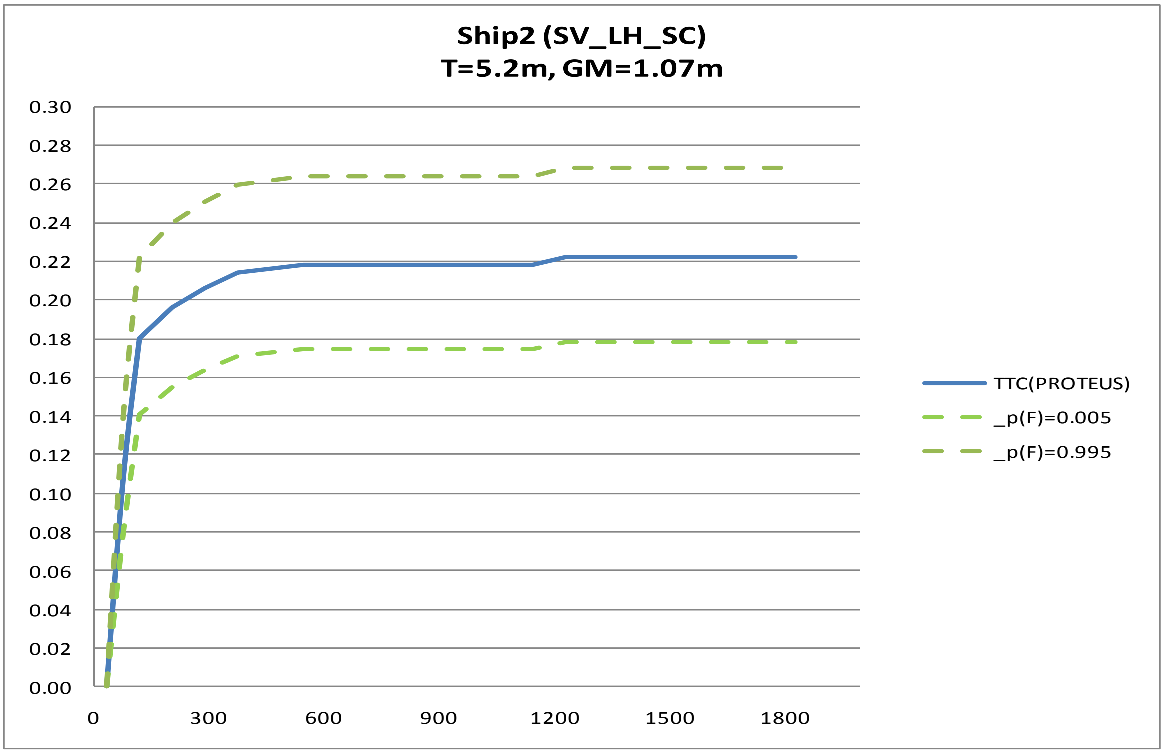


Figure 130 - Monte Carlo simulation results for SHIP 2

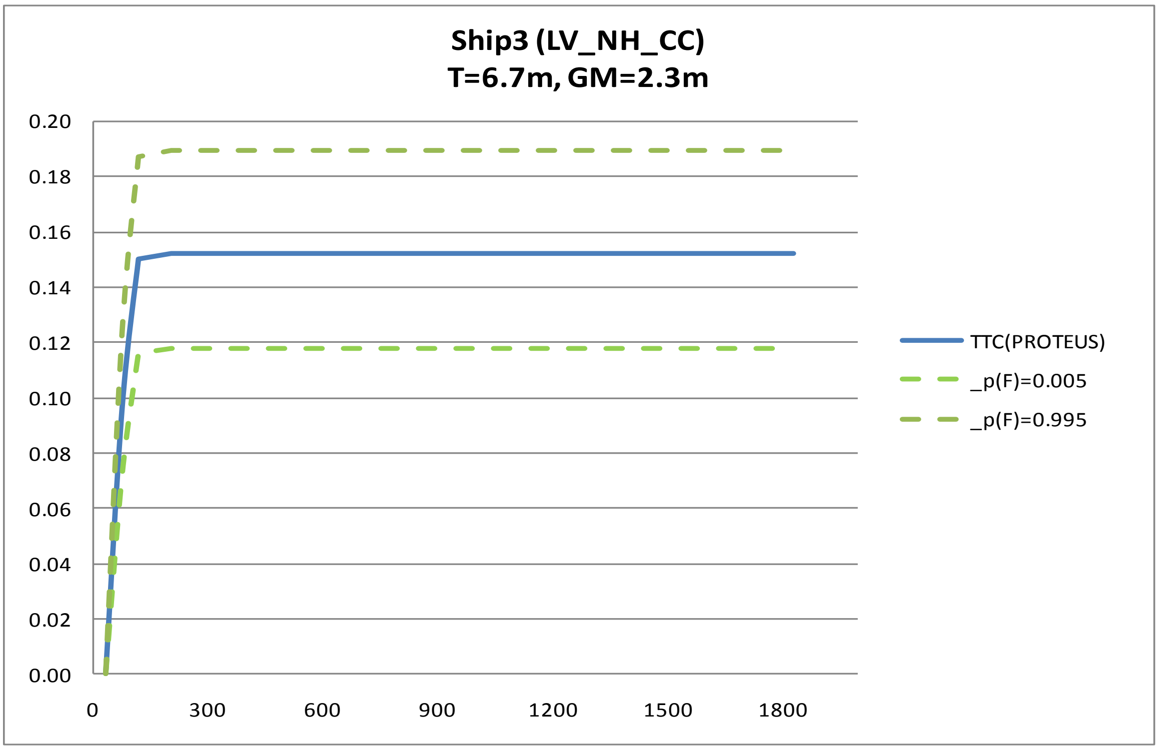


Figure 131 - Monte Carlo simulation results for SHIP 3

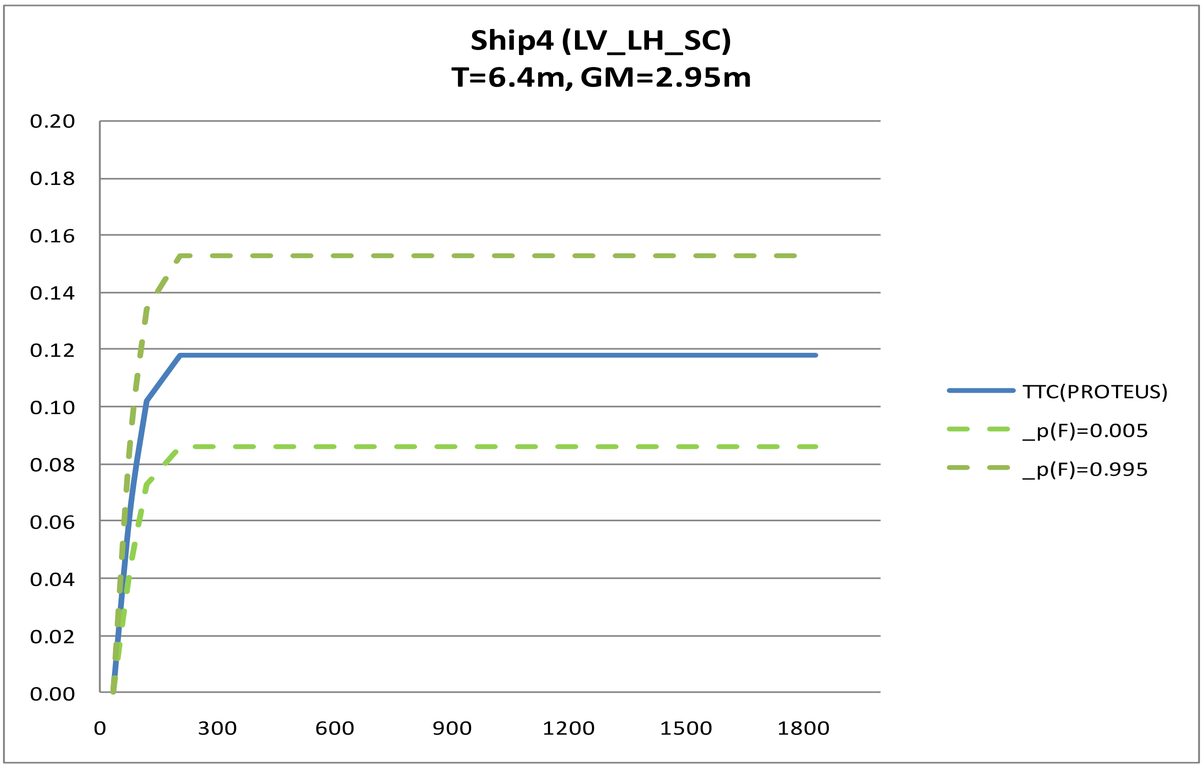


Figure 132 - Monte Carlo simulation results for SHIP 4

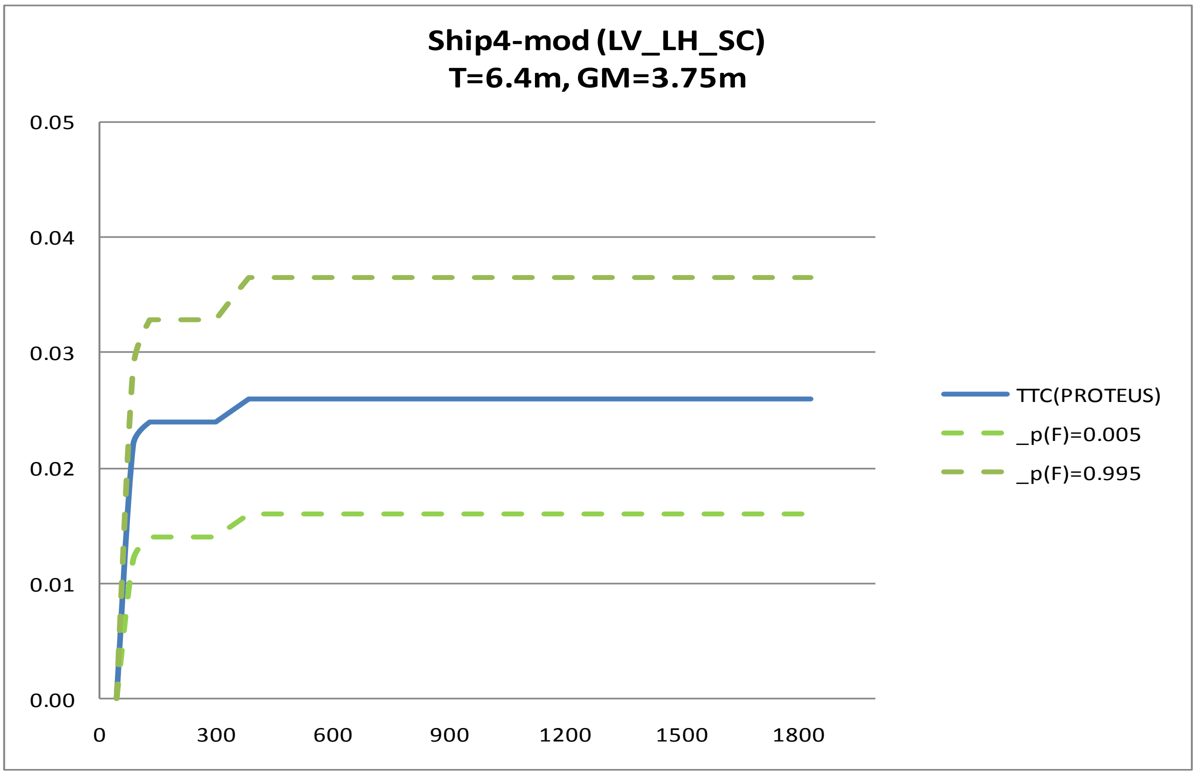


Figure 133 - Monte Carlo simulation results for SHIP 4 modified

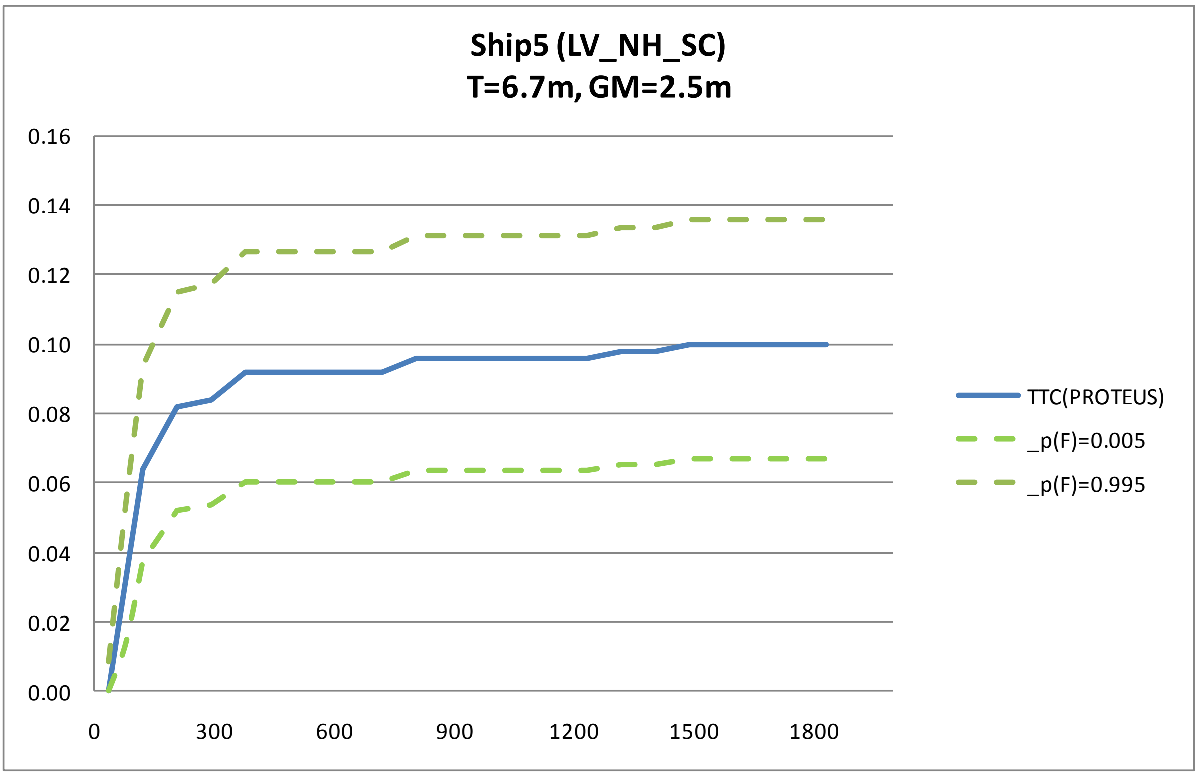


Figure 134 - Monte Carlo simulation results for SHIP 5

5.3. Note of Uncertainties

This project has attempted to adhere to systematic analysis of risk to life arising due to collision and flooding events, with underlying objectives of reconciling of the intents of the Stockholm Agreement and SOLAS 2009 stability standards, as well as quantitatively establishing the relevance of stability to safety of life. At every step of the analysis, assumptions had to be made, which by their very nature are subject to judgement, and therefore result in uncertainties in conclusions.

Whilst this is part of any engineering activity, the following few notes aim to highlight what appear to be the key pertinent areas where uncertainty could or should be debated and agreed to, as part of the process of compromise on proposed amendments.

Permeability and modelling assumptions

As was demonstrated during this project by the NTUA team reported in Annex 4, assumption such as the permeability of the internal spaces could be critical for the predicted survivability, see Annex 4. No further effort were spent on investigation of what impact these assumptions could have on the overall survivability, as the assessment of the spread in the levels of overall risk to life posed by the RoPax fleet is judged to adequately reflect on these kind of discrepancies. However, these discrepancies might prove detrimental in routine assessment of compliance by individual ships, and hence perhaps sensitivity studies should be considered as part of the typical approval process.

Watertight door operation

It is common knowledge that whilst operating a ship in real life, use is made of the water tight doors, which are otherwise assumed to remain closed for demonstrating compliance with stability standards. The degree of impact on the actual instantaneous survivability (probability A) could be dramatic with some **50% reduction in probability A** observed when a series of doors are left opened whilst at sea.

Therefore, it is highly recommended that the amendments to standards proposed in this report be considered as the minimum, and the reality of management of watertight integrity onboard ships be incorporated in the future by either further raised stability requirements or very strict operation guidelines.

Other hazards and other ships not considered

The basis for the proposed stability standards derives from consideration of collision events. Whilst this has also been the fundamental hazard underlying SOLAS 2009, it seems imperative that the study be extended for all hazards that are capable of impairing stability, such as contact, foundering and stranding, each of which has great capability to bring about the ultimate consequence of loss of life.

Therefore, the limited consideration of collision hazards alone in this study is another reason to regard the proposed revision for required probability R as the minimum.

Fleet size and accident frequencies

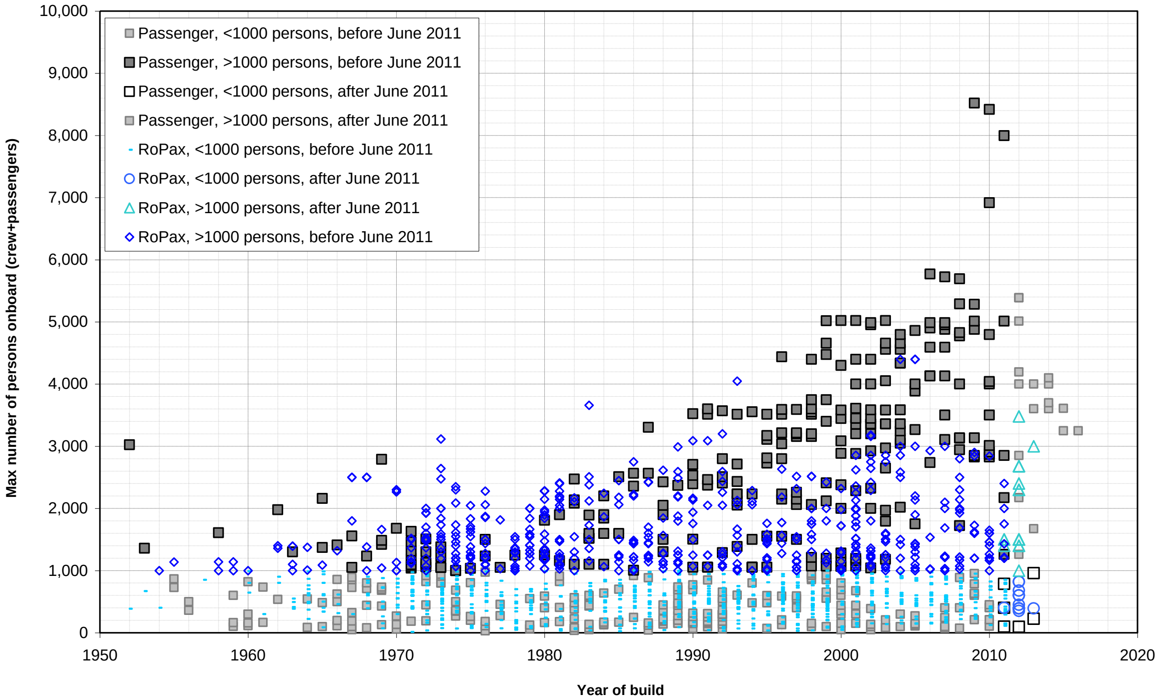
Last, but not least, it should be mentioned that a fairly critical element of the study seems to be the size of the fleet considered for assessing risks.

The Fairplay database was used in this project to analyse the RoPax fleet development.

The focus on RoPax ships was dictated by the terms of reference, however, when deliberating international safety standards, addressing hazards such as flooding, all relevant or affected ships should be considered. Therefore, it seems that all passenger ships should have been considered, as shown in Table 31 and Figure 135. Moreover, the annual increase in the number of passenger ships by some 30 new units has been observed over the past 30 years, year on year. Hence, a very pertinent question arises on the fleet to be considered for a standard that is expected to be in force for decades? The risk of a catastrophic accident increases with the increase in fleet size, and hence the stability standard should be adjusted accordingly.

Table 31 - Summary of the passenger fleet size in June 2011 (including ships on order), built after 1950 and at least 1,000 GT

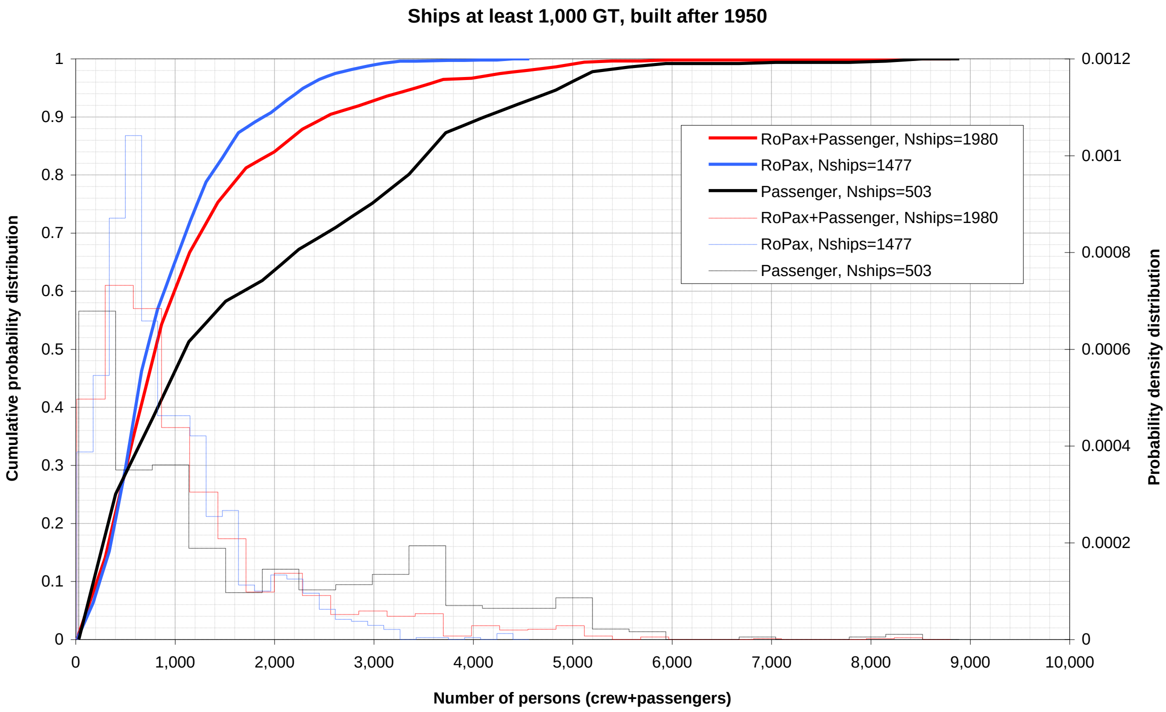
	Number of persons onboard (crew+passengers), Nmax				
	<1000	<1000 after June 2011	>1000	>1000 after June 2011	Total
RoPax	950	12	499	16	1,477
Passenger	220	6	259	18	503
Subtotal	1,170	18	758	34	1,980
Total		**1,188**		**792**	1,980



Source: Fairplay database

Figure 135 - Evolution of the passenger ships fleet, cruise and RoPax

It can also be noticed that various references quote different fleet sizes (see Table 32) and therefore, the records on the global fleets remain yet to be standardised for reliable assessments.



Source: Fairplay database

Figure 136 - Character of the passenger ships fleet, cruise and RoPax

Table 32 - Information on the size of the passenger ship fleet

	RoPax (>1,000GT)	Cruise and Pax (>20,000 GT)	Total	Criteria
IMO	1,162	n/a		in 2006
SAFEDOR, [45]	1,637	172	1,809	in 2006
Kanerva et al, [57]	1,153	n/a		in 2000
GOALDS, [55]	944	286 + 99	1,329	in 2010
SaS Fairplay	1,449	217	1,666	Built 1950 - June 2011
SaS Fairplay	1,477	503	1,980	Built/Ordered 1950 – 2016
EMSA IHS/LRF	1,552			Active 2011
EMSA LLI/LMIU	1,087			Active 2011

A brief note has been made of the uncertainties underlying analyses such as those presented in this report. Some of these uncertainties can only be resolved as a debated compromise, and hence further discussions are highly advisable.

6. Recommended Regulatory Amendments

The following recommendations could be made to amend the current SOLAS 2009 Chapter II regulations to ensure a unified level of safety as required by the Stockholm Agreement and SOLAS 2009, but also to ensure that the societal risk to life is ALARP.

Revise MSC216 (82) Reg. 7-2.3

It is proposed that Regulation 7-2.3 be revised by replacing $GZ_{\max}$ with a suitable value of approximately 0.25m for passenger ships, that the $Range$ be taken as no more than 25deg, and that the coefficient K be taken as 1.

This amendment would consistently accommodate the data on survivability of Ro-Ro passenger ship types, as derived in the HARDER project (currently underlying the SOLAS 2009 rules). The revision would lead to a reduction in the value of index A to the order of 0.2% - 6%. However, removing of the factor K from current Regulation 7-2.3 would encourage the building in of stability at higher angles of heel. Instead of factor K intent, it may be required that relevant ship systems operate at higher angles of heel of up to 25deg.

Revise MSC216 (82) Reg. 6.1 and Reg. 7.1

It is proposed that Regulations 6.1 and 7.1 are revised to assure that the Attained Index of Subdivision A is equal to or higher than the Required Index of Subdivision R for every loading condition during ship operational life, rather than be "weighted" according to the assumed probability of occurrence of various loading conditions. None of the loading conditions should be regarded as a random variable, but as a well-defined range for which an adequate level of stability should be maintained at all times.

Revise MSC216 (82) Reg. 6.2.3

Set R as follows:

$$R(N_{\max}) \geq \begin{cases} 0.875 & \text{for} \quad N_{\max} < 100 \\ 1 - \dfrac{1}{0.0845 \cdot N_{\max} - 36.67 \cdot 10^{-6} \cdot N_{\max}^2} & \text{for} \quad 100 \leq N_{\max} < 375 \\ 1 - \dfrac{1}{0.0845 \cdot N_{\max} \cdot \exp\left(\dfrac{-(N_{\max} - 250)}{704}\right)} & \text{for} \quad 375 \leq N_{\max} \leq 704 \\ 0.968 & \text{for} \quad N_{\max} > 704 \end{cases}$$

This recommendation aims to ensure that catastrophic accidents do not occur more often than once per 100 years on average. N is the number of persons onboard (crew and passengers).

Revise MSC216 (82) Reg. 8-1.2

It is proposed to consider the intent of the factor K in Regulation 7-2.3 to be accommodated by the following text of Regulation 8-1.2:

“Availability of essential systems in case of flooding damage”

“A passenger ship shall be designed so that the systems specified in regulation II-2/21.4 remain operational and sustain heel angles of up to 25 degrees when the ship is subject to flooding.”

This recommendation aims to ensure that all adequate systems needed for facilitating orderly evacuation are available for all feasible flooding cases.

Revise Reg. 1.1 of Annex I of Directive 2003/25/EC

As a possible alternative to all of the above proposed amendments, a direct method of ensuring the intent of the Stockholm Agreement is met under SOLAS 2009, it may be required that the provisions of Regulation II-1/B/8.2-3 shall be complied with by demonstration that s=1.

7. Conclusions

The report summarises all studies performed in this project to identify specific parameters governing the stability of RoPax ships and to find a solution to the problem of reconciliation between the stability standards of SOLAS 2009 and the Stockholm Agreement, as well all their other deficiencies identified.

A series of specific recommendations for suitable amendments has been derived.

Based on the assessments made, a serious of improvements to ship stability may be obtained in a cost effective manner, reducing risk to life by approximately 2-4 averted fatalities per ship lifecycle.

8. Literature

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Annex 1 - Assessment of Sampling Error

See separate document.

Annex 2 - Numerical Calculations

See separate document.

Annex 3 - Physical Model Experiments Protocols

See separate document.

Annex 4 - Sensitivity of Stability Assessment to Permeability Assumptions

See separate document.