FLOODSTAND
FP7-RTD- 218532

Integrated Flooding Control and Standard for Stability and Crises Management

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Standard for decision making in crises
- loss and likelihood functions

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An outline of elements of an effective decision making during flooding crises has been presented, with tentative proposals of 4-step process and a criterion for committing to decisions. The process reflects the uncertainties underlying assessments of ship’s residual stability and the effectiveness of the abandonment and the rescue operations. Additionally an effective paradigm of instantaneous crew preparedness for crises was developed and demonstrated in live testing.</td></tr>
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Executive Summary

This report summarises efforts to develop an integrated standard for making decisions for managing flooding crises situations.

Models for loss function and likelihood functions have been proposed, and an integrated format of decision making process addressing ship's residual stability, the abandonment and the rescue operations, as well as dominant inherent uncertainties have been proposed, as follows:

Step 1 - Order mustering and follow with situation assessment at the first sign of distress

Step 2 - If flooding extent not determinable or escalating then abandon

Step 3 - Else if [$\min(0.125 \cdot Hs, 1) \cdot < F_{cap}(3hrs|Hs)$] then abandon

Step 4 - Else stay onboard.

Some fundamental uncertainties reported in D4.1 to D4.5 related to the assessment of the extent of flooding do not seem resolvable at present, and given considerable level of typical ship vulnerability to flooding with possible rapid capsize, it is recommended in the above process that the order to muster is an automatic and immediate crew reaction to first report or a sign that distress occurs. During the mustering time all efforts to assess the extent of flooding must be made, and in case doubts remain as to the scenario, or in case the flooding is escalating, an order to abandon should be given. In case flooding situation is well established, a quantitative criterion is given to make judgement on the risk balance between decisions of abandonment and staying onboard.

Naturally, the above process is susceptible to subjective interpretations as to what constitutes "doubt" or "well established" situation awareness, and these are proposed to remain discretionary judgements of the crew.

It follows that technologies (better sensors, their denser distribution and good maintenance) and procedures for monitoring of all of ship spaces should be developed, so that this fundamental uncertainty is resolved. However the proposed above procedure would seem competent and generic independent of the state of technology.

The process highlights the important decision making elements, which when used in training may allow the crew to better understand importance of their preparedness for handling crises.

Assessment of the likelihood function $F_{cap}(3hrs|Hs)$ is proposed to be adopted for any type and size of the vessel, even though its key validation was performed for RoPax type ships only, as the formulation is based on generic parameters of residual stability, as well as generic assumptions on the impact of the process of floodwater progression ("GZ cut-off at down-flooding points"), with the latter mitigating the mentioned expected uncertainties of situation assessment.

Additionally, a mathematical model for an instantaneous stability monitoring paradigm is proposed, facilitating efficient upkeep of crew preparedness for handling crises, should these occur. Such preparedness is possibly the most effective means of handling crises or its prevention in the first place.

The proposed prototype of the standard seems robust and reflective of the identified physics prevailing during flooding, loss of stability and abandonment, as well as the state of today's infrastructure available for establishing ship's status.

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APPENDIX 1 THE CONCEPT OF VULNERABILITY LOG

1 Introduction

Improving safety and security of surface transport may be achieved by developing technologies and intelligent systems, including monitoring systems, rescue procedures, and crisis management, to protect vulnerable persons.

One of key elements of providing with such intelligent systems is development and deployment of a crisp merit function to form basis of a decision support.

When decisions must be made during an evolving crisis, the function of decision support becomes the last option for its effective mitigation that is available to the crew.

In case of passenger ships, loss of life is the consequence that would be considered in making the final decision of ship abandonment, and at present the decision is discretionary and it rests with the captain (or on-shore command officer).

Whilst it seems rational that the responsibility for the persons onboard a ship in crises must remain with the master, it would seem prudent that decisions made, such as on ship abandoning, are reflective of the state of the art scientific understanding, possibly expressed as a clear and agreed internationally criterion. This would help the crew to make more efficient decisions, assure a degree of uniformity in handling serious crises situations, and more importantly, it would transfer some of the burden of responsibility for outcomes of the crises to the whole professional community or indeed, the society, which in the end may help the decisions to be less stressful and thus more rational.

This report summarizes a proposal on such specific criteria for decision-making or indeed, for the process of handling crises involving many persons.

2 Objectives

This task sets to devise a basis, a standard, for decisions on abandonment, so that either the crew or the on-shore team advises accordingly to rigorous criteria accommodating for all information that is relevant to such decision making at every instant of time, as well as for all the uncertainties associated with eventually committing to this decision.

It was proposed to form such a standard on the basis of concept of risk, and its two elements, a loss function $loss(N)$ and $p_{N|i}(N|decision_i)$ were set to be developed.

The loss function must reflect in a balanced manner the societal concerns pertinent to a "large" loss. The $p_{N|i}(N|decision_i)$ must reflect the state of stability, evacuation and rescue process as well as the associated uncertainty.

This report describes the implementation of the loss and likelihood functions in an integrated standard for decision making.

3 Approach adopted

The approach evolved somewhat during developments in the project from the initial outlines.

After basic literature review pertaining to the decision making and an initial prototype modelling, majority of the effort was spent on examining the decision function in an integrated format, whereby all elements of ship survivability as well as the whole process of evacuation and abandonment were examined in detail.

The outline of the reasoning that led to putting forward of the ultimate proposal is presented in this report.

4 Frameworks of decision making

Bad decisions can exacerbate crises and good decision making can help to steer a situation away from, or out of crisis, [7]. Most people may consider themselves good decision makers, reflective when needed, intuitive and decisive when that is required, prepared to consider alternative perspectives and aware of the mistakes that others have made in the past. The reality however may be less forgiving, especially with respect to handling crises situations.

Crises abound and few institutions and organisations seem immune to them. Crises defy precise characterization, but typically they are unexpected, abnormal and novel, volatile, inherently unpredictable and giving rise to conflict between objectives. Impacts may be interdependent and non-obvious, and participants will be under time pressure and other forms of psychological stress in responding to them.

A general conclusion of the mental models and sense making literature is that typical reasoning based on cognition is relatively reliable for basing decisions under previously experienced, routine, cognitively manageable, clearly structured and low stress conditions. As conditions move progressively towards the characteristics of extreme crises, then the reliability of these frameworks as a basis for intuition degrades.

As such, decision making to mitigate crises seems to be particularly subjected to uncertainty of not only the inherent situational characteristics, but also the whole process of its handling, from human effects of the crew, to the availability of the necessary hardware in case scenario such as collision or grounding occurred.

Practically, crises will not typically allow decision makers to ‘wait and see’ until critical uncertainties are (certainly) resolved, and decisions will often need to be made when events, their implications and future developments are unclear.

It is for these reasons that the process of decision involving serious flooding crises should be formalised, as it does not seem rational that the weight of responsibility for (often) so many is in hands of so few and given the degree of uncertainties involved, as described in WP4 of this project. For these reasons also the formalism adopted must reflect the key problem of handling crises, namely the presence of uncertainty.

Choice under uncertainty represents the heart of decision theory, and the concept of expected utility has been considered for centuries as the means for rationalising such choice.

The idea of expected utility is that, when faced with a number of actions, each of which could give rise to more than one possible outcome with different probabilities, the rational procedure is to identify all possible outcomes, determine their utility (positive or negative) and the probabilities that will result from each course of action, and multiply the two to give an expected utility. The action to be chosen should be the one that gives rise to the highest (lowest) total expected utility.

However, Tversky and Kahneman, [8], have demonstrated in numerous highly controlled experiments that most people systematically violate all of the basic axioms of subjective expected utility theory in their actual decision making behaviour at least some of the time. These findings run contrary to the normative implications inherent within classical subjective expected utility theories. In response to these findings, they provided an alternative empirically supported theory of choice, one that accurately describes how people actually go about making their decisions. This model is called prospect theory. Prospect theory predicts that individuals tend to be risk averse in a domain of gains, or when things are going well, and relatively risk seeking in a domain of losses, as when a leader is in the midst of a crisis.

In making a decision, a decision maker multiplies the value of each outcome by its decision weight, just as expected utility maximizers multiply utility by subjective probability, [8]. However, decision weights in prospect theory differ from those in subjective expected utility theory, because decision weights do not obey any of the rational choice probability maxims.

Decision weights do not serve solely as measures of the perceived likelihood of an outcome, as probability does in subjective expected utility theory. Rather, decision weights represent an empirically derived assessment of how people actually arrive at their sense of likelihood, rather than a normative standard about how they should derive probability, as subjective expected utility theory advocate.

5 Flooding crises management

As can be seen, either of these basic concepts of decision making underlines subjectivity of decision maker in rationalising choices, which is the key reason for the proposal of an alternative standard for handling crises involving ship flooding, devoid of subjective assessment.

Neither the probability should remain subjective in expected utility nor the weights should reflect the inefficiencies of human decision making when for instance under stress in prospect theory.

It is proposed that the framework of the standard for handling flooding crises follows the concept of expected utility, however, with all its elements derived through the available scientific reasoning, as presented in WP4 and WP5, to allow decisions uniformity.

The proposed concept is given by the following formulae (1).

$$E\left(loss \middle| decision_i\right) = \sum_j loss(j) \cdot p_{N|i}\left(j \middle| decision_i\right) \qquad (1)$$

For $j = 1 \ldots N_{\max}$ and where $N_{\max}$ is total number of persons onboard.

5.1 The loss function

The key argument for scrutiny of the element $loss(j)$ in equation (1) is due to the recognised non-linear aspect of human reaction to catastrophes, [9]. Society appears more willing to accept a technology that will result in a number of separate fatalities than one which results in a large number of fatalities from a single event, even though the totals over time may be the same.

To reflect this observed tendency the following heuristic set (2) of loss functions is proposed to be considered for decision making.

$$\begin{aligned} Loss(j) &= j^{0.5} \\ Loss(j) &= j^{1} \\ Loss(j) &= j^{2} \\ Loss(j) &= j^{3} \end{aligned} \qquad (2)$$

5.2 The likelihood function

The likelihood functions have been proposed throughout WP4 and WP5 of this project, and will be summarised here for easy reference and final proposition.

5.2.1 Abandonment and rescue process

As described in D5.1 to D5.5, probability of observing a number of fatalities in abandonment and rescue process, (3), can be assigned using Casualty Calculator, as shown by means of the sample in Figure 1.

$$p_{N|i}\left(j \middle| decision = abandon\right) \qquad (3)$$

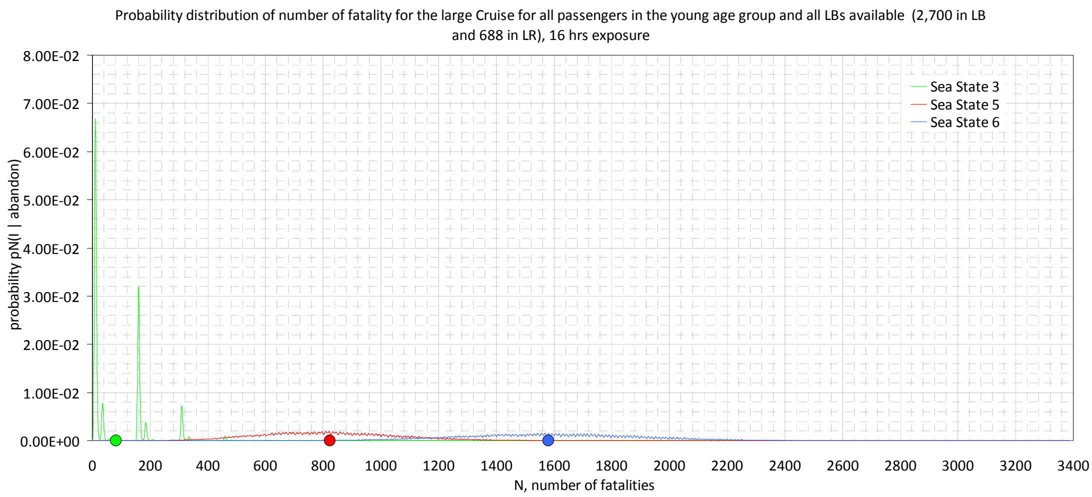


Figure 1 Distribution of probability for number of fatalities given decision is made to abandon the ship. Large Cruise, all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure. Three sea states considered. The E(N) is shown as circles.

The extensive sensitivity studies in WP5 indicate the sea state as the most dominant variable that would affect the occurrence of fatalities.

Distribution of the probability for considerable range of fatalities shows the degree of uncertainty present in any assessment of consequences of the decision to abandon.

5.2.2 Loss of stability

As explained in WP4, D4.2, equation (35), the probability of loss of stability may be assigned by the formulae (4).

$$F_{T|scenario}(t|Hs) = 1 - \left[1 - \Phi\left(\frac{Hs - (H_{crit} - \varepsilon)}{0.061 \cdot (H_{crit} + \varepsilon)}\right)\right]^{\frac{t}{t_0}} \quad \text{for } Hs \geq 0, H_{crit} \geq 0 \qquad (4)$$

$$H_{crit} = 4 \cdot \left(\frac{GZ_{\max\_scenario}}{0.25} \cdot \frac{Range_{scenario}}{25}\right) \quad \text{scenario-dependent}$$

Where: $\Phi(z)$ is cumulative standard normal probability distribution function.
$t_0 = 30\,\text{min}$ is benchmark physical testing time.
$\varepsilon = 10^{-12}$ is some small number used to avoid singularity in (4).

Decision to abandon is in principle preceded by the process of mustering. Whilst the process of person's assembly at muster stations is an integral part of abandonment, their wellbeing is dependent on the stability of the ship before their complete disembarkation.

By disregarding possibility of persons survival by means of disorderly abandonment, e.g. jumping to water, or climbing on the back of a capsizing ship, etc, the probability of loss may be assigned as follows.

$$p_{N|i}(j|decision = stay\_onboard) = \begin{cases} 0 & if \quad j < N_{\max} \\ F_{T|scenario}(t = 3hrs|Hs) & if \quad j = N_{\max} \end{cases} \qquad (5)$$

Formulae (5) assumes that $N_{\max}$ number of fatalities would result if the ship capsizes when subject to given flooding scenario and at a known sea state. If the ship does not capsize then no fatalities would occur if all persons stay onboard.

The assignment of probability (4) for a capsize within some time of t=3hrs or less from the instant of decision enquiry on, is proposed on the basis that evacuation from a ship in distress can take considerable time, with ~3hrs seen in the past accidents (e.g. Sea Diamond). Therefore, the anticipated risk of staying onboard is the risk of total loss over next 3 hours, and it can happen rapidly at any instant. At no point is it possible to definitively say that at this or the other instant the capsize is taking place or not, as was shown with some extended analyses in the D4.4. Occurrence of capsize may only be identified after considerable heel occurred, or after total turn-over, i.e. when it is already too late to deliberate decision options.

5.3 Integrated standard

Given the models for abandonment and rescue and ship stability as given above, the concept of conditional expectation given by (1) allows for automatic integration of all decision-critical situational parameters, such as flooding scenario (location, extend of flooding, etc), ship geometry and loading, sea environment.

As reported in WP4 and WP5, many other parameters such as e.g. proximity to SAR operations, might have relevance, however, based on assessments made, these are of far lesser significance than the key parameters identified and proposed to be used above.

Since the consequence of decisions are mutually exclusive (e.g. if fatalities occur due to ship capsize, they do not occur due to rescue, and vice versa), the implementation of the concept of integrated standard comes down to quantitative comparison between the expectation of consequence conditional on decisions made, as given by (6).

$$E(N|abandon) \overset{?}{\geq} E(N|stay\_onboard) \qquad (6)$$

The following sensitivity studies serve for demonstration how the concept would work.

5.3.1 Sensitivity of abandonment model

Based on a sample study case, the effect of assuming different loss functions may be assigned as given in Table 1.

Table 1 Expected fatalities given decision to abandon, or E(N | abandon), and E(N^1/2 | abandon), E(N^2 | abandon), E(N^3 | abandon), all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure.

Sea State	E(N^0.5)	E(N)	E(N^2)	E(N^3)
SS3	7	82	16690	4407956
SS5	28	824	738384	712711205
SS6	40	1580	2600537	4435876324

Sea State	E(N) / Nmax
SS3	2.4%
SS5	24.3%
SS6	46.6%

It is also proposed to consider a simplified version of the expected fatalities given abandonment, and a tentative degree of simplification is proposed by the following formulae (7), with resultant calculations shown in Table 2 and Figure 2. More reasoning on this proposal is provided later on in the report, for the time being it is to demonstrate the format of the model that may be considered as part of an auditable and robust decision standard.

$$E(N|abandon) = \min(C \cdot Hs, 1) \cdot N_{\max} \qquad E(N|abandon) \leq N_{\max} \qquad (7)$$

Where the coefficient $C = 0.125$ [1/m].

Table 2 Approximation to the expectation of fatalities given decision to abandon, or E(N| abandon), and E(N^1/2| abandon), E(N^2| abandon), E(N^3| abandon), based on (7).

Sea State	E(N^0.5)=0.125Hs Nmax^0.5	E(N)=0.125Hs Nmax	E(N^2)=0.125Hs Nmax^2	E(N^3)=0.125Hs Nmax^3
SS3	6	373	1262640	4277823778
SS5	24	1376	4663159	15798780998
SS6	36	2118	7174090	24305816920

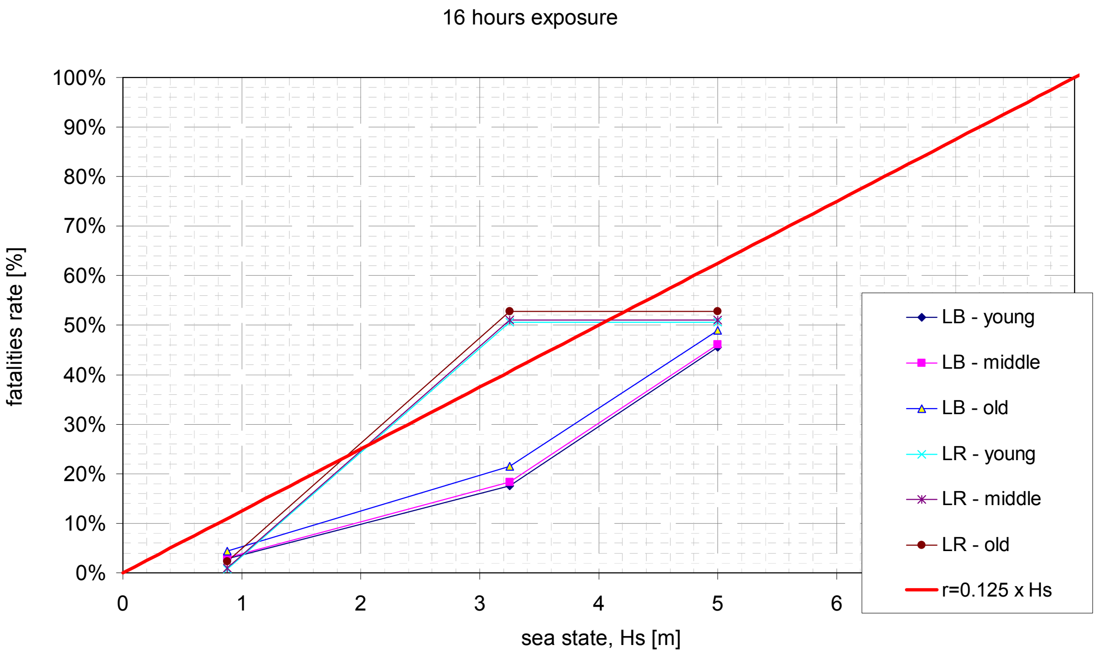


Figure 2 Rate of fatalities, E(N)/ $N_{\max}$, as a function of sea state, age and type of LSA. Simplified criterion given by (7).

The following Figure 3 to Figure 6 show the relationship between the expectation of fatalities, given decision to abandon, as a function of the key parameter influencing it, the sea state.

As anticipated, since the simplified formulation is expressed as a function of total persons onboard $N_{\max}$, the expectation of the function of fatalities, or the loss function, deviates from what the outcome would be if the probability was assigned according to the complex model of WP5 (Casualty Calculator).

The impact of this assumption is shown in the next chapter, when the decision options are compared.

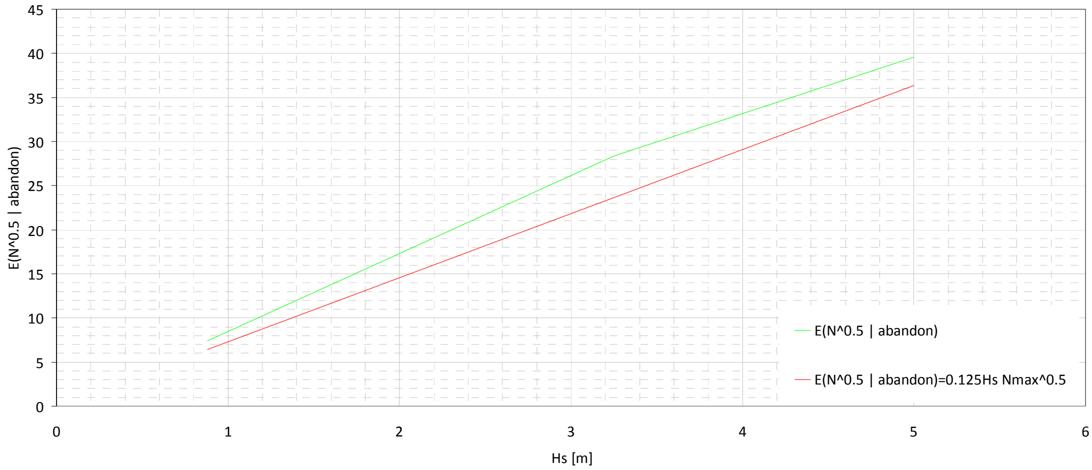


Figure 3 Relationship between the expectation E(N^0.5) and the sea state calculated based on Casualty calculator and approximate formulae. Case of Large Cruise, all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure.

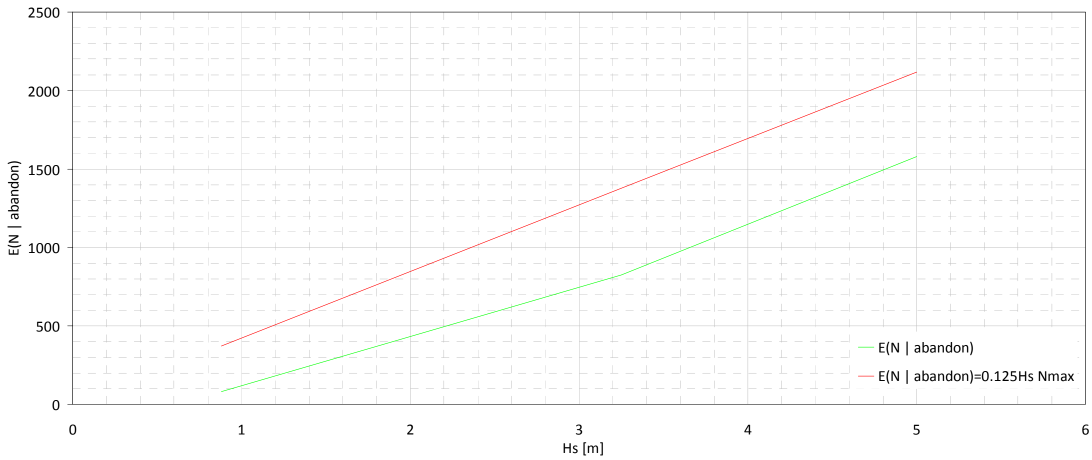


Figure 4 Relationship between the expectation E(N) and the sea state calculated based on Casualty calculator and approximate formulae. Case of Large Cruise, all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure.

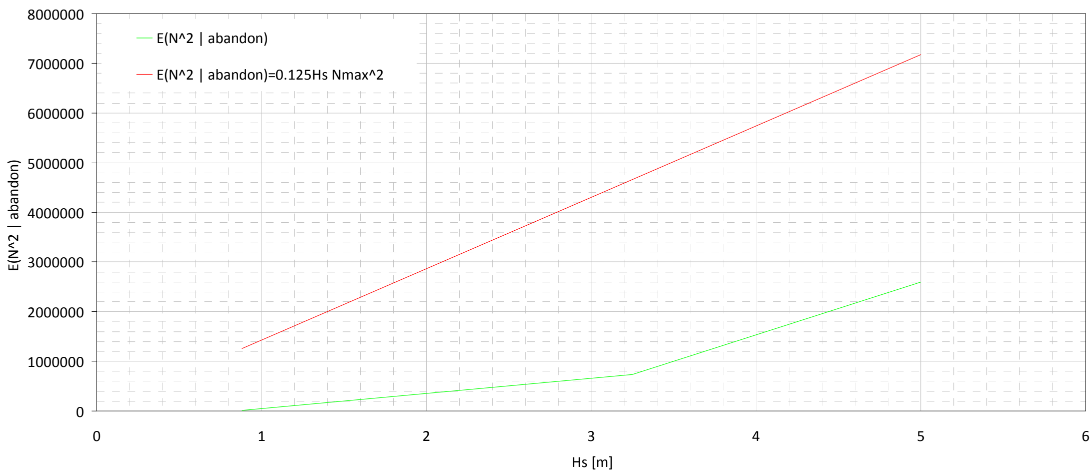


Figure 5 Relationship between the expectation E(N^2) and the sea state calculated based on Casualty calculator and approximate formulae. Case of Large Cruise, all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure.

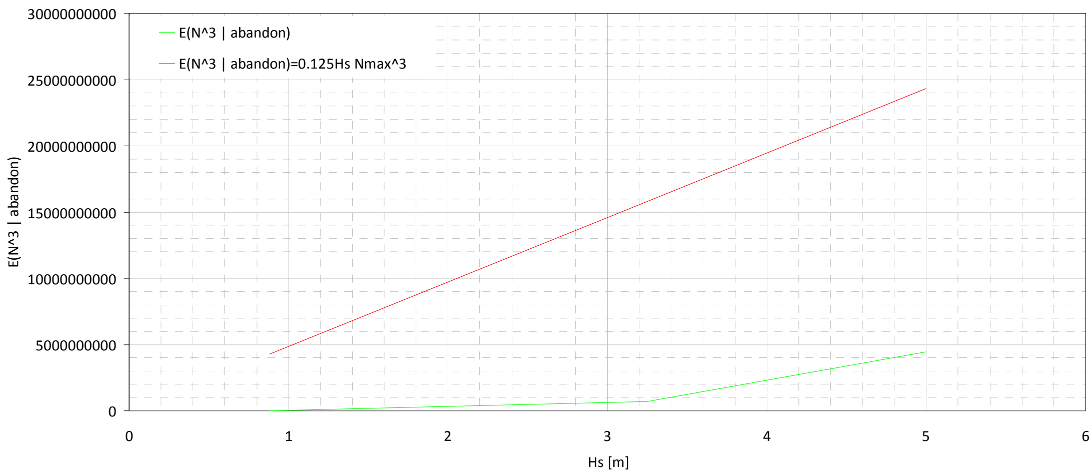


Figure 6 Relationship between the expectation E(N^3) and the sea state calculated based on Casualty calculator and approximate formulae. Case of Large Cruise, all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure.

5.3.2 *Sensitivity of the "stay-onboard" model*

Deriving from (4) and (5) the risk function for the decision of staying onboard can be written as (8), with loss function other than N derived by the powers of $N_{\max}$.

$$E(N|stay\_onboard) = F(3hrs|Hs) \cdot N_{\max} \tag{8}$$

Sample calculations are shown in Table 3, with further higher moment loss functions analyses shown together with risk functions for decision to abandon, given in Figure 8 to Figure 10.

Table 3 The expectation of fatalities E(N) given decision to stay onboard, based on model (8) for four sample flooding cases, d1 … d4, with given stability characteristics (GZmax, Range).

Gzmax	m	0.07	0.12	0.18	0.25
Range	deg	10	16	22	25
Hcrit	m	0.448	1.2288	2.5344	4
tcap	min	180			

Hs	E(N | Hs &d1 &stay_onboard)	E(N | Hs &d2 &stay_onboard)	E(N | Hs &d3 &stay_onboard)	E(N | Hs &d4 &stay_onboard)
0	0	0	0	0
0.25	0	0	0	0
0.5	3388	0	0	0
0.75	3388	0	0	0
1	3388	23	0	0
1.25	3388	3376	0	0
1.5	3388	3388	0	0
1.75	3388	3388	0	0
2	3388	3388	6	0
2.25	3388	3388	616	0
2.5	3388	3388	3248	0
2.75	3388	3388	3388	0
3	3388	3388	3388	0
3.25	3388	3388	3388	21
3.5	3388	3388	3388	391
3.75	3388	3388	3388	2135
4	3388	3388	3388	3335
4.25	3388	3388	3388	3388
4.5	3388	3388	3388	3388
4.75	3388	3388	3388	3388
5	3388	3388	3388	3388

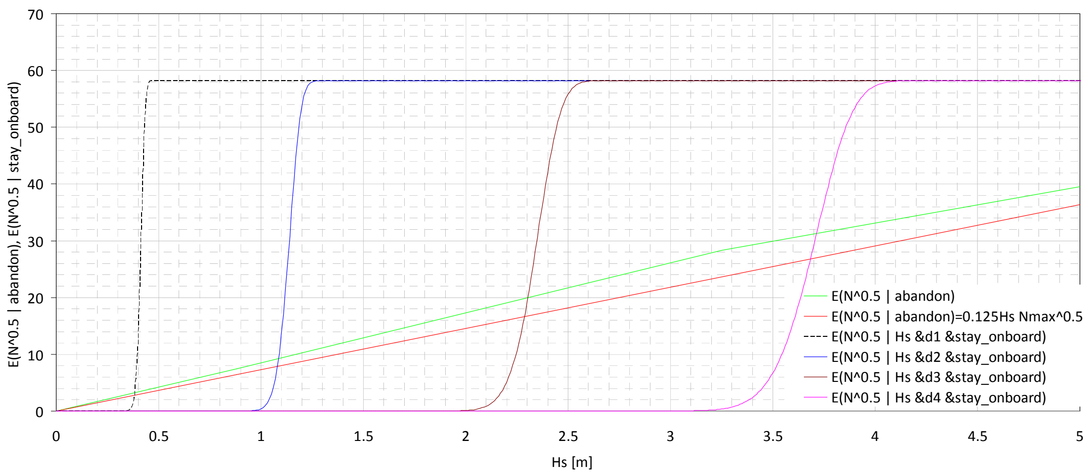


Figure 7 Relationship between the expectation E(N^0.5 | abandon) or E(N^0.5 | stay onboard) and the sea state for several flooding cases. Case of Large Cruise, all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure.

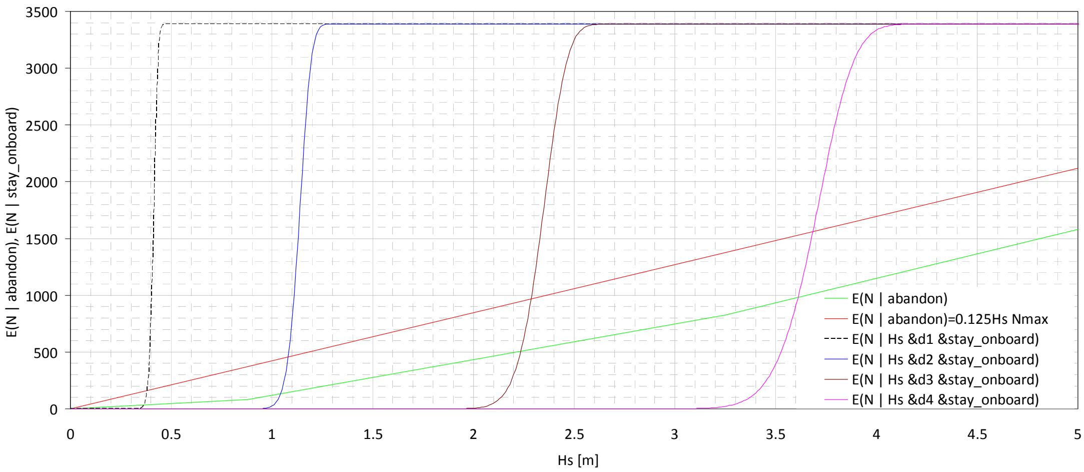


Figure 8 Relationship between the expectation E(N | abandon) or E(N | stay onboard) and the sea state for several flooding cases. Case of Large Cruise, all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure.

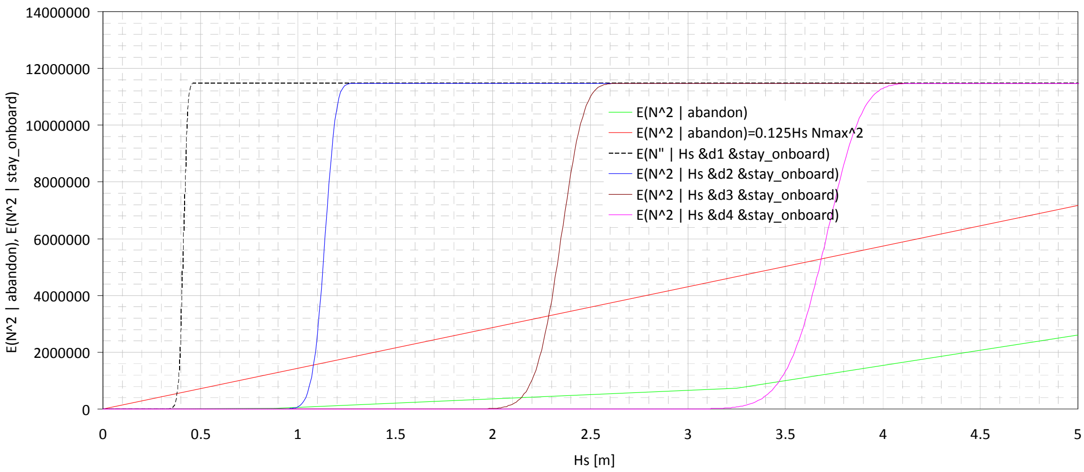


Figure 9 Relationship between the expectation E(N^2 | abandon) or E(N^2 | stay onboard) and the sea state for several flooding cases. Case of Large Cruise, all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure.

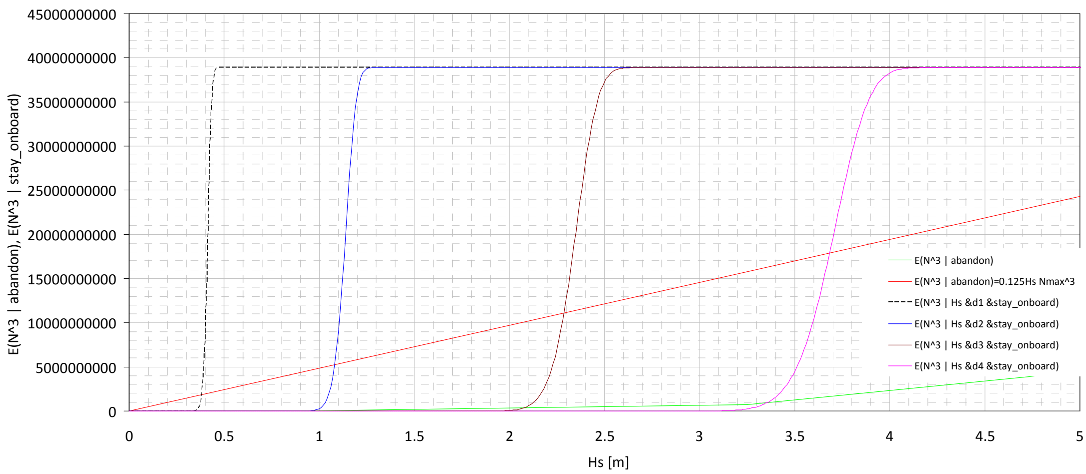


Figure 10 Relationship between the expectation E(N^3 | abandon) or E(N^3 | stay onboard) and the sea state. Case of Large Cruise, all passengers considered in the young age group and all LBs available (2,700 in LB and 688 in LR), 16 hrs exposure.

5.3.3 Sensitivity on the commitment to a decision

As it is shown in Table 4, the impact of the format of the loss function on the ultimate decision is nearly nil, when the approximate model (7) is extended to higher "moments".

Table 4 Sea state, Hs [m], at the instant the risk to life (abandoning) is lesser than the risk to life (staying onboard).

	E(N^0.5)	E(N)	E(N^2)	E(N^3)
d1	0.39	0.39	0.39	0.38
d2	1.09	1.09	1.08	1.07
d3	2.3	2.29	2.28	2.27
d4	3.7	3.69	3.68	3.67

When the actually simulated data from WP5 are used, some impact of ΔHs~0.2m in terms of the level of sea state which would trigger the decision to abandonment can be noticed when comparing E(N|*) with loss function E(N^2 | abandonment), see difference between Figure 8 and Figure 9 for Hcrit=4m, or Table 3. Approximate ΔHs~0.6m can be seen when extending the loss function to E(N^3 | abandonment).

Therefore, it seems sensible to conclude that the impact of the loss function may be disregarded for the purpose of providing with a prototype of decision making function.

The proposed loss function then may be based on traditional concepts of risk commonly applied in the industry, and is therefore proposed to be: loss(j) = j.

Deriving from the above, allows considering now (7) and (8) of the decision making standard (6) as follows:

$$\min(0.125 \cdot Hs, 1) \cdot N_{\max} \overset{?}{\geq} F(3hrs|Hs) \cdot N_{\max} \quad (9)$$

This reiterates the conclusions seen in Table 4 regarding the concept of the loss function loosing its relevance in the risk comparison process, as the element $N_{\max}$ of the loss function can be eliminated from (9) to form the decision making merit function (10).

$$\min(0.125 \cdot Hs, 1) \cdot \overset{?}{\geq} F_{cap}(3hrs|Hs) \quad (10)$$

Where the left hand side term of equation (10) is such that $0.125 \cdot Hs \leq 1$, i.e. is it is expected that 100% fatalities may be observed after abandonment in seas of $Hs \geq 8m$.

The right hand side term of equation (10) represents the capacity of the vessel to sustain its up-right attitude and floatability for at least 3 hrs at the instant of calculation during actual crises. As it is shown in D4.2 it is proposed that due to the recognized generic nature of the relationship between ship residual stability parameters, (irrespective of ship size) and the environment, the function (4), and therefore criterion (10) can be applied to any type of the vessel.

The likelihood to capsize may be affected by the ship watertight arrangement more than the basic stability parameters $GZ_{\max}$ and Range might disclose in (4), where e.g. progressive flooding is protracted in time rather than happen instantaneously as assumed through cut-off down-flooding points for processing properties of GZ curve.

However, given the underlying uncertainties in assessment of the extent of flooding during flooding situation, the proposed approximation (4) may be considered as means of mitigation of these uncertainties.

Once "better" models for assignment of probability of ship capsizing within given period of time for case of complex ship geometries become available, they can be applied directly as alternatives to RHS of the criterion (10), which is proposed as rather generic in itself.

5.3.4 Uncertainties and crises management process

As just mentioned, the criterion (10) for decision on abandonment or staying onboard seems very simplistic, however, given the studies reported in WP4 and WP5, it does seem rational, given the key uncertainties underlying especially (5) are resolved.

And it seems that some key such uncertainties are inherently not easy to resolve with today's technology.

Namely, it was shown that the knowledge on the extent of flooding is detrimental to establishing the level of survivability based on (5). Any deviation would result in overestimation or underestimation of the risk, which ultimately bears on the decision made, see examples in Table 3, Figure 8 to Figure 10.

Therefore, it seems imperative that a procedure to account for these uncertainties is addressed.

The proposed solution is to acknowledge that prior probability (before any details of the casualty are known) may be assigned based on the (1-A), with A assigned according to MSC218, or extended for other flooding hazards and applied according to principle shown in Chapter 6, and that therefore this outlines the prior risk, which is of the order of 20%-30% N_{max} for typical ships operating today assuming that watertight integrity is preserved at all times. If any of watertight or semi-watertight enclosures is compromised, the risk is higher.

Therefore, the immediate course of action should be to order mustering of all persons at the very first sign of distress situation, as there might be no time available for this. During this time all efforts should be made to ensure that the exact casualty conditions are know "completely", and that they are not escalating. If there is any doubt as to what is the condition, or if there is any sign that the situation is escalating, the abandoning should be ordered at once. If the condition does appear stable and it is known, then the criterion (10) may be used to make the decision.

A schematic view of this proposal for the decision making paradigm is shown in Figure 11 and Figure 12 below.

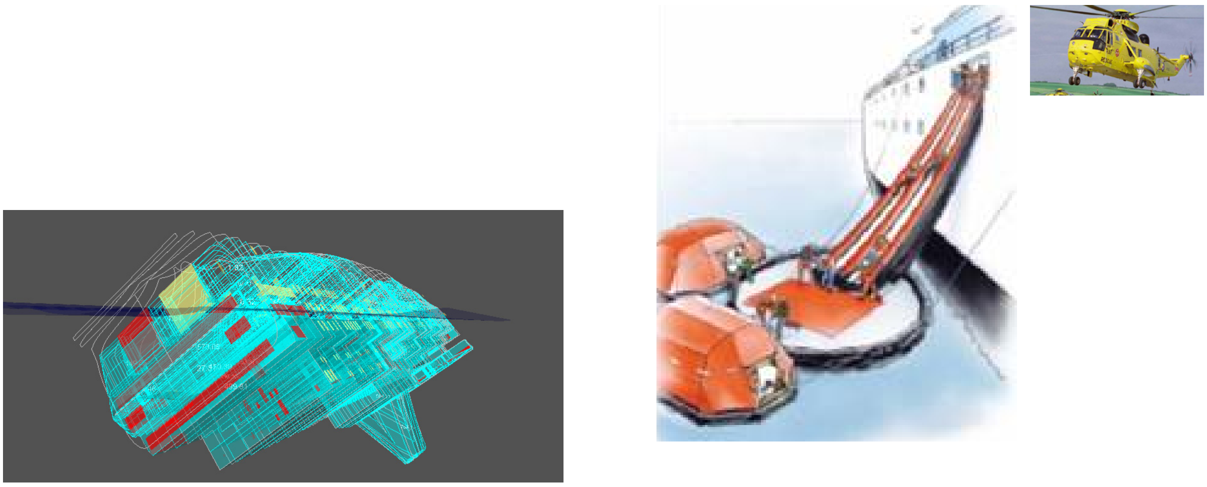


Figure 11 Decision dilemma, "stay onboard" or "abandon"?

Step 1 - Order mustering and follow with situation assessment at the first sign of distress

Step 2 - If flooding extent not determinable or escalating then abandon

Step 3 - Else if [$\min(0.125 \cdot Hs, 1) \cdot < F_{cap}(3hrs|Hs)$] then abandon

Step 4 - Else stay onboard

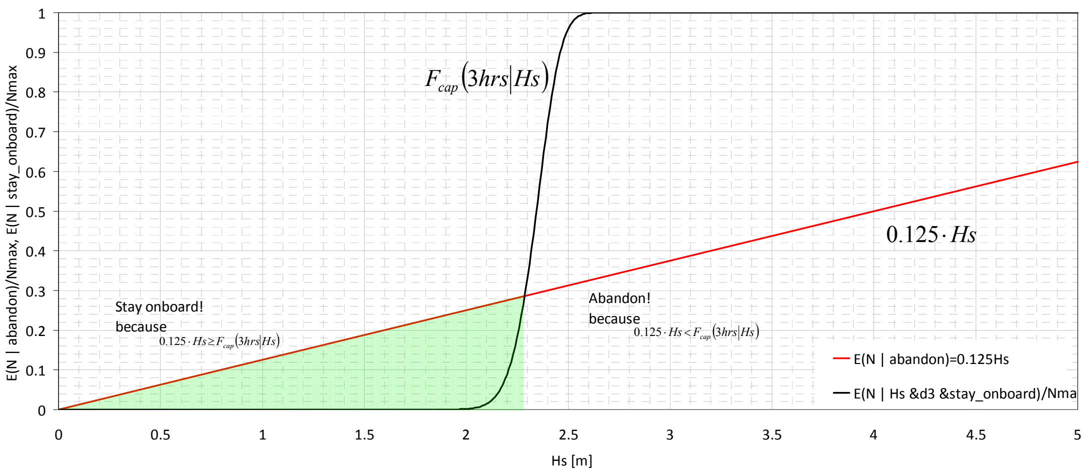


Figure 12 The decision making process, accommodating for key uncertainties.

As a general observation it may be seen in Figure 12 that the decision option of abandonment seems to be dominating flooding crises situation, on one hand, due to the inherent uncertainties of crew and ship sensor hardware capability to allow accurate situation assessment, and on the other, due to inherent risk to life resulting from loss of stability, with expectation of extensive loss of life.

At any instant when the sea state is such that $Hs > H_{crit}$, it seems that decision to abandon is immediately the best option to take, as the expectation of loss of life is lesser in seas known to be feasible during flooding situations. This might be considered as an alternative prototype to the proposed criterion (10).

It can be seen in Figure 12, or the standard (10) that apart from the extent of flooding, the variables of ship loading (fluid loads, KG), ship spaces geometries, draught, as well as sea state Hs, all contribute to some degree to the uncertainty, and as reported in D4.5, all play an important role in appropriate projection and ultimately decision making. Therefore care should bee taken at all times that their estimates are as reflective of reality as it is feasible, and that if any doubts remain on their actual values, that the Step 1 and Step 2 of the proposed procedure be exercised.

6 Life-cycle crises management

Consider model (4) as applicable for a specific flooding scenario j, and denoted as model (11).

$$F_{T|*}(t|Hs,j)=1-\left[1-\Phi\left(\frac{Hs-(H_{crit,j}-\varepsilon)}{0.061\cdot(H_{crit,j}+\varepsilon)}\right)\right]^{\frac{t}{t_0}} \quad \text{for } Hs\geq 0,\ H_{crit}\geq 0 \qquad (11)$$

The following functionality (12), referred to as VLog (vulnerability log), see Appendix 1 for more details, is proposed to encourage the culture of situation awareness and adequate preparedness.

$$F_T(t_c|Hs)=\sum_j p_j\cdot F_{T|*}(t_c|Hs,j) \qquad (12)$$

The quantity $F_T(t_c|Hs)$ may be monitored at all times, and displayed as e.g. a "clock" (ref: a car's speedometer) or as time record, see Figure 13, or it can be displayed in terms of probabilities $F_{T|*}(t|Hs,j)$ colour-coded for each "diamond" for immediate identification of local vulnerabilities of the ship, preceding flooding casualty.

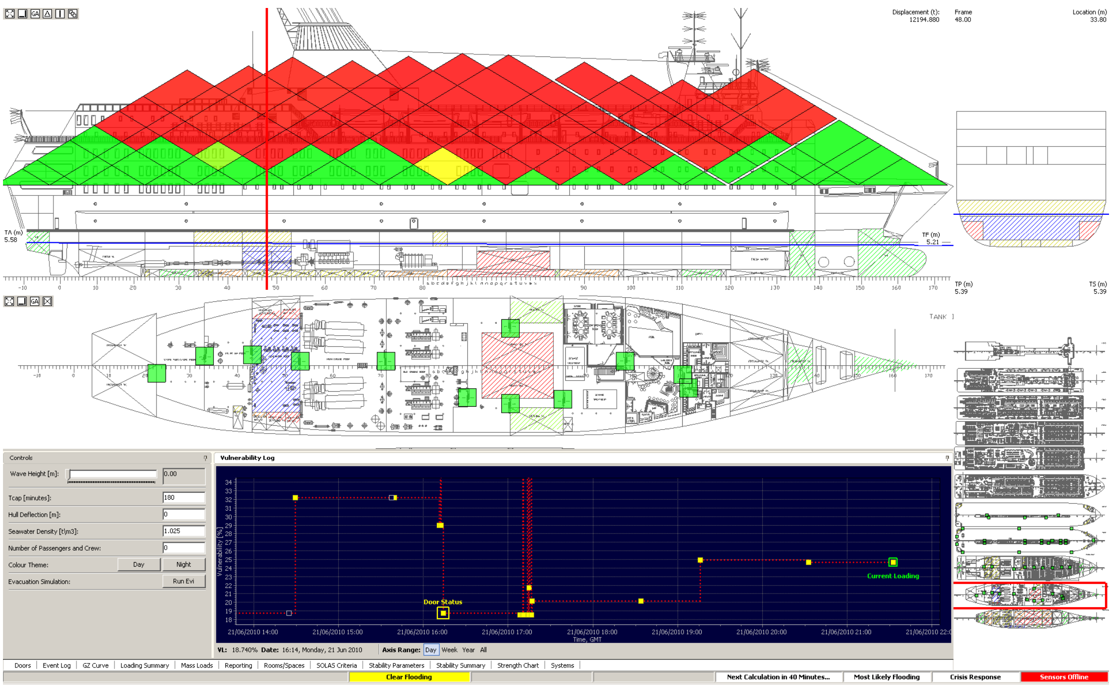


Figure 13 The concept of vulnerability log for instantaneous preparedness.

The key feature of this functionality is ergonomically accessible information to the crew on the instantaneous ship vulnerability to flooding.

Such information allows the crew to have notion at all times on ships capacity to cope with any feasible flooding scenario, and thus allows for making informed and instant decisions on how to respond with mitigating actions at the first sign of distress.

Most importantly, the crew can take precautionary actions at any time of the ship operation to knowingly reduce vulnerability to the lowest levels possible for a particular ship design.

Therefore, crew preparedness for response to distressed situation can be promoted at all times.

7 Conclusions

An integrated standard for making decisions for managing flooding crises situations was proposed, based on models for loss and likelihood functions.

An integrated standard addresses ship's residual stability, the abandonment and the rescue operations, as well as dominant inherent uncertainties.

Assessment of the likelihood to capsize within given period of time is proposed to be adopted for any type and size of the vessel, even though its key validation was performed for RoPax type ships in WP4 only, as the formulation is based on very generic parameters of residual stability, as well as generic assumptions on the impact of the process of floodwater progression ("GZ cut-off at down-flooding points"), with the latter mitigating expected uncertainties of situation assessment.

These uncertainties relate to the assessment of the extent of flooding, and do not seem resolvable, and given considerable level of typical ship vulnerability to flooding (20-30% of feasible cases non-survivable) with possible rapid capsize, it was recommended that the standard is a process rather than a criterion. Four-step decision making procedure was proposed.

Additionally, a mathematical model for an instantaneous stability monitoring paradigm is proposed, facilitating efficient upkeep of crew preparedness for handling crises, should these occur. Such preparedness is possibly the most effective means of handling crises or its prevention in the first place.

The proposed prototype of the standard seems robust and reflective of the identified physics prevailing during flooding, loss of stability and abandonment, as well as the state of today's infrastructure available for establishing ship's status.

8 Literature

[1] Ian Hacking, *“The emergence of probability”*, Cambridge University Press, 1975.

[2] Francis J Wall, *“Statistical Data Analysis Handbook”*, McGRAW-HILL BOOK COMPANY, 1986.

[3] Hines, W, W, Montgomery, D, C, Goldsman, D, M, Borror, C, M, *“Probability and statistics in engineering”*, 4th edition, John Wiley & Sons, Inc, 2003.

[4] Jaynes E T, *“Probability Theory: The Logic of Science”*, Washington University, 1995.

[5] Cox T Richard, *“The algebra of Probable Inference”*, Oxford University Press, 1961.

[6] Claes Kallstrom and Bjorn Allenstrom, *“Benchmark data on time to capsize”*, SSPA 4007 4581-1, October 2010.

[7] Robert MacFarlane, *“Thinking About Thinking About Crises”*, Business Leadership Review VII:III, July 2010, www.mbaworld.com/blr.

[8] Daniel Kahneman; Amos Tversky, *“Prospect Theory: An Analysis Of Decision Under Risk”*, Econometrica (Pre-1986*);* Mar 1979; 47, 2; Abi/Inform Global, Pg. 263.

[9] John D. Whittaker, *“Evaluation of Acceptable Risk”*, The Journal of the Operational Research Society, Vol. 37, No. 6 (Jun., 1986), pp. 541-547.

[10] Peter C. Fishburn, “Foundations of Risk Measurement. I. Risk As Probable Loss”, Management Science, Vol. 30, No. 4, Risk Analysis (Apr., 1984), pp. 396-406.

[11] Andrew W. Evans, *“Accidental Fatalities in Transport”*, Journal of the Royal Statistical Society. Series A (Statistics in Society), Vol. 166, No. 2(2003), pp. 253-260.

[12] Terje Aven, “*On How to Approach Risk and Uncertainty to Support Decision-Making”*, Risk Management, Vol. 6, No. 4 (2004), pp. 27-39.

APPENDIX 1 THE CONCEPT OF VULNERABILITY LOG

Preamble

This appendix introduces an extension of the element of the developed decision making function for aiding of life-cycle crew preparedness to handling of flooding situations.

The key feature is provision of ergonomic information to the crew on the instantaneous ship vulnerability to flooding.

Such information allows the crew to have notion at all times on ships capacity to cope with any feasible flooding scenario, and thus allows for making informed and instant decisions on how to respond with mitigating actions at the first sign of distress.

Most importantly, the crew can take precautionary actions at any time of the ship operation to knowingly reduce vulnerability to the lowest levels possible for a particular ship design.

Therefore, crew preparedness for response to distressed situation can be promoted at all times.

INTRODUCTION

Technological advances in computing hardware over the last decades have facilitated solution of many problems in ever decreasing amount of time. However, the progress in technical calculus, involving modelling based on the fundamental physical laws, has been just as significant, and despite the availability of ever grater processing power, many cases of numerical approximations to reality remain impractical to compute. It is for this reason that advanced prognosis have only had limited success in proliferating the field of instantaneous decision support.

Although highly advanced computerised safety management systems (SMS), have found accelerated support, their advisory functionality are mostly limited to detection only, with more sophisticated prognosis and advisory capabilities remaining at prototyping and development stages.

Such prototype simulation approaches available for use in prognosis comprise a range of phenomena such as (a) ship response to flooding progression, modelled through various but direct solution to conservation of momentum laws, Letizia et al, 1995 and 1997, Papanikolaou et al, 2000, Schreuder 2008, de Kat 2002, Jasionowski 2001, Petey 1988, or through quasi-static iterative approximations, e.g. Varela et al, 2007, or Ruponen 2006, (b) structural stress evolution under flooding, Bole, 2007, (c) mustering process, Vassalos et al, 2001, Piñeiro et al, 2005, (d) fire and smoke spread, Guarin et al 2004, and possibly many other.

Some of the reasons inhibiting their more wide use for decision support arise due to a series of practical problems in addition to sheer computational effort, such as the following:

- Each of these processes may vary at any instant of time due to changing conditions.
- The input is subject to considerable uncertainty.
- For any set of input information the outcome is random due to computational and modelling uncertainties as well as due to random nature of environmental or process conditions themselves.
- Each may be seriously influenced by decision choices.

The nature as well as inseparable combination of these engineering challenges imply that the projection functionality would need to be iterated for a range of uncertain conditions of either of the scenarios occurring as well as for a range of decision options, so that the best choice can be identified with controllable degree of confidence.

This, in turn, implies that the computational task of scenario projection in real time in support of decision making will likely remain a serious challenge, as most of these analyses require substantial amount of processing time, at present accounted in hours.

This is in contrast to real life cases of casualty scenarios, which in many occasions evolve in a matter of minutes, during which decisions could prove critical. The following recent casualties can be viewed to elaborate the issue.

MV Estonia, 1994, 852 fatalities

852 human lives were lost when the passenger Ro-Ro ferry MV Estonia sank on the night of 27/28th of September 1994 in the Baltic Sea, while on route between Tallinn, Estonia, and Stockholm, Sweden, Bergholtz et al 2008, Jasionowski et al 2008. The notable observation is that most of the 137 survivors are those that reacted fast, within the first approximate 10-20 minutes into the casualty.

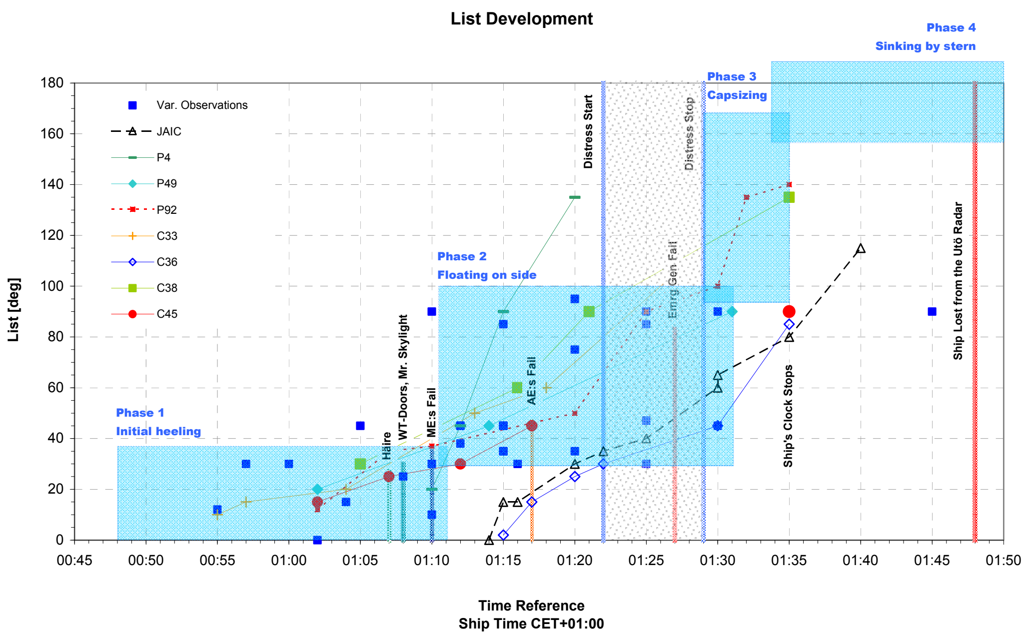


Figure 14 MV Estonia, statements by survivors on the heel angle experienced during abandonment, Bergholtz at all 2008.

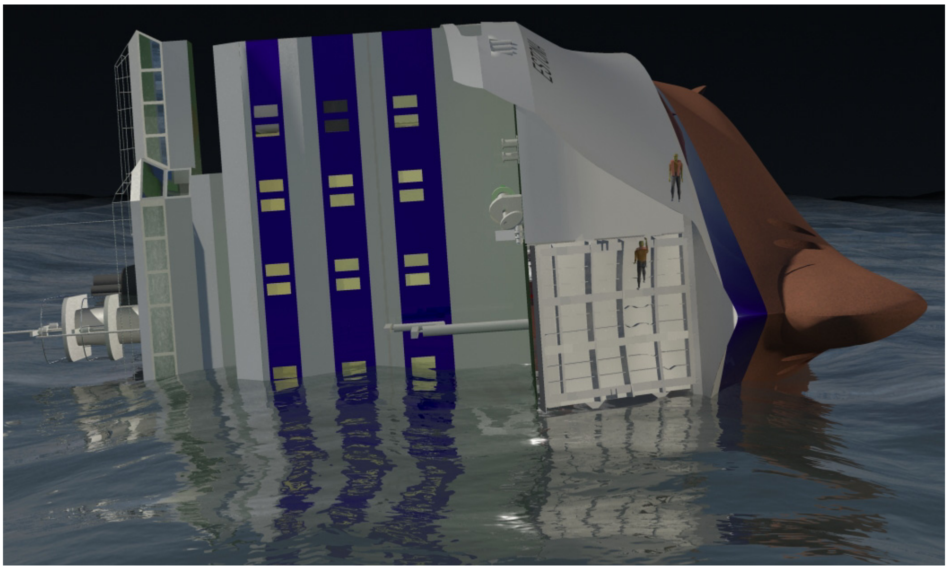


Figure 15 MV Estonia, Jasionowski et al 2008. At some instant two survivors managed to climb down the closed ramp, using its stiffening arrangement and abandon the ship. Heel angle 93deg.

Perhaps if crew were aware of what “to expect” they could have reacted quicker to casualty or averted it in the first place.

Monarch of The Seas, 1998, no fatalities

According to the accident report by Paulsrud et al 2003, “At about 0130 hours, …, the Monarch of the Seas raked the Proselyte Reef at an approximate speed of 12 knots without becoming permanently stranded”. Subsequently, “At 01:35 hours and owing to the water ingress, all watertight doors were closed from the bridge …” and “At 01:47 hours the general emergency signal, seven short and one long blast, was given …”. See Figure 16.

It appears that it took the crew 5minutes to decide about closure of water tight doors (WTD), and 17 minutes to inform the persons onboard of the casualty. Whilst this accident resulted in no fatalities, it should be clear that this time might as well not have been available, was the damage more severe. Decisions before as well as during every minute of the accident could have proven far more critical to this accident. A decision support system might have informed the crew if the situation is critical or not, and in this particular scenario it would have need to have been shown as moderate or perhaps not critical, after the watertight doors closure.

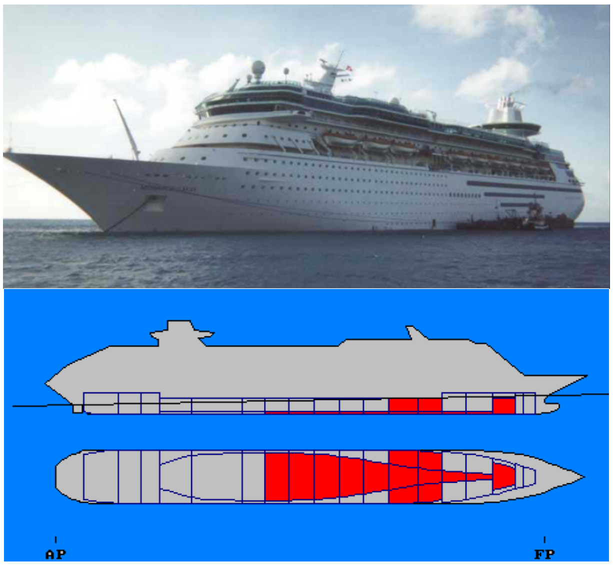


Figure 16 Monarch of the Seas, actual casualty in 1998 and flooding extent, Paulsrud et al 2003.

Of note is the fact that even though importance of WTD closure is identified in the report on this accident as critical, none of the ultimately recommended 20 safety actions, nor the pointed 20 lessons to be learned, mentioned issue of ship watertight integrity explicitly, highlighting only importance of SMS (Safety Management System) procedures.

<u>Rockness, 2004, 18 fatalities</u>

On the 19 of January 2004 the Antigua & Barbuda flagged cargo vessel MV 'Rocknes' capsized within a number of minutes in a strait south of Bergen, Norway, resulting in 18 fatalities, see Figure 17. At the time, the ship was loaded with ground rock-like cargo (stones, gravel) that were to be delivered in Emden, Germany.

Figure 17 MV Rocknes, actual casualty in 2004, Jasionowski et al 2005.

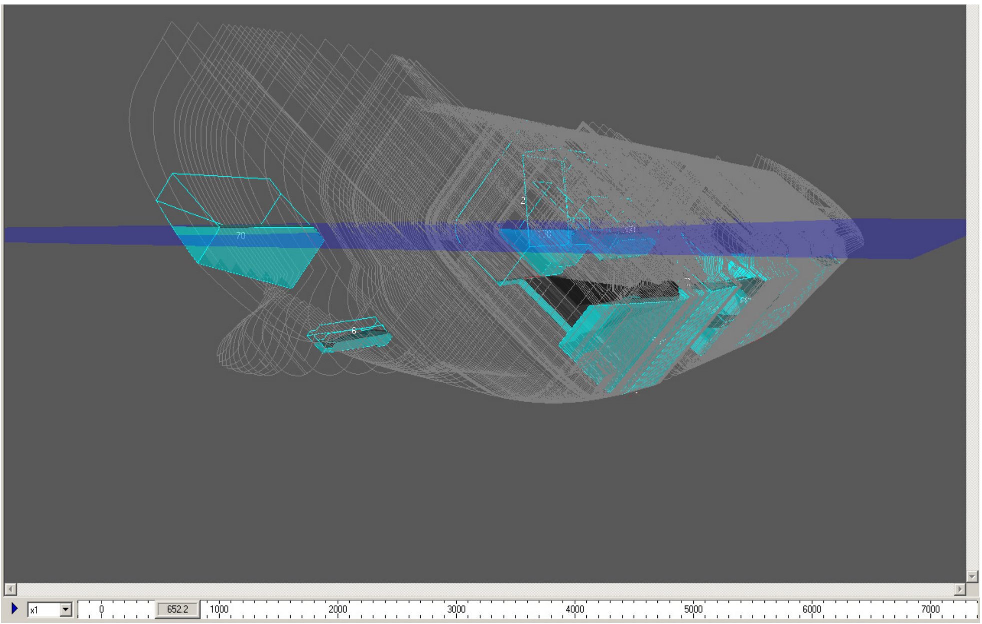


Figure 18 MV Rocknes, numerical reconstruction when heeling to 42 degrees during capsize process. The vessel capsizes in 2 minutes. Visible in a light blue colour are the intact ship free surface tank loads as well as compartments flooded due to damage, Jasionowski et al 2005.

The crew had perhaps 2-3 minutes into the casualty, for making their minds up on what, or if, any action was to be taken, as the rate of ship capsize due to flooding was very high, see Figure 18. Perhaps all these lives could have been saved if the crew was informed at all times of the vulnerability of the vessel to any flooding extent that was feasible, allowing them to react instantly at the first sign of distress.

It can be seen that any projections for supporting decisions for crises management in either of these different ship flooding scenarios would need to have been made virtually within first vital minutes from the very instant of loss of watertight integrity.

Indeed, it could be argued, that even more effective would have been for the crew to know beforehand the crises occurring, as to how to react to the arising situation.

This is the principle, in the search of which the VLog functionality has been developed as a possible ergonomic solution for sustaining the crew's preparedness for response to a crises situation, as described next.

VULNERABILITY LOG (VLog)

Vulnerability Log, or VLog for short, is hereby proposed to be the functionality to inform the crew at all times on the instantaneous vulnerability to flooding of the vessel, considering its actual loading conditions, the environmental conditions and the actual watertight integrity architecture. The vulnerability is proposed to be measured in terms of the probability that a vessel might capsize within given time when subject to any feasible flooding scenario.

Since until a casualty occurs it is impossible to anticipate any specifics of a flooding case a ship might suffer and therefore let the crew prepare for it, it seems plausible that instead the crew is made aware of the range of such flooding specifics together with projected impact these can have on the ship state. The crew would be able to infer the criticality of the situation evolving immediately, based on their own awareness, and hence decide instinctively of the best possible actions to follow.

Ship vulnerability to flooding will naturally vary significantly from a flooding case to a flooding case, and subject to what condition the vessel operates at, at which environment and what is the watertight integrity status. All these must, therefore, be considered.

The flooding scenario considered in this article pertains to a flooding resulting from a ship-to-ship collision event, and the vulnerability will be expressed as a probability of a capsize subject to specific events of loading $W = w$, flooding extent $D = d$, environment $E = e$ and capsize within time of $T = t_c$. The probability mass for such an event can be assigned as follows:

$$p_{W\&D\&E\&T}(w \cap d \cap e \cap t_c) \quad (13)$$

The event $w \cap d \cap e \cap t_c$, can also be referred to as a "compound event" or a flooding "**<u>scenario</u>**", and is regarded as **un**conditional[1], although it would be more appropriate to consider $p_{W\&D\&E\&T|\cdot}(w \cap d \cap e \cap t_c | flooding)$ or in fact $p_{W\&D\&E\&T|\cdot}(w \cap d \cap e \cap t_c | collision \cap flooding)$, however for convenience the conditional notation of $collision \cap flooding$ is omitted.

Considering now that the events of loading and flooding extent can be considered independent, as well as applying the chain rule of probability calculus (Baye's theorem), allows for expressing probability (13) as follows:

$$\begin{aligned} & p_{W\&D\&E\&T}(w \cap d \cap e \cap t_c) = \\ & = p_W(w) \cdot p_D(d) \cdot p_{E|D^*}(e) \cdot p_{T|W\&D\&E}(t_c | w \cap d \cap e) \equiv \\ & \equiv p_W \cdot p_D \cdot p_{E|D^*} \cdot p_{T|W\&D\&E} \end{aligned} \quad (14)$$

Note that $p_{E|D^*}$ is a probability mass distribution for the environment encountered during a collision, and hence should be viewed as probability of event conditional on the collision event occurring, however, for the reasons of practical availability of data, it is not conditional on any specifics of the collision damage.

The mass function of unconditional[1] probability that a joint event of specific loading condition $W = w$, environment $E = e$ as well as the capsize within time of $T = t_c$ occurs can be obtained by marginalization, as follows:

[1] by "unconditional" is implied unconditional on any of the four events of loading W, flooding, D, environment, E, or time to capsize, T, with that the only underlying condition being the occurrence of a collision with hull breach event and ensuing flooding

$$p_{W\&E\&T}(w \cap e \cap t_c) = \sum_{\Omega \setminus (W\&E\&T)} p_{W\&D\&E\&T}(w \cap d \cap e \cap t_c) = \\ = p_W \cdot p_{E|D^*} \cdot \sum_D p_D \cdot p_{T|W\&D\&E} \quad (15)$$

Where $\Omega = \{W, D, E, T\}$.

Deriving from this, the mass function of conditional probability that an event of capsize within time $T = t_c$ occurs, given specific loading $W = w$ and environment $E = e$ occurred can be assigned as follows:

$$p_{T|W\&E}(t_c | w \cap e) = \frac{p_{W\&E\&T}(w \cap e \cap t_c)}{p_W(w) \cdot p_{E|D^*}(e)} = \\ = \sum_D p_D \cdot p_{T|W\&D\&E} \quad (16)$$

For ease of numerical notation, let the probability mass $p_{T|W\&D\&E}$ be denoted as $F_{T|*}(t_c | Hs, j)$, assigning probability (cumulative) distribution for capsize within time t_c, given the environment attained significant wave height Hs, the loading conditions were $W = w$, and the vessel suffered a collision leading to flooding, $collision \cap flooding$, and the specific extent of which can be described as number j out of all feasible flooding extents for the ship at given watertight architecture arrangement. The probability for the extent of flooding, p_D, can consequently be denoted as p_j. Furthermore, let the probability mass $p_{T|W\&E}$ be denoted as $F_T(t_c | Hs)$, and assign cumulative probability for capsize within time t_c, given specific environment condition Hs, loading $W = w$, and the vessel suffered any of the many feasible flooding extents as a result of a collision and ensuing flooding.

Given the above presented theoretical model and the subsequent numerical notations, the following framework, given by equations (12) and (18), is hereby proposed as an instrument to provide with the vulnerability functionality, whereby VLog refers to F_T logged continuously in real ship-operation time.

$$F_T(t_c | Hs) = \sum_j p_j \cdot F_{T|*}(t_c | Hs, j) \quad (17)$$

Where:

$$F_{T|*}(t_c | Hs, j) = 1 - \left(1 - \Phi\left(\frac{Hs - H_{crit,j}}{\sigma}\right)\right)^{\frac{t_c}{t_0}} \quad (18)$$

$$Hs_{crit,j} = 4 \cdot \frac{GZ_{\max,j}}{0.25} \cdot \frac{Range_j}{25} \quad (19)$$

$$\sigma\left(Hs_{crit,j}\right) = 0.061 \cdot Hs_{crit,j} \tag{20}$$

And, furthermore, where:

F_T is, again, cumulative probability distribution for occurrence of ship capsize within time t, conditional on event of a sea state of Hs occurring and subject to <u>any</u> feasible flooding scenario.
$F_{T|*}$ is cumulative probability distribution for occurrence of capsize within time t, conditional on events of a sea state of Hs and a <u>specific</u> flooding scenario j occurring.
t_c is time, minutes.
$t_0 = 30\,\text{min}$ is benchmark physical testing time.
Hs is significant wave height, metres.
j is ship flooding scenario considered.
p_j is probability mass of flooding scenario j occurring, according to MSC 84, 2006, with theoretical details available at Pawłowski, 2004 and 2005.
$\Phi(z)$ is cumulative standard normal probability distribution function.
$H_{crit,j}$ is 50th percentile significant wave height in which a ship subjected to flooding scenario j might capsize.
$GZ_{\max}$, $Range$ is maximum restoring lever and range of positive restoring moment for a ship subjected to flooding scenario j, metres and degrees, respectively.

Note that both probabilities F_T and $F_{T|*}$ are assigned for events of capsize conditional on all other implicitly considered events, such as sea state, loading condition and instantaneous watertight architecture arrangement occurrences.

Considering a special case of loading conditions, say corresponding exactly to the deepest subdivision draught DS as it is used in calculations for SOALS CH II, the following can be observed:

$$s_j = \int_0^\infty dHs \cdot f_{Hs|coll}\left(Hs\right) \cdot \left(1 - F_{T|*}\left(t_c = 30\,\text{min} \middle| Hs, j\right)\right) \tag{21}$$

Which is the marginal probability of ship surviving in any sea states Hs expected in a collision accidents, also known as "s" factor of MSC82/24, with $f_{Hs|coll}\left(Hs\right)$ representing probability density distribution for such sea states.

And with so assigned probability s_j, and accounting for other phenomena, as regulatory instruments MSC82/24 stipulates, one can relate equation (12) to the well know probabilistic subdivision index A_{DS} which is calculated as

$$A_{DS} = \sum_j p_j \cdot s_j \tag{22}$$

More details on theory of models (12), (18) and (20) can be found in Jasionowski 2006a and 2007, whereas on model (19) in Tagg et al, 2002.

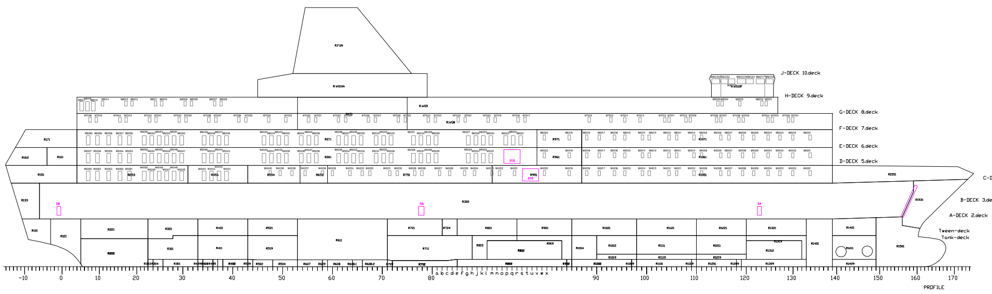
The next paragraph aims to demonstrate and then explain how the VLog functionality would work in practice, including giving practical interpretations of F_T as well as $F_{T|*}$.

SENSITIVITY STUDY

A case of MV Estonia is hereby used to demonstrate the VLog functionality. Loading condition at the time of the loss of the vessel in 1994 were used, see Table 5 and Figure 19.

Table 5 MV Estonia, ship particulars.

L_{bp}	137.4m
B	24.2m
Displacement	11,930 [m^3]
Draught mean	5.39m
Trim	0.435m aft
GM	1.17m
KG	10.62m



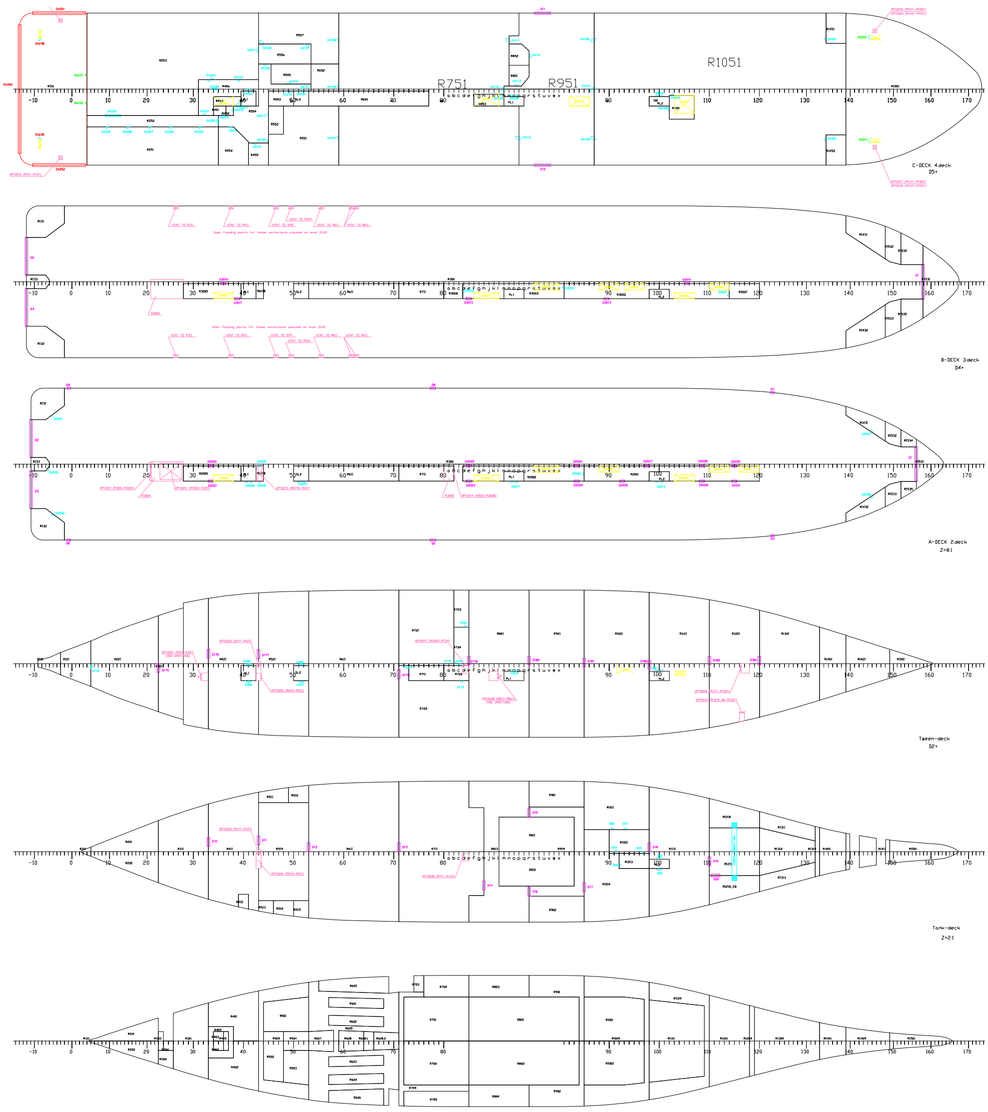


Figure 19 The GA of MV Estonia assumed for numerical modelling.

Let some characteristics of the kernel function (18) be examined first. For this reason a flooding case No 36 out of total 1368 flooding cases considered, and No 36 with adjacent watertight door opened, are used, as shown in Figure 20 to Figure 22 below.

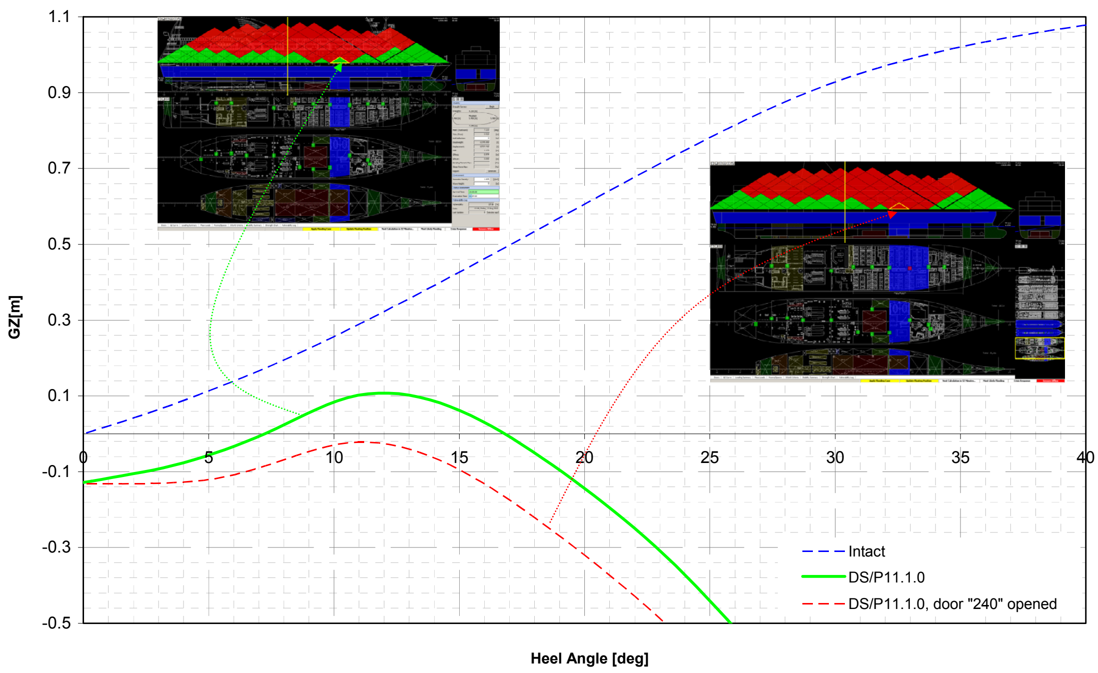


Figure 20 MV Estonia, flooding case No 36, all doors closed, hydrostatic properties.

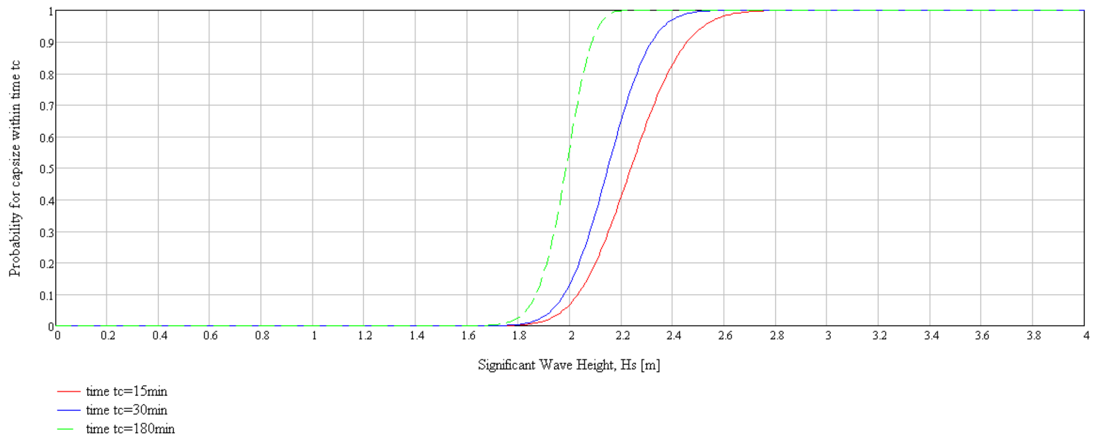


Figure 21 Probability for capsize within time tc. Case No 36 with all doors closed. Effect of significant wave height.

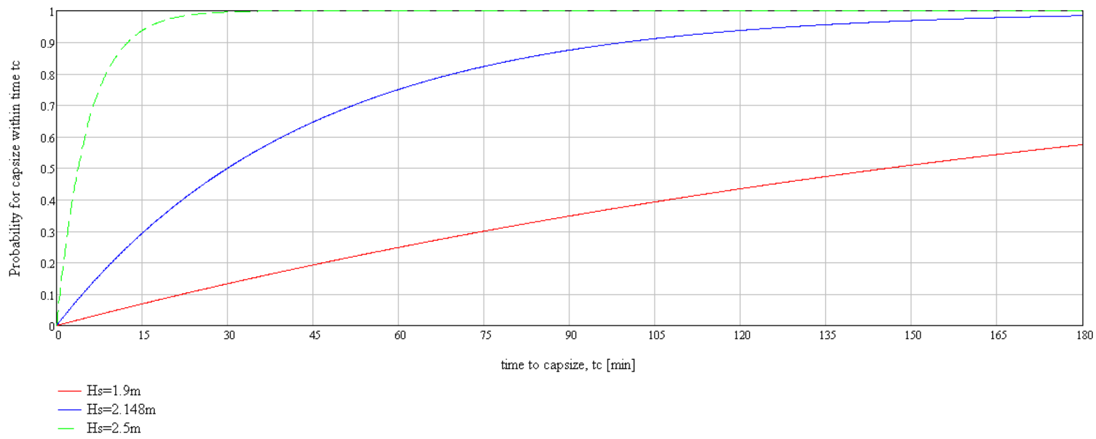


Figure 22 Probability for capsize within time t_c. Case No 36 with all doors closed. Effect of assumed time to capsize.

As can be seen the probability assigned to the event of capsize varies significantly from a flooding case to flooding case, as well as due to the environment conditions. The lesser the stability, or the higher the sea state, the more likely it is that a ship will capsize within given period of time. Note also that the longer a period of time one wishes to infer on the fate of the ship, the more likely it is that capsize will occur, as one would expect.

Perhaps worth of note is assigning of $F_{T|*}\left(t_c = 30\,\text{min} \middle| Hs = 0m, j = 36\right) = 0.5$ for a case of adjacent watertight door left opened, where the ship has no stability whatsoever. Although it is expected that capsize would be imminent, that is the probability should be 1.0, the approach is consistent with the assumptions of critical sea state underlying model (19), that is likelihood of capsize within bench-testing time of 30min is 0.5. This small detail is subject of ongoing investigation, however, given that sea state is hardly ever 0m, it seems to bear little practical significance.

Next, the following series of figures, Figure 23 to Figure 31, are presented to allow for thorough interpretation of the VLog functionality.

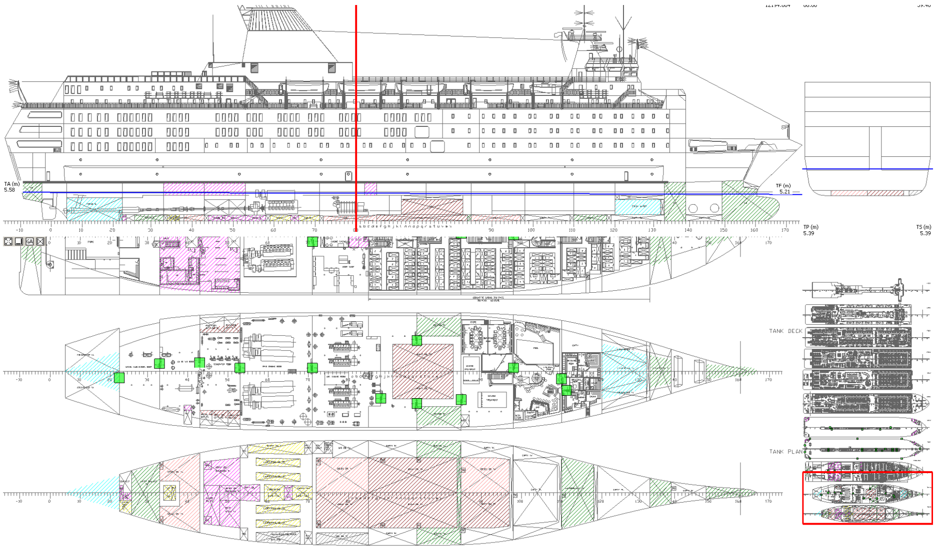


Figure 23 Ergonomic communication interface, model of MV Estonia, screenshot of watertight doors (WTD) closure status, green indicates "closed", red "opened".

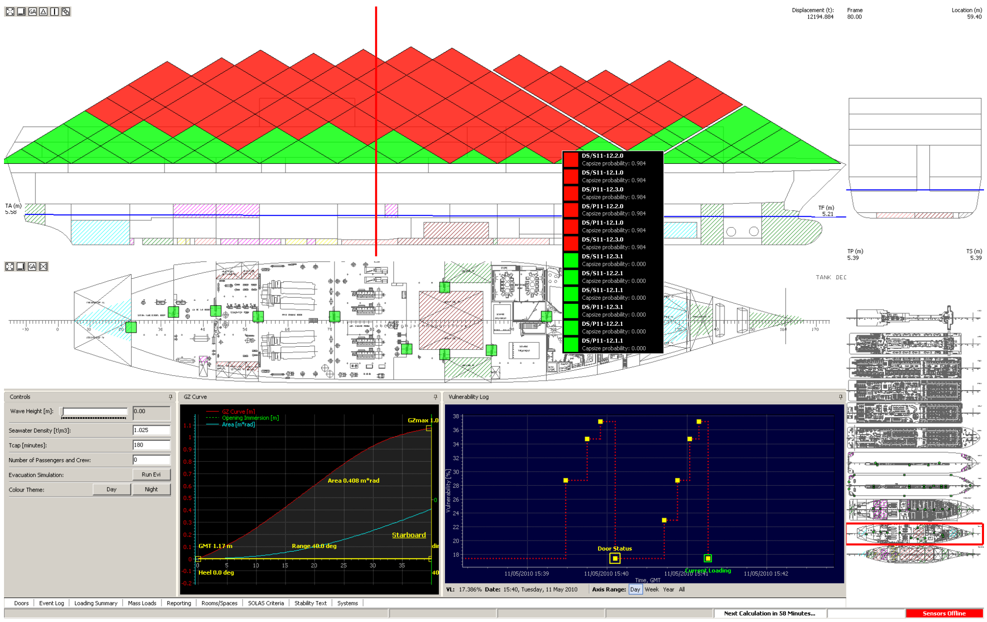


Figure 24 Vulnerability information, screenshot of the colour-coded values of $F_{T|*}(3hrs|Hs = 0m, j)$ for each of the $j = 1 \ldots 1368$ flooding cases, each represented by a "diamond", as well as $F_T(3hr|0m) = 17.38\%$ of ship overall vulnerability, all logged down at **15:40:06** hours (example time marked by the yellow square at 15hrs 40min 06seconds). For overlapping "diamonds" (e.g. multiple penetration or vertical extent for the same length of flooding case), the worst cases are shown.

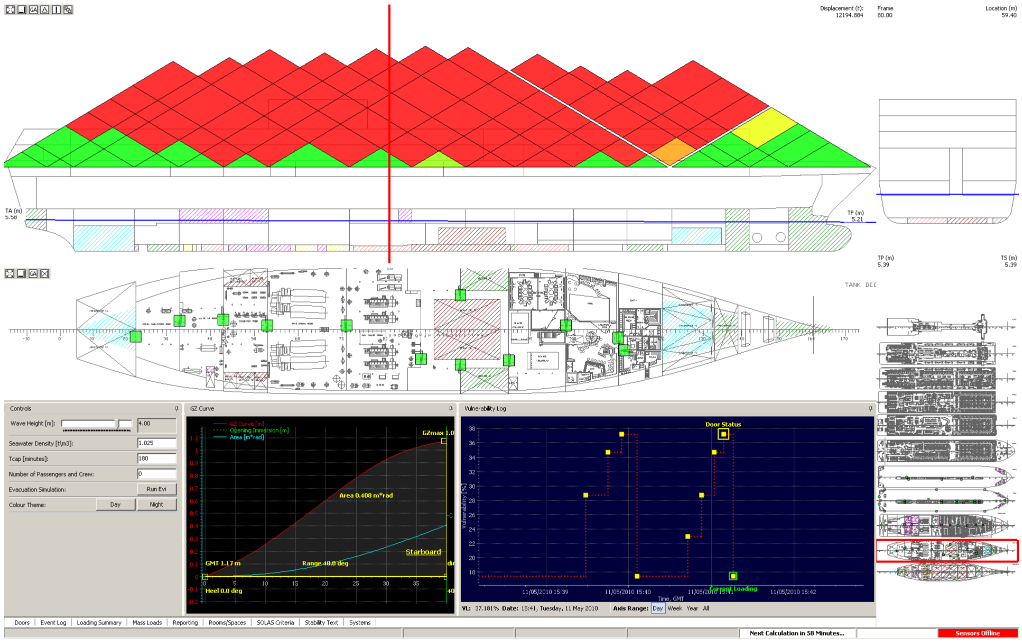


Figure 25 Screenshot of the colour-coded values of $F_{T|*}(3hrs|Hs=4m, j)$ for each of the flooding cases, ship vulnerability $F_T(3hr|4m)=37.18\%$ (purple window), logged down at **15:41:09** hours (example time marked by the yellow square at 15hrs 41minutes 09seconds). The green coloured "diamonds" indicate $F_{T|*}=0\%$, and red $F_{T|*}=100\%$. GZ curve and draught marks shown for the ship in intact condition. Sea state Hs manual input shown in the left lower corner.

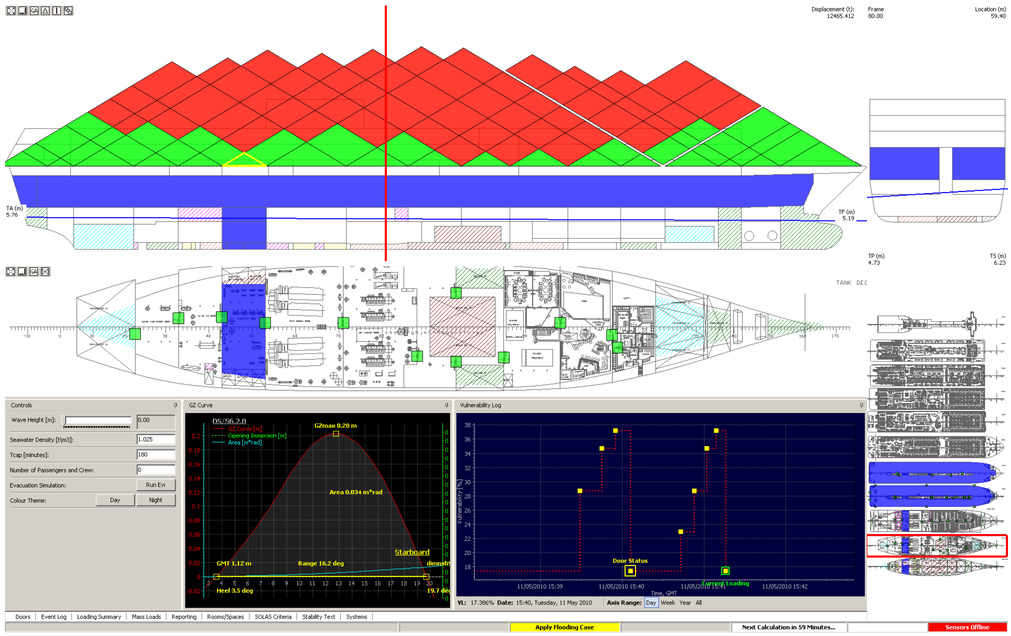


Figure 26 Flooding extent for damage case j=702, DS/S6.2.0, (diamond/triangle in yellow frame), with corresponding GZ curve logged at **15:40:06**, see Figure 24. Ship vulnerability $F_T(3hr|0m)=17.38\%$. Note that draught marks correspond to ship condition of the most recent log at 15:41:16.

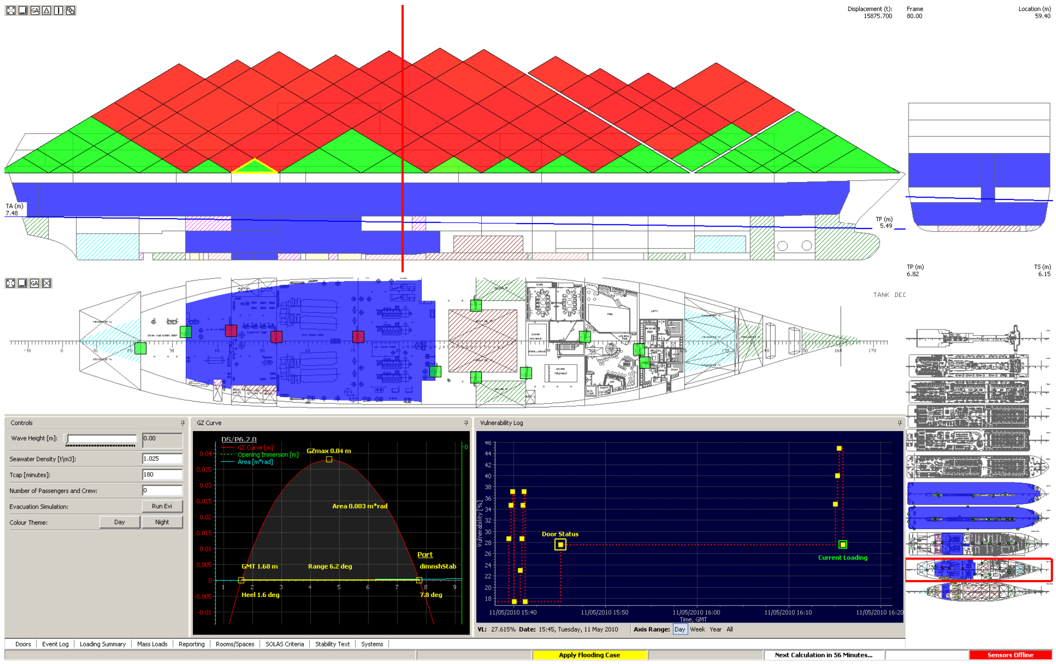


Figure 27 Flooding extent for damage case j=702, DS/S6.2.0, (diamond/triangle in yellow frame), with corresponding GZ curve logged at **15:45:09**, ship vulnerability $F_T(3hr|0m) = 27.61\%$. Note the three watertight doors, #216, #217 and #218, on the tank deck opened with the ensuing impact on the flooding extent. Note again Hs=0m.

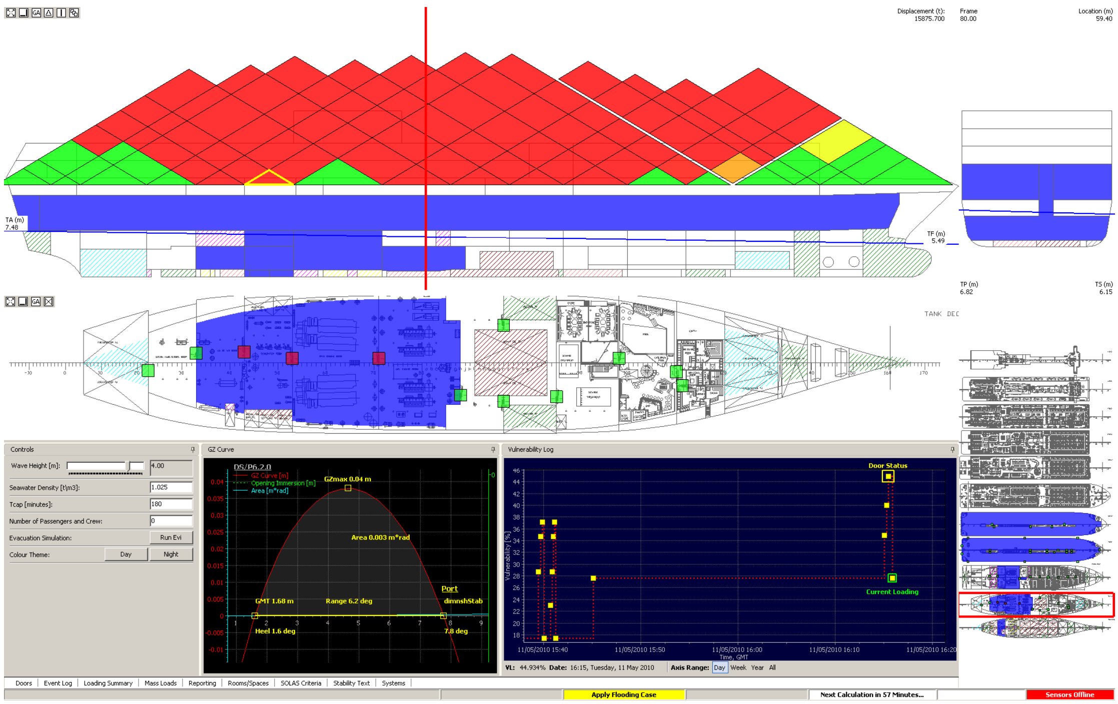


Figure 28 Flooding extent for damage case j=702, DS/S6.2.0, (diamond/triangle in yellow frame), with corresponding GZ curve logged at **16:15:28**, ship vulnerability $F_T(3hr|4m) = 44.93\%$. Note Hs=4m.

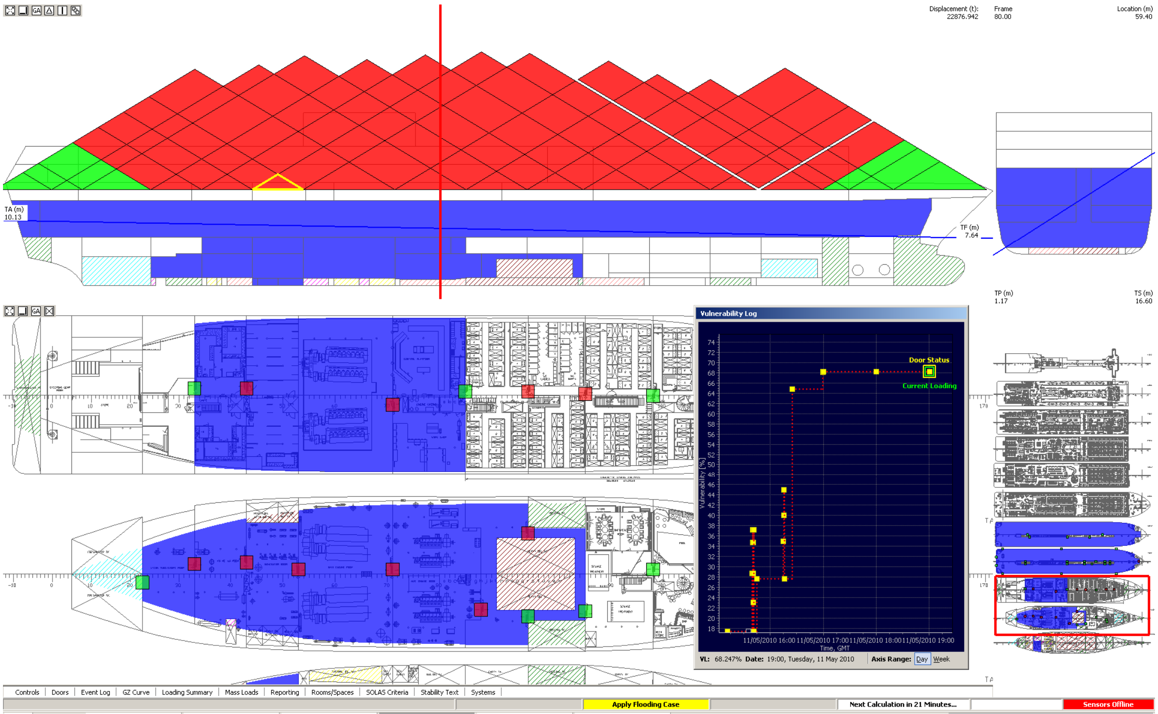


Figure 29 Flooding extent for damage case j=702, DS/S6.2.0, (diamond/triangle in yellow frame), with corresponding GZ curve logged at **19:00:30**, ship vulnerability $F_T(3hr|4m) = 68.24\%$. Note Hs=4m and many WTD opened. Very likely state of the vessel on the night of the ship loss in September 1994.

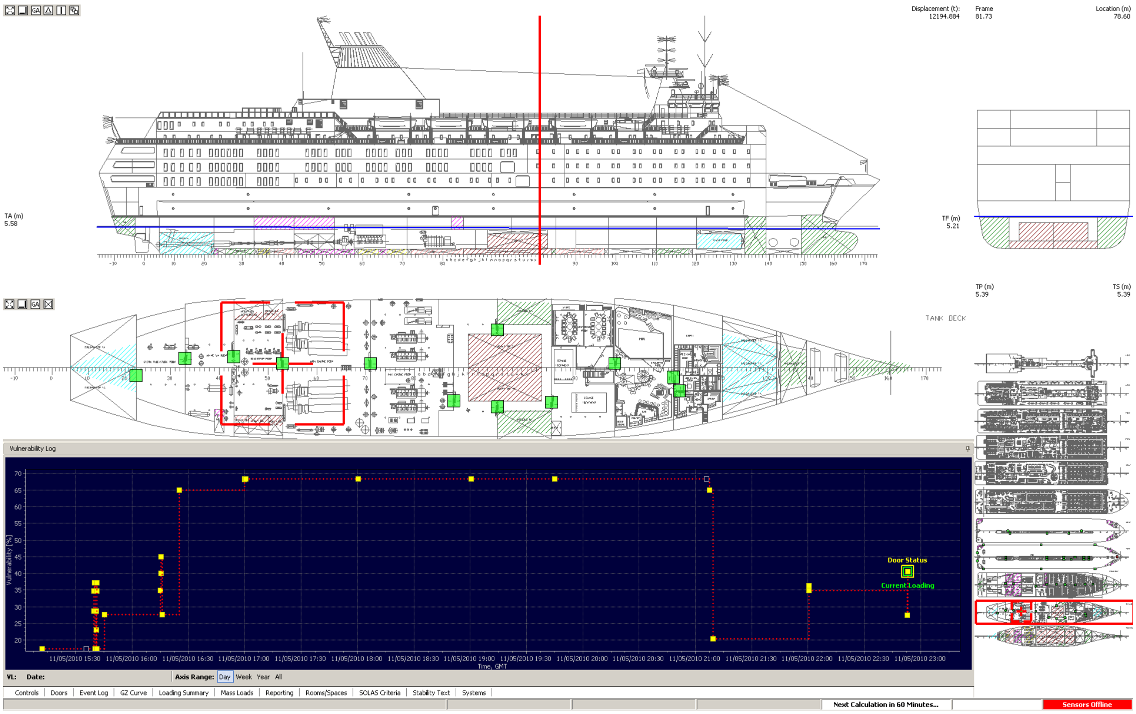


Figure 30 Sample of 8 hours vulnerability log (VLog).

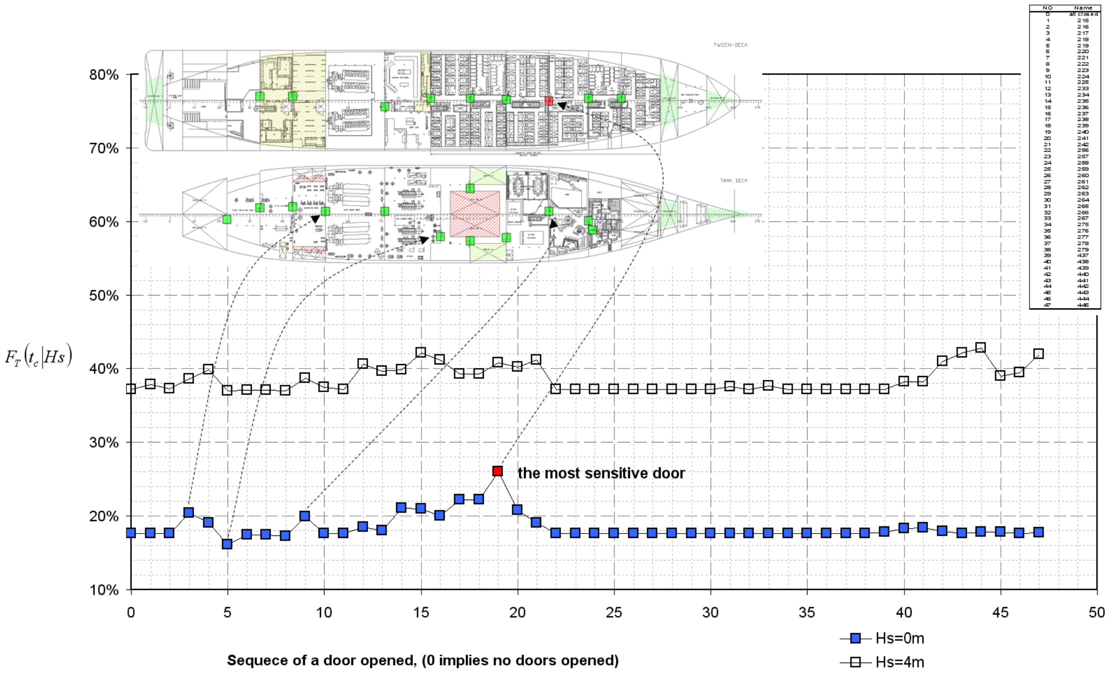


Figure 31 Impact of single doors opening on overall ship vulnerability.

Before expanding discussions of the VLog functionality for decision support, the following further set of real-life sample of results gathered on an undisclosed ship is presented to demonstrate the significance of the VLog for daily use. As can be seen, the crew awareness of vulnerability at any one time can lead to its substantial and material reduction.

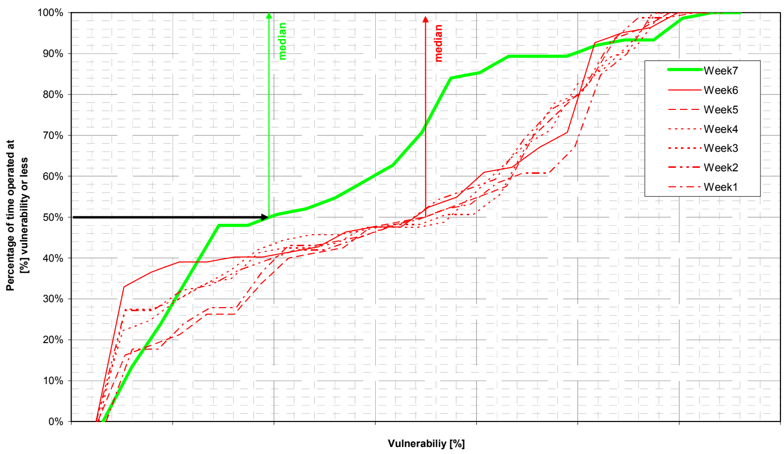


Figure 32 Distribution of vulnerability logged on a demonstration ship. The actual vulnerability values are undisclosed. The impact of the awareness of the crew on the day-to-day management of watertight integrity, and hence crew and ship preparedness, can be seen in the Week 7, when explanation and training on use of VLog had been given.

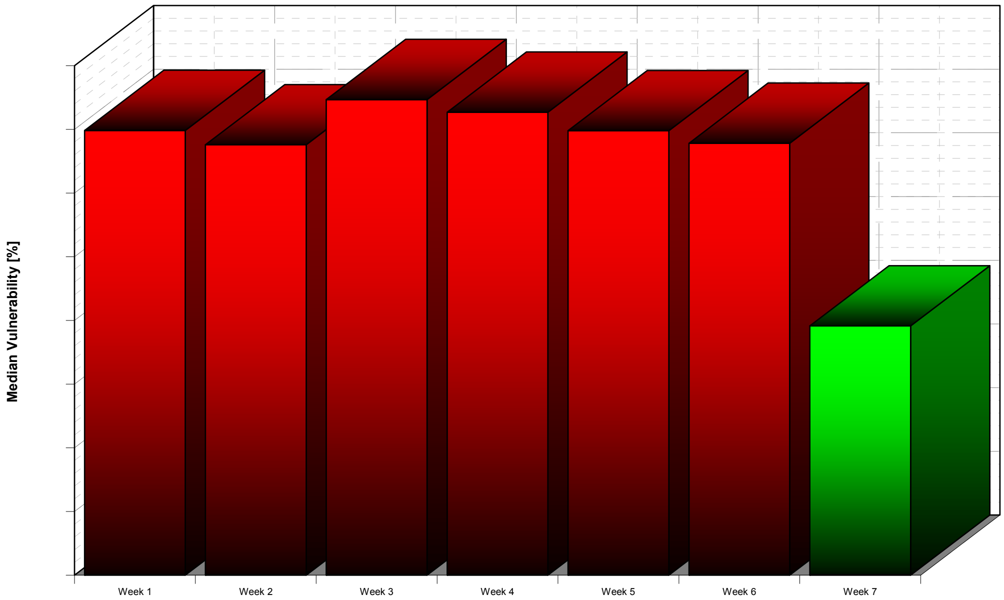


Figure 33 Median of vulnerability logged on a demonstration ship. The actual vulnerability values are undisclosed. The impact of the awareness of the crew on the day-to-day management of watertight integrity, and hence crew and ship preparedness, can be seen in the Week 7, when explanations and training on use of VLog had been given.

DISCUSSIONS

The first element worth mentioning is the interpretation of "vulnerability". As mentioned earlier, ship vulnerability to flooding is proposed to be measured by means of the probability that an event of ship capsizing within given period of time occurs, subject to status assumptions.

For a flooding scenario resulting to final floating attitude, it is expected that ship's residual stability will be sufficient to sustain its functional attitude for a level of environmental excitation. The relationship between residual stability and the environment has been derived in project HARDER, as reported in Tagg 2002, and as given here by equation (19). It has subsequently been shown in the project SAFEDOR, Jasionowski at al 2006a, 2006b, 2007, that this relationship can be used to describe stochastic nature of ship capsize for any given environment, and that it can be marginalised for all feasible flooding scenarios.

Thus, for an example of a specific flooding case j, a vulnerability of $F_{T|*}\left(3hrs \middle| Hs = 2m, j\right) = 40\%$ recorded in a given instant of time, implies probability of 40% that a ship may capsize in 3 hours, when subject to specific environmental conditions of Hs=2m. In other words, applying "frequentist" interpretation of probability, should the vessel suffer 10 accidents involving **exactly** flooding extent j, and each time at sea state of Hs=2m, it would be expected to observe 4 capsizes within less than 3 hours, or between 0 and 8 capsizes, when accommodating for sampling uncertainty. This vulnerability can be derived for any feasible flooding extent for given ship design, and it can be conveyed to the crew in an ergonomic manner by means of colour coding, see the colourful "diamonds" in either of Figure 24 to Figure 29.

Furthermore, the vulnerability can be "averaged" for all flooding cases with "weights" corresponding to likelihood of any flooding extent occurring, in the marginalisation process. Thus, an example of an overall vulnerability of $F_T(3hr|4m) = 70\%$, indicates probability of 70% that a ship may capsize in 3 hours, when subject to specific environmental conditions of Hs=4m and for any among the many feasible flooding extents a ship might suffer. In other words, should the vessel suffer 10 accidents involving **any** flooding extent, and each time at sea state of Hs=4m, it would be expected to observe 7 capsizes within less than 3 hours, or between 3 and 10 capsizes, when accounting for sampling uncertainty. This "overall" vulnerability can be derived periodically for given ship conditions and conveyed to the crew in an ergonomic manner as a time-log, see Figure 30.

It can be noted in Figure 30 the "enormity" of the extent to which operation can have on the ship's instantaneous vulnerability, that is its ability to sustain stable attitude when subject to loss of watertight integrity. The vulnerability can increase from some 18% to nearly 70%, for the sample study cases used. The various conditions leading to this dramatic variation can again be found from Figure 24 to Figure 29. The impact of each of the watertight doors considered in separation, can be seen in Figure 31, which seems to be a powerful method that can be used during design stage, to guide distribution of watertight architecture in the vessel in the first place.

The variation in time reflects changes to ship loading conditions, environment conditions Hs, as well as watertight integrity through opening of watertight doors.

The very process of logging in time of quantified and meaningful measure of vulnerability allows for auditing of the "goodness" of the operation. Such information, easily inferable from typical on-board computer display, allows for development and sustaining of understanding on what to expect, should flooding casualty occur. The actual field-testing has demonstrated the merit of VLog functionality, as shown in the records in Figure 32 and Figure 33.

For instance, given the vulnerability of MV Estonia on the night of the loss as shown in Figure 29, it can easily be seen that the vessel is extremely likely to capsize due to flooding.

The fact that specific type of flooding which is thought to have happened on the night of the casualty is not taken into account in cases used in Figure 29 is immaterial. The crew would not know what was happening exactly, but given projections as shown in Figure 29 with vulnerability of 70%, it would be instantly obvious that immediate action is required at the first sign of problems. More importantly, the crew might have taken greater vigil, were they aware of how vulnerable their ship can be, and how this can be managed through their own actions.

REFERENCES

Bergholtz, J, Rutgersson, O, Schreuder, M: *“WP2.1 Review of evidence Report No. 2 Conceivable course of events”*, Department of Shipping and Marine Technology, Chalmers, Technical Report, March 2008.

Bole Marcus, *“Introducing damage structural assessment to onboard decision support tools”*, Graphics Research Corporation Ltd, UK, ca 2007.

Guarin Luis, Jayanta Majumder, Vladimir Shigunov, Guro Vassalos and Dracos Vassalos, *“Fire and flooding risk assessment in ship design for ease of evacuation”*, Design for safety Conference, Osaka, 2004.

Jasionowski, A, *“An integrated approach to damage ship survivability assessment”*, PhD thesis, University of Strathclyde, 2001.

Jasionowski Andrzej, Khattab Omar, *“Time Domain Simulation of the Dynamics of Progressive Flooding and Capsizing MV Rockness”*, TQRN01-RE-001-AJ, *12 September 2005.*

Jasionowski A, Bulian G, Vassalos D, Francescutto A, Pawłowski, M, Maccari A, *“Modelling survivability”*, EC SAFEDOR, D2.1.3., November 2006a.

Jasionowski Andrzej, Dracos Vassalos, *“Conceptualising Risk”*, 9th International Conference on Stability of Ships and Ocean Vehicles, Rio de Janeiro, September 2006b.

Jasionowski Andrzej, Dracos Vassalos, Andrew Scott, *“Ship Vulnerability To Flooding”,* 3rd International Maritime Conference on Design for Safety, Berkeley California, Sept 26 28th, 2007.

Jasionowski, A, Vassalos, D: *“Technical Summary of the Investigation on The Sinking Sequence of MV Estonia”*, Safety at Sea Report No VIES01-RE-005-AJ, May 2008, Technical Summary of the Investigation on The Sinking Sequence of MV Estonia.

de Kat Jan O, Peters Andrew J, *“Model experiments and simulations of a damaged frigate”,* IMAM 2002 congress, Crete, May 2002, No. 129.

Letizia, L and Vassalos, D, "Formulation of a Non-Linear Mathematical Model for a Damaged Ship With Progressive Flooding", International Symposium on Ship Safety in a Seaway, Kaliningrad, Russia, May 1995.

Letizia, L, “Damage Survivability of Passenger Ro-Ro Vessels Subjected to Progressive Flooding in a Random Sea”, PhD Thesis, University of Strathclyde, 1997.

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

Papanikolaou A, Zaraphonitis G, Spanos D, Boulougouris V, Eliopoulou E, *“Investigation into the capsizing of damaged Ro-Ro passenger Ships in Waves”,* Proc. 7th Inter. Conf. On Stability of Ships & Ocean Vehicles STAB2000, Australia, Tasmania, 2000.

Paulsrud Finn, Farley J Timothy, Norwegian/US Coast Guard, *“Report of investigation into the circumstances surrounding the grounding of the Monarch of The Seas on proselyte reef in Great Bay, Philipsburg, St Maarten, Netherlands Antilles on December 15, 1998, resulting in major vessel damage, no loss of life and minor pollution”*, 10 April 2003.

Pawłowski, M, **“***Subdivision and damage stability of ships*”, 2004, Euro-MTEC book series, Foundation for the Promotion of Maritime Industry, Gdansk, ISBN 83-919488-6-2.

Pawłowski, M, *"Probability of flooding a compartment (the pi factor) – a critique and a proposal*", Proceedings of the Institution of Mechanical Engineers, Part M: *J. Engineering for the Maritime Environment*, 2005, Vol. 219, pp. 185–201.

Ruponen Pekka, Sundell Tom, Larmela Markku, *"Validation of a simulation method for progressive flooding"*, 9thInternational Conference on Stability of Ships and Ocean Vehicles, 2006.

Petey, F, *"Ermittlung der Kentersicherheit lecker Schiffe im Seegang"*, Schiffstechnik *35*, 155-172, 1988.

Piñeiro A Lopez, F Perez Arribas, R Donoso, R Torres, *"Simulation of Passengers Movement on Ship Emergencies: Tools for IMO Regulations Fulfillment*", J. Maritime Research, vol. 2, no. 1, 2005, pp. 105-125.

Schreuder, M, *"Numerical Simulations Of Foundering Scenarios, Research Study Of The Sinking Sequence Of M/V ESTONIA",* Research Report No.134, SSPA, Göteborg, Sweden, 2008.

Tagg R, Tuzcu C, *"A Performance-based Assessment of the Survival of Damaged Ships – Final Outcome of the EU Research Project HARDER"*, Proc. of the 6th Intern. Ship Stability Workshop, Webb Institute, 2002.

Varela Jose M, G Guedes Soares, *"A virtual environment for decision support in ship damage control"*, August 2007, IEEE Computer Society.

Vassalos Dracos, Hyunseok Kim, Guro Christiansen and Jayanta Majumder, *"A Mesoscopic Model for Passenger Evacuation in a Virtual Ship-Sea Environment and Performance-Based Evaluation",* Pedestrian and Evacuation Dynamics – April 4-6, 2001 – Duisburg.