

## **Safety Level of Damaged RoPax Ships – Risk Modelling and Cost Effectiveness Analysis**

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### **ABSTRACT**

This paper elaborates on results of a recent risk analysis study for RoPax vessels, carried out as part of the activities of the SAFEDOR Integrated Project, targeting possible improvements on safety levels following large scale flooding. The study is based on a comprehensive analysis of accident statistics for the period 1994-2004, through which a high-level risk model (in the form of event trees) is established. This is then used to determine the current safety level of RoPax vessels (in various risk metrics, such as individual risk, potential loss of life and on an F-N curve), reconfirming that even though safety levels are improving, risk is still “*high in the ALARP region*”. In search of ways to further improve the situation possible risk control options are examined, by performing a sensitivity analysis on the effects of the Attained Index of Subdivision A onto the safety levels and by evaluating their cost-effectiveness.

### **KEYWORDS**

Damaged RoPax ships; risk modelling; cost-effectiveness

### **INTRODUCTION**

The main consequences on a RoPax following an accident may be graceful sinking or capsize and/or fire which can result in great loss of life among the passengers and crew onboard. The focus of this paper is on the evaluation of potential risk control options relating to credible accident scenarios that may lead to large scale flooding, using a high-level risk model. The work has been performed in accordance with the IMO FSA Guidelines [IMO, 2002].

At IMO, regulations on subdivision and damage stability of RoPax ships (SOLAS Chapter II-1) have received considerable attention over the years. Currently, the global standard for damage stability of RoPax ships is the vessel to be able to sustain any two-

compartment damage and also fulfilling a set of deterministic requirements known as SOLAS 90. This represents a significant improvement with the standards applicable at the beginning of 1990s. In North West Europe, an increased standard is applied for existing ships, known as the “Stockholm Agreement” or SOLAS 90+50, which requires either fulfillment of the deterministic standards of SOLAS 90 with an additional height of water on deck (maximum of 50 cm), or the demonstration by means of a model experiments that the vessel can survive in damaged conditions the sea state at the area of operation.

The IMO’s Sub-Committee on Subdivision, Load Lines and Fishing Vessel Safety (SLF) has developed a new set of probabilistic rules for all ship types for global application from 2009 onwards. These rules follow the

approach developed at Resolution A.265 (IMO issued this resolution at 1974, as an alternative to the deterministic SOLAS damage stability requirements) and are mainly based on extensive research work carried out at the late 1990s / early 2000s as part of the activities of the EC-funded research project HARDER.

Following background information on the risk acceptance criteria used and an overview of relevant accident statistics, the paper provides details of the high-level risk model developed, discusses potential risk control options and evaluates their risk reduction potential as well as their cost-effectiveness. On the basis of these considerations some recommendations on appropriate safety levels of RoPax ships are given.

## BACKGROUND INFORMATION

### *Risk Acceptance Criteria*

The following outlines the acceptance criteria used in this study for individual risk (passengers and crew members) and for societal risk.

Individual risk is usually expressed as the frequency of an individual fatality per year. MSC72/16 proposes criteria for individual risk for shipping operations at the same level as those used by the UK Health and Safety Executive. These criteria are reproduced below for passengers and crew members.

|   |                    |
|---|--------------------|
| Boundary between negligible risk and the ALARP area                                   | $10^{-6}$ per year |
| Maximum tolerable risk for passengers (risks below this limit should be made ALARP)   | $10^{-4}$ per year |
| Maximum tolerable risk for crew members (risks below this limit should be made ALARP) | $10^{-3}$ per year |

Societal risk acceptance criteria for RoPax ships are established in the SAFEDOR public deliverable D4.5.2 (Risk Acceptance Criteria), in accordance with to the approach presented in

document MSC 72/16, i.e. based on the economic importance of RoPax shipping. These criteria are presented in Figure 1.

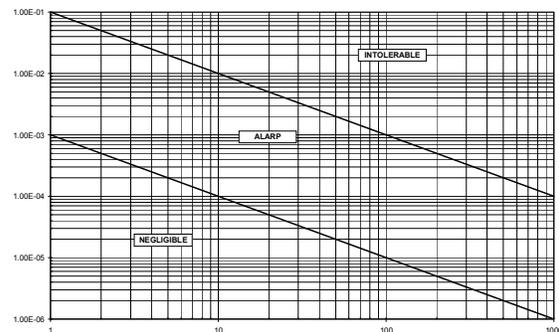


Fig. 1: Societal risk acceptance criteria for RoPax ships

### *Accident Statistics*

A thorough casualty statistics analysis has been carried out, based on historical data for the period 1994-2004, obtained by the Lloyds Maritime Information Unit (LMIU) and on fleet statistics for the same period, obtained by Lloyds Register Fairplay (LMFP).

The LMIU casualty database includes 1,147 incidents for RoPax ships world-wide for the period 1994-2004. 54 incidents have happened during repairs or conventions, labour and other disputes, on vessels that were already laid-up or to be broken up (9 incidents for RoPax of 1,000 to 4,000 GRT range and 45 incidents for RoPax of 4,000 GRT and above). These incidents have not been taken into account in the analysis. Also, there were a further 3 incidents which are attributed as acts of terrorism (notably one explosion involving considerable number of fatalities), which have also not been taken into account in the analysis.

42 of the incidents included in the database have occurred on RoPax ships of 100 to 1,000 GRT. These are excluded from the analysis due to the fact that these smaller ships are usually engaged on short crossings and passages and are often of an open-type configuration and hence are not representative for a generic risk analysis study on RoPax ships (typically of a closed-type configuration and with part of her trip exposed to weather).

Casualty records held by LMIU classify incidents as serious and non-serious. An incident is considered as serious if it has involved a single or multiple fatalities, damage to the vessel that has interrupted her service or if the vessel has been lost.

Table 1 contains an analysis of the LMIU RoPax casualty data for the period 1994-2004, for RoPax of 1,000 GRT and above.

Figure 2 illustrates the F-N for RoPax based on world-wide operation for the period 1994-2006 (i.e. including the Al Salam Boccaccio 98

incident, which caught fire on 3 February 2006 resulting in 1,000 fatalities among the 1,300 people onboard). The figure also includes, for comparison purposes, the F-N line representing experience with fatal incidents in North West Europe during the period 1978-2004.

Comparison on the F-N curve of the potential loss of life of the period 1994-2004 world-wide with North West European experience for the period 1978-1996, demonstrates a considerable risk reduction, however, it also demonstrates that risk is still high at the ALARP region.

Table 1: Number of Incidents and Frequencies

|                          | # Incidents  |            | % Total       | % Serious     | Frequency (per ship year) |                 |
|--------------------------|--------------|------------|---------------|---------------|---------------------------|-----------------|
|                          | Total        | Serious    |               |               | Total                     | Serious         |
| Collision                | 194          | 20         | 18.4%         | 11.0%         | 1.25E-02                  | 1.29E-03        |
| Contact                  | 193          | 21         | 18.3%         | 11.6%         | 1.25E-02                  | 1.36E-03        |
| Fire/Explosion           | 128          | 50         | 12.2%         | 27.6%         | 8.28E-03                  | 3.23E-03        |
| Wrecked/Stranded         | 148          | 47         | 14.1%         | 26.0%         | 9.57E-03                  | 3.04E-03        |
| Hull Damage              | 35           | 7          | 3.3%          | 3.9%          | 2.26E-03                  | 4.53E-04        |
| Foundered                | 2            | 2          | 0.2%          | 1.1%          | 1.29E-04                  | 1.29E-04        |
| Machinery damage/failure | 289          | 31         | 27.5%         | 17.1%         | 1.87E-02                  | 2.00E-03        |
| Miscellaneous            | 63           | 3          | 6.0%          | 1.7%          | 4.07E-03                  | 1.94E-04        |
| <b>TOTAL</b>             | <b>1,052</b> | <b>181</b> | <b>100.0%</b> | <b>100.0%</b> | <b>6.80E-02</b>           | <b>1.17E-02</b> |

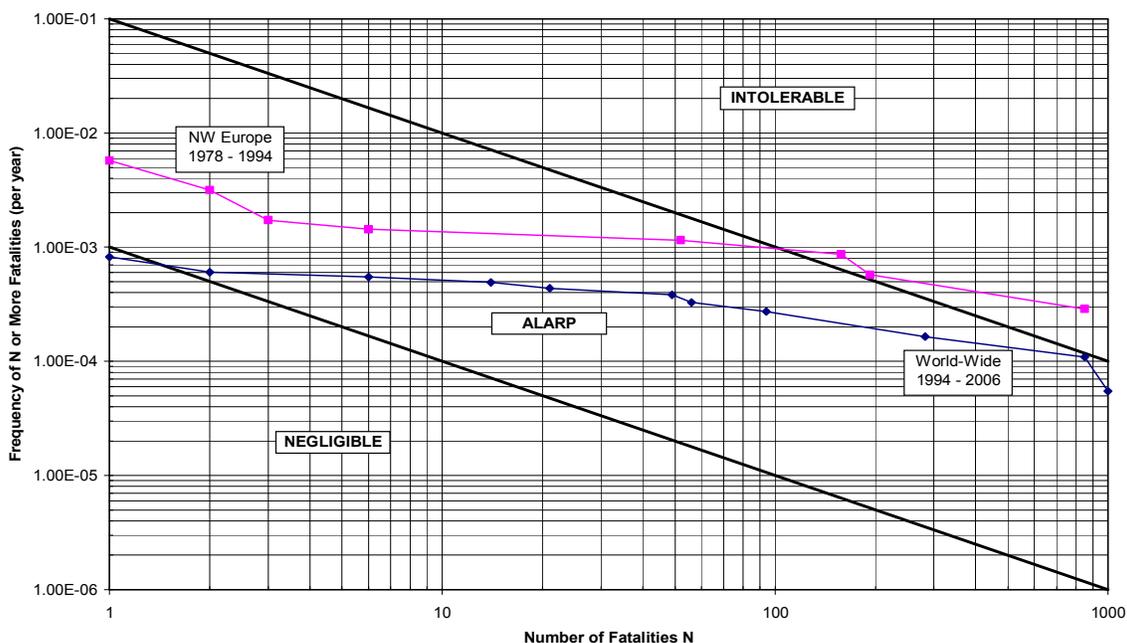


Fig. 2: RoPax F-N Curve (Historical Risk)

**RISK MODELLING**

Based on the results of a HAZID session purposely organised (SAFEDOR, 2006) and the analysis of available accident statistics, five generic top events were selected for further analysis, namely collision, grounding, impact, flooding from other causes and fire/explosion.

Accident experience for the period 1994-2004 provides an accurate basis for the estimation of frequencies of these five generic top events. The results are presented in Table 1.

The next step in risk modelling was to assess the expected consequences for each of the identified events. This was done using event trees, i.e. by constructing and quantifying a

sufficient number of scenarios of potential outcomes. The event trees relevant to the work presented in this paper, namely event trees for collision, grounding, impact and flooding from other causes, are illustrated in Figures 3 to 6.

Assignment of branch probabilities in the event trees of Figures 3 to 6 was done using accident statistics for the period 1994-2004, results from past relevant research studies (such as the Joint North West European Project, DNV Technica, 1996, and the HARDER project) and, where necessary, expert judgement.

Table 2 provides a summary of the risk calculations carried out, whilst Figure 7 presents the F-N curve calculated by the risk model.

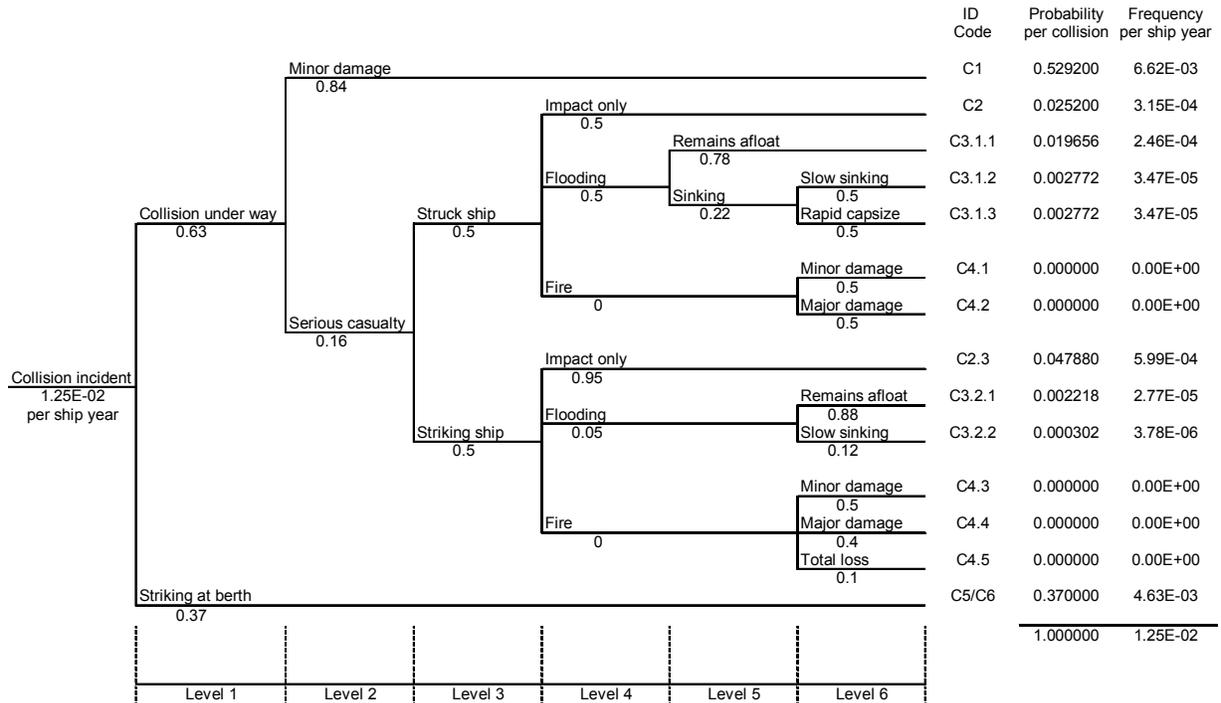


Fig. 3: Generic Collision Event Tree

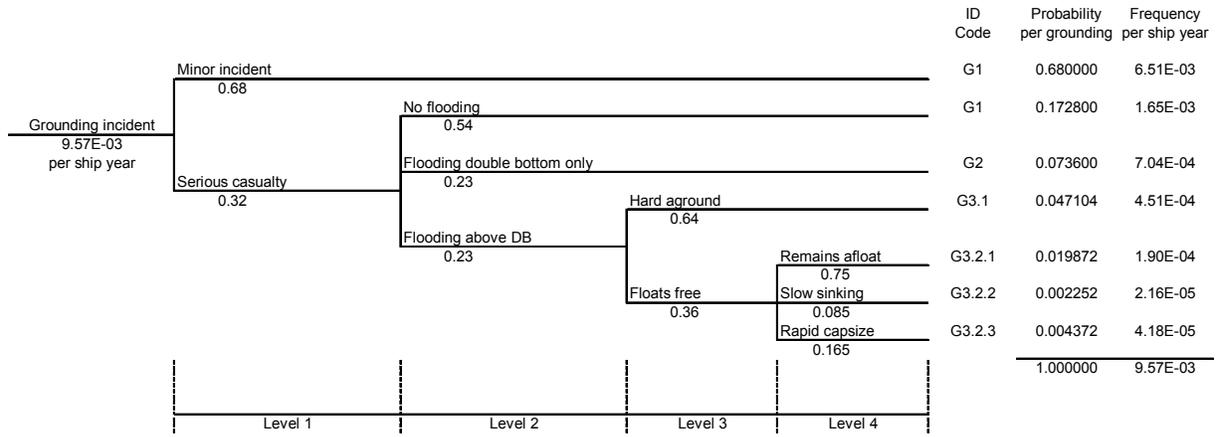


Fig. 4: Generic Grounding Event Tree

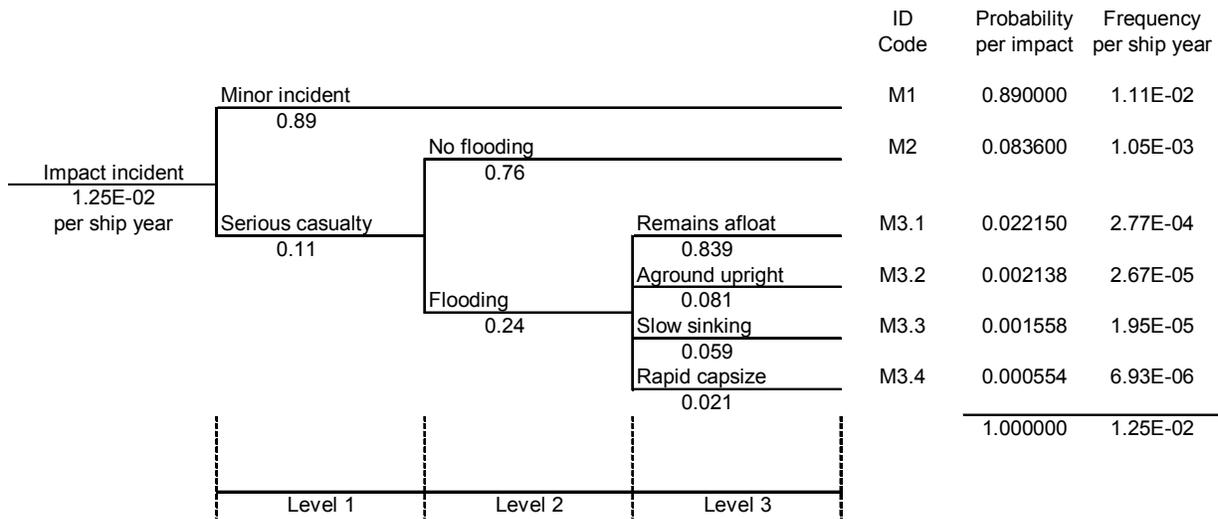


Fig. 5: Generic Impact Event Tree

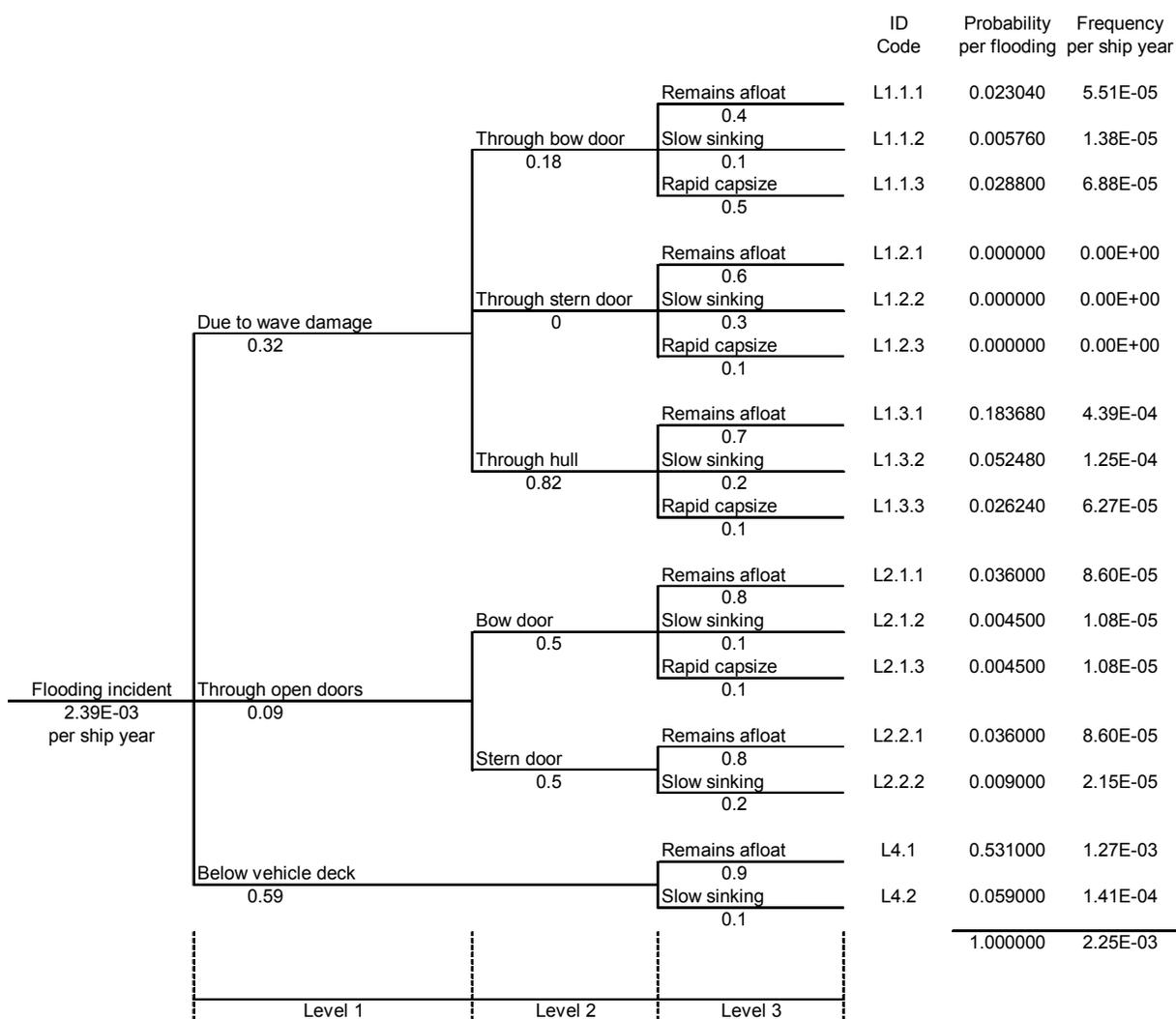


Fig. 6: Generic Flooding Event Tree

Table 2: Summary Risk Calculations (Risk Model)

|                  | Frequency (per ship year) | Frequency (%) | Individual Risk (per year) | PLL (per ship year) | PLL (%)     | Fatalities (per year) |
|------------------|---------------------------|---------------|----------------------------|---------------------|-------------|-----------------------|
| <b>Collision</b> | 1.25E-02                  | 28%           | 2.75E-05                   | 2.34E-02            | 11%         | 31                    |
| <b>Grounding</b> | 9.57E-03                  | 21%           | 3.02E-05                   | 2.57E-02            | 12%         | 23                    |
| <b>Impact</b>    | 1.25E-02                  | 28%           | 1.63E-06                   | 1.39E-03            | 1%          | 2                     |
| <b>Flooding</b>  | 2.39E-03                  | 5%            | 1.31E-04                   | 1.12E-01            | 50%         | 148                   |
| <b>Fire</b>      | 8.28E-03                  | 18%           | 7.00E-05                   | 5.95E-02            | 27%         | 79                    |
| <b>TOTAL</b>     | <b>4.52E-02</b>           | <b>100%</b>   | <b>2.61E-04</b>            | <b>2.22E-01</b>     | <b>100%</b> | <b>282</b>            |

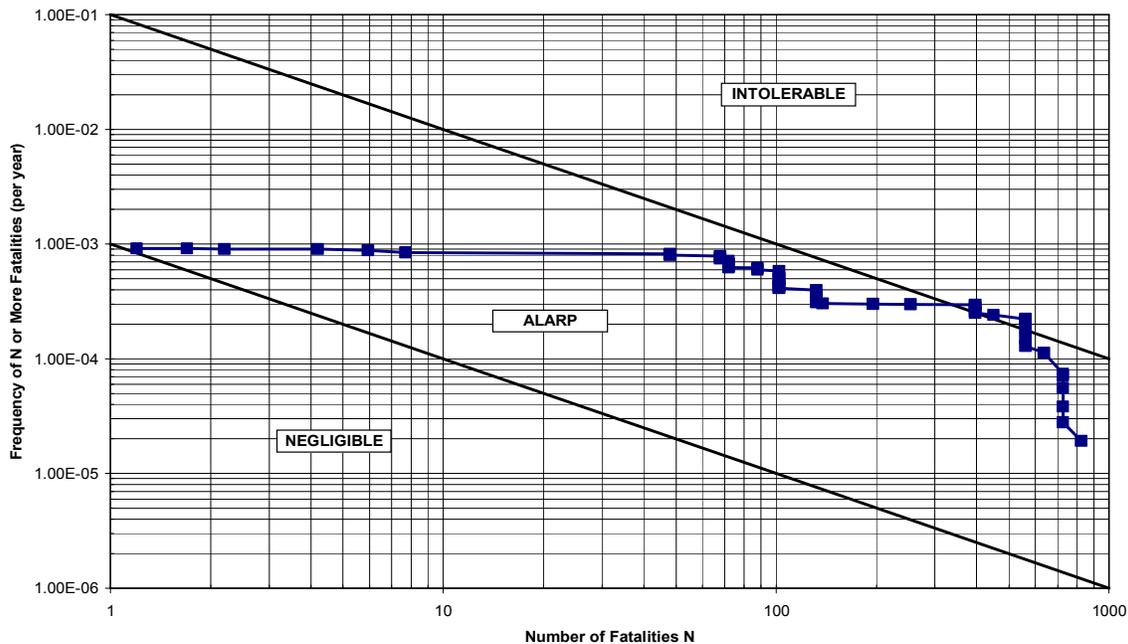


Fig. 7: RoPax F-N Curve (Risk Model)

## RISK CONTROL OPTIONS

Improved damage stability and survivability after flooding to avoid rapid capsize relates to the ability to stay afloat and upright for as long as necessary to allow for recovery of the vessel, safe continuation of the voyage or safe return to port, assistance to the vessel, or ultimately to allow for safe and orderly abandonment of the vessel.

Stability deterioration resulting from hull breach and subsequent flooding to internal compartments, had led in the past to major loss of life on RoPax ships (*MV Estonia*, *MV Jan Heveliusz*, *MV El Salam Bocaccio*, among others). Hence damaged ship stability is one of the fundamental areas of safety legislation as it deals with mitigating the consequences of water ingress related flooding.

The capsize mechanism of RoPax ships or any other ships with large un-subdivided horizontal spaces near the damaged waterline is associated with accumulation of water on deck due to wave action (see for instance, Tagg and

Tuzcu, 2002, and Pawlowski, 2004). The height of the water gradually increases until either a reasonably stable equilibrium level is reached where inflow is approximately equal to outflow for ships with sufficient reserve stability, or if stability is inadequate, the heeling moment of the water will cause the ship to capsize. On this basis, a number of measures are known to be beneficial for the stability of RoPax ships following water ingress. Among others, the following can be quoted from (Pawlowski, 2004):

- Fitting of buoyant spaces (additional reserve buoyancy) on the car deck or below the weather deck, as appropriate, along the ship sides. This would increase the  $GZ_{max}$  and decrease the heeling level due to water accumulated on deck.
- Use of down-flooding arrangements which counteract the accumulation of water on the vehicle deck, and if properly designed, can largely reduce or even eliminate this phenomenon.
- Application of sheer of the deck and/or trim of the ship to limit the extent of water

accumulation on deck by increasing water outflow; this is of importance for midship flooding cases, the most detrimental for residual stability.

For new RoPax designs, the above three measures can be effectively incorporated without greater difficulties, taking the form of a lifebelt around the ship's sides, leading to designs of unprecedented high levels of survivability (Pawlowski, 1999). A good illustration of the above measures on a RoPax design can be found in a public report of the DESSO project where, the vessel was conceived with the philosophy of the ship functioning as "its own lifeboat". Among the measures introduced in this design, efficient cross-flooding arrangements (for achieving symmetric flooding and avoiding excessive heel) as well as enclosed watertight side casings for providing reserve buoyancy up to the first accommodation deck, can be accounted for.

As the results of risk analysis suggest, *rapid capsizing* – as a consequence of various accident categories leading to various extents of flooding, is the main contributor to ship losses and the cause of a large number of fatalities. In this sense, during the concept design stages of a new ship project, in addition to 'conventional' (static stability) design methods for quantifying damage stability, the issue of verification of the survival time in cases of flooding would help to improve the survivability performance of the ship.

In relation to the above and for the purpose of the cost-effectiveness study, two high-level RCOs have been considered:

- **RCO2a:** relates to measures aimed at improving damage stability in a statutory sense only. The effectiveness of different measures is quantified on the basis of 'conventional' methods i.e. static stability calculations and it is expressed with the probabilistic Attained Index of Subdivision A. The explicit issue of the survival time is not directly addressed in Index A

calculations, although the implicit *s* factor formulation encodes implicitly information on sea state as well as the time the vessel is expected to survive in specific damage conditions. It is expected that this RCO would lead to moderate increases of Index A, and that the associated costs are not major or significant.

- **RCO2b:** relates to improved damage stability as above, but the issue of the survival time is also directly and explicitly addressed with a performance-based approach (model tests and/or numerical simulations). This will ensure that the problem of *rapid capsizing* is addressed for all possible flooding scenarios and it is not limited to collision damages. It is assumed that this RCO would lead to moderate increases of Index A and that in addition, its implementation would also lead to reduce the probability of rapid capsizing (as opposed to slow sinking) in those situations in which the vessel "does not remain afloat". This RCO is meant to achieve high levels of survivability in line with the concept of "casualty threshold" and safe return to port (Vassalos, 2007) therefore the marginal costs associated with RCO2b are expected to be much higher than with RCO2a.

The risk reduction potential of all measures associated with improved damage stability and survival time, can be evaluated by assessing the impact of all related measures on the branch probabilities of the event trees constituting the (high-level) risk model. Accordingly, the maximum risk reduction potential associated with RCO2 is  $\Delta R_{\max} = 73\%$  (of total PLL<sub>basis</sub>) and relates to all collisions, groundings, cases of impacts and flooding from other causes.

#### ***RCO2a (improved capability to "stay afloat")***

All possibilities and specific design solutions associated with implementing RCO2a would lead to varying degrees of improved stability after flooding. This increased level can be quantified in terms of Index A (as defined in the newly adopted SOLAS 2009 Chapter II-1

regulations), and the improvements would positively impact the probability of “staying afloat” in all *collision* and *flooding* events defined in the risk model.

The Required Index of Subdivision R for the representative RoPax vessel adopted in this study is equal to  $R=0.735$  and is a function of the subdivision length ( $L_s$ ) and the number of persons the vessel is certified to carry. In the risk model, an Index A of 0.78 (average value of a sample of 38 RoPax vessels) has been used for the calculation of the basis risk. Since  $A>R$ , then the vessel complies with the probabilistic rules, and the same value of Index A is adopted here for consistency.

According to the concept behind the probabilistic framework, if a ship attains an Index A value of 0.78, it can be interpreted as meaning that in 78% of all potential collisions resulting in water ingress and flooding, the survival time would – theoretically at least – be 30 minutes<sup>1</sup> or more. This also means that the remaining 22% of the collisions, the time would be less than 30 minutes!

For a given damage case, the  $s$  factor formulation is assumed to reflect the percentage of cases the ship would survive for at least 30 minutes. Accordingly, if  $s=1.0$ , the mean survival time would tend to infinity, this is assuming of course that the current  $s$  factor formulation reflects appropriately the conditional probability that the ship will not capsize in a given critical sea state. In this respect, note the following comments with respect to the current  $s$  factor formulation as adopted in the SOLAS 2009 rules:

- The positive impact of many design measures to improve damage stability may not be reflected in the resulting Index A value (for more details see Vassalos et al, 2006).

- Recent studies (Vassalos and Jasionowski, 2007) suggest that the  $s$  factor formulation eventually adopted in the SOLAS 2009 rules is based on a regression of data corresponding to conventional cargo ships, which would tend to overestimate (not conservative!) the probability of survival of RoPax (low freeboard) ships.

Consequently, it is not known with certainty whether the  $s$  factor formulation adequately reflects the true damage stability and the level of survivability of passenger ships, in particular of RoPax vessels.

Notwithstanding the above, for the purpose of this study, it can be assumed that Index A is a measure of damage stability and as such, any design measure introduced to increase Index A value, would lead to a higher probability of “staying afloat”. Thus, a systematic increase from  $A=0.78$  (the basis level) up to  $A=0.99$  is considered for estimating the range of risk reduction implied by implementing RCO2a. The impact on the specific branches of the event tree (ET, the risk model) is as indicated in Table 3. The results of sensitivity of the risk level to different values of Index A, (i.e. to different levels of success in the implementation of these measures) are presented in Table 4.

As can be noted, for example, if the vessel attains an Index A of 0.90, the resulting reduction of the total Potential Loss of Life ( $\Delta R$ ) is estimated at 44%; the breakdown into the considered accident categories is shown in Table 5 for the  $A=0.90$  case. The resulting FN curve is illustrated in Figure 8. In the extreme case of  $A=0.99$  the level of risk reduction of the total PLL in relation to the basis case can be as much as  $\Delta R =63\%$ .

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<sup>1</sup> Duration of model tests on the basis of which the  $s$  factor formulation was derived (Tagg and Tuzcu, 2002)

**Table 3: Impact of RCO2a (Index A=0.90 Case) on the Risk Model**

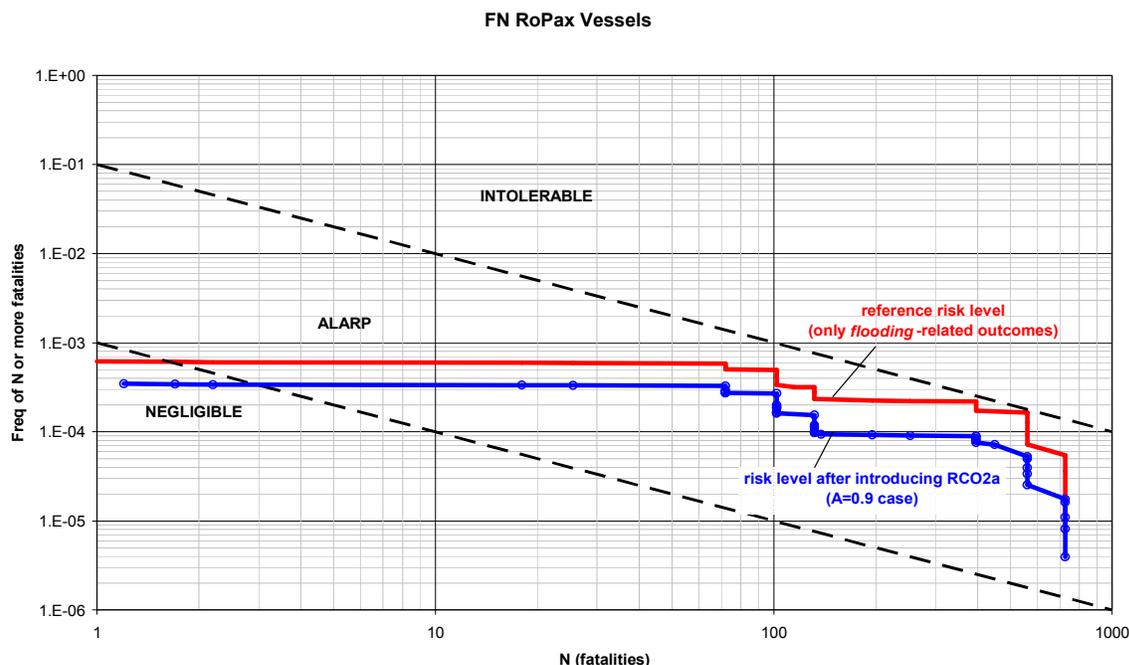
| Accident Category | ET level 3  | ET branch probability |     | change |
|-------------------|---|-----------------------|-----|--------|
|                   |   | basis                 | new |        |
| Collision         | Under way/serious/struck ship/flooding/remains afloat | 0.78                  | 0.9 | 15%    |
| Grounding         | Serious/flood above DB/floats free/remains afloat     | 0.75                  | 0.9 | 20%    |
| Impact            | Serious/flooding/remains afloat                       | 0.839                 | 0.9 | 7%     |
| Flooding          | Wave damage/bow door/remains afloat                   | 0.4                   | 0.9 | 125%   |
|                   | Wave damage/stern door/remains afloat                 | 0.6                   | 0.9 | 50%    |
|                   | Wave damage/hull/remains afloat                       | 0.7                   | 0.9 | 29%    |
|                   | Open doors/bow/remains afloat                         | 0.8                   | 0.9 | 13%    |
|                   | Open doors/stern/remains afloat                       | 0.8                   | 0.9 | 13%    |
|                   | Below car deck/remains afloat                         | 0.9                   | 0.9 | 0%     |

**Table 4: Risk Reduction from Improved Damage Stability (RCO2a)**

| Index A     |            | Total Ind. Risk (per year) | Total PLL (per ship year) | Averted fatalities per ship | Total ΔR % of PLL |
|-------------|------------|----------------------------|---------------------------|-----------------------------|-------------------|
| 0.78        | basis      | 2.61E-04                   | 2.22E-01                  | -                           |                   |
| 0.80        | 3%         | 2.01E-04                   | 1.71E-01                  | 1.5                         | 23%               |
| 0.85        | 9%         | 1.73E-04                   | 1.47E-01                  | 2.2                         | 33%               |
| <b>0.90</b> | <b>15%</b> | <b>1.46E-04</b>            | <b>1.24E-01</b>           | <b>2.9</b>                  | <b>44%</b>        |
| 0.95        | 22%        | 1.18E-04                   | 1.00E-01                  | 3.6                         | 55%               |
| 0.99        | 28%        | 9.55E-05                   | 8.12E-02                  | 4.2                         | 63%               |

**Table 5: Risk Reduction Breakdown after Improving Damage Stability (RCO2a - Index A=0.90 Case)**

| RCO2a A=0.90 | Frequency (per ship year) | Ind. Risk (per year) | PLL (per ship year) | ΔPLL (%)   |
|--------------|---------------------------|----------------------|---------------------|------------|
| Collision    | 1.25E-02                  | 1.27E-05             | 1.08E-02            | 54%        |
| Grounding    | 9.57E-03                  | 1.15E-05             | 9.82E-03            | 60%        |
| Impact       | 1.25E-02                  | 1.01E-06             | 8.62E-04            | 38%        |
| Flooding     | 2.39E-03                  | 5.04E-05             | 4.28E-02            | 62%        |
| Fire         | 8.28E-03                  | 7.00E-05             | 5.95E-02            | 0%         |
| <b>TOTAL</b> | <b>4.52E-02</b>           | <b>1.46E-04</b>      | <b>1.24E-01</b>     | <b>44%</b> |



**Fig. 8: Societal Risk Associated with Flooding-Related Outcomes (collision, grounding, impact and flooding accident categories included)**

***RCO2b (improved capability to “stay afloat longer”)***

This RCO assumes that all measures implemented are much more effective in achieving the design goal of “stay afloat for longer”; it is expected that more effective measures can be designed if in addition to ‘conventional’ design verification methods based on static stability, state-of-the-art performance-based methods (numerical simulations) are utilised at early design stages for verification and systematic improvement of survivability performance not only for collision-related damages, but for a range of representative scenarios related to groundings, impact and other flooding scenarios. Modern performance-based methods are used for verification of structural strength, hull resistance, aerodynamic performance, evacuation, etc. There is no reason why modern survivability analyses should not be utilised to design and verify one of the key safety ship design goals (“stay upright and afloat”) for as

long as necessary to recover the ship or eventually to allow for safe abandonment.

Obviously, the impact on survivability can also be expressed in terms of Index A, which is likely to be higher than that achieved in RCO2a, as there will be more cases for which the *s* factor is unity, hence survival time would tend to infinity. In addition to this, for all cases where the ship does not remain afloat, the proportion of ‘slow sinking’ to ‘rapid capsizing’ is assumed also equal to the expected probability of survival (Index A). In this RCO the confidence in the “adequateness” of the *s* factor formulation implicit in Index A calculations is high.

The results of sensitivity of the risk level to different values of Index A, (i.e. to different levels of success in the implementation of these measures) are illustrated in Table 7. As can be noted, for example, if the vessel attains an Index A of 0.95, the resulting reduction of the total Potential Loss of Life ( $\Delta R$ ) is estimated at

62%; the breakdown into the considered accident categories is shown in Table 8 for the

A=0.95 case. The resulting FN curve is illustrated in Figure 9.

**Table 6: Impact of RCO2b (Index A=0.95 Case) on the Risk Model**

| Accident Category             | ET level 3  | ET branch probability |       | change |
|-------------------------------|---|-----------------------|-------|--------|
|                               |   | basis                 | new   |        |
| Collision                     | Under way/serious/struck ship/flooding/remains afloat       | 0.78                  | 0.95  | 22%    |
|                               | Under way/serious/struck ship/flooding/sinking/slow sinking | 0.5                   | 0.95  | 90%    |
|                               | /striking ship/flooding/remains afloat                      | 0.88                  | 0.95  | 8%     |
| Grounding                     | Serious/flood above DB/floats free/remains afloat           | 0.75                  | 0.95  | 27%    |
|                               | /slow sinking   | 0.085                 | 0.048 |        |
| Impact                        | Serious/flooding/remains afloat                             | 0.839                 | 0.95  | 13%    |
|                               | /sinking  | 0.059                 | 0.024 |        |
| Flooding                      | Wave damage/bow door/remains afloat                         | 0.4                   | 0.95  | 128%   |
|                               | /slow sinking   | 0.1                   | 0.05  |        |
|                               | Wave damage/stern door/remains afloat                       | 0.6                   | 0.95  | 58%    |
|                               | /slow sinking   | 0.3                   | 0.05  |        |
|                               | Wave damage/hull/remains afloat                             | 0.7                   | 0.95  | 36%    |
|                               | /slow sinking   | 0.2                   | 0.05  |        |
|                               | Open doors/bow/remains afloat                               | 0.8                   | 0.95  | 19%    |
|                               | /slow sinking   | 0.1                   | 0.05  |        |
|                               | Open doors/stern/remains afloat                             | 0.8                   | 0.95  | 19%    |
| Below car deck/remains afloat | 0.9   | 0.95                  | 6%    |        |

**Table 7: Risk Reduction from Improved Damage Survivability (RCO2b)**

| Index A     |            | Total Ind. Risk (per year) | Total PLL (per ship year) | Averted fatalities per ship | Total ΔR % of PLL |
|-------------|------------|----------------------------|---------------------------|-----------------------------|-------------------|
| 0.78        | basis      | 2.61E-04                   | 2.22E-01                  | -                           |                   |
| 0.80        | 3%         | 1.54E-04                   | 1.31E-01                  | 2.7                         | 40%               |
| 0.85        | 9%         | 1.32E-04                   | 1.12E-01                  | 3.2                         | 49%               |
| 0.90        | 15%        | 1.14E-04                   | 9.68E-02                  | 3.7                         | 56%               |
| <b>0.95</b> | <b>22%</b> | <b>9.95E-05</b>            | <b>8.47E-02</b>           | <b>4.1</b>                  | <b>62%</b>        |
| 0.99        | 28%        | 9.12E-05                   | 7.75E-02                  | 4.3                         | 65%               |

**Table 8: Risk Reduction Breakdown after Improving Damage Survivability (RCO2b - Index A=0.95 Case)**

| RCO 2b A=0.95 | Frequency (per ship year) | Ind Risk (per year) | PLL (per ship year) | ΔPLL (%)   |
|---------------|---------------------------|---------------------|---------------------|------------|
| Collision     | 1.25E-02                  | 2.50E-06            | 2.13E-03            | 91%        |
| Grounding     | 9.57E-03                  | 1.05E-06            | 9.61E-04            | 96%        |
| Impact        | 1.25E-02                  | 1.10E-07            | 9.34E-05            | 93%        |
| Flooding      | 2.39E-03                  | 2.59E-05            | 2.20E-02            | 80%        |
| Fire          | 8.28E-03                  | 7.00E-05            | 5.95E-02            | 0%         |
| <b>TOTAL</b>  | <b>4.52E-02</b>           | <b>9.95E-05</b>     | <b>8.47E-02</b>     | <b>62%</b> |

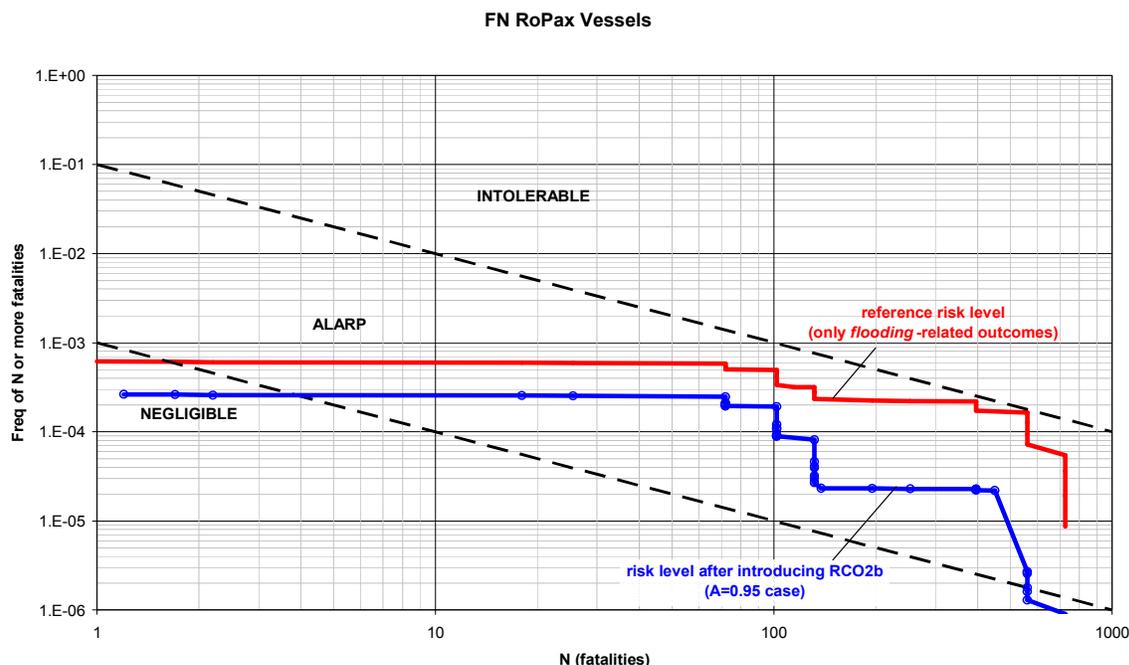


Fig. 9: Societal Risk Associated with Flooding-Related Outcomes (collision, grounding, impact and flooding accident categories included)

## COST-EFFECTIVENESS ANALYSIS

### Generic Model / Ship System

For the purpose of evaluating the risk reduction potential ( $\Delta R$ ) and costs ( $\Delta C$ ) of the various RCOs considered, a representative reference ship has been selected, the main parameters of which are presented in Table 7. The parameters of the reference ship correspond to a RoPax vessel with capacity for approximately 1,000 passengers and 100 crew, consistently with the assumptions made in the risk analysis study.

All costs and benefits were depreciated to a Net Present Value (NPV) using a depreciation rate of 5% and assuming an expected lifetime of 30 years for RoPax ships.

As the marginal costs are a function of the operational profile of the vessel, a specific profile was defined as summarised in Table 10. For consistency with the risk model assumptions, three operational profiles are considered: winter, spring/autumn and summer.

Table 9: Reference Ship for Evaluation of RCOs

| Parameters              | Value       |
|-------------------------|-------------|
| Gross Tonnage, GT       | 25,000 tons |
| Length overall          | 180 m       |
| Breadth                 | 25 m        |
| LSA Capacity            | 1,100       |
| Passengers              | 1,000       |
| Crew                    | 100         |
| No. cabins / 2 capacity | 50          |
| No. cabins / 4 capacity | 225         |
| Total lane metres       | 1,900 m     |
| Lightweight             | 12,000 tons |

The following additional assumptions are made:

- The vessel operates 356 out of 365 days per year (99% availability)
- The trip distance is 300 nm, travelled at average speed of 25 knots in 12 hours

The cost-earning profile is shown in Table 12, based on the cost/revenue unit data presented in Table 11. From these considerations the following indicative cost considerations can be made:

The annual total revenue is estimated at EUR 18,440,000. Given the vessel's capacity parameters, the annual average revenue is EUR 42,475 (per cabin) and EUR 4,117 per lane metre.

After excluding the annual operational costs, estimated at approximately EUR 17,108,000,

then the NET annual profit is EUR 731 per cabin and EUR 605 per lane metre.

The above figures will be used for making indicative estimates of the marginal costs associated with the implementation of design changes and alternatives affecting the layout and of course capacity of the vessel.

**Table 10: Reference Vessel Operational Profile**

|                            | season                              | Low<br>(winter) | Middle<br>(spring / autumn) | High<br>(summer) |
|----------------------------|-------------------------------------|-----------------|-----------------------------|------------------|
| annual number of trips     | No. service days                    | 89              | 178                         | 89               |
|                            | Return trips / day (daily frq)      | 1               | 1                           | 1                |
|                            | Return trips per year               | 89              | 178                         | 89               |
|                            | <i>Annual breakdown<sup>2</sup></i> | <i>25%</i>      | <i>50%</i>                  | <i>25%</i>       |
| pax / vehicle distribution | cars                                | 90              | 150                         | 301              |
|                            | bus                                 | 5               | 8                           | 3                |
|                            | lorries                             | 80              | 60                          | 7                |
|                            | trailer                             | 100             | 90                          | 40               |
| loading profile            | lane metres used                    | 1885            | 1845                        | 1454             |
|                            | lane metres usage (% of max)        | 99.2%           | 97.1%                       | 76.5%            |
|                            | Pax (car&bus) / trip                | 420             | 690                         | 993              |
|                            | Pax (drivers) / trip                | 80              | 60                          | 7                |
|                            | Pax total / trip                    | 500             | 750                         | 1000             |
|                            | <i>Level of service</i>             | <i>50%</i>      | <i>75%</i>                  | <i>100%</i>      |

**Table 11: Unit Cost Data**

| pertaining to         | item                              | value | units                |
|-----------------------|-----------------------------------|-------|----------------------|
| design / construction | consultant hourly rate            | 90    | EUR / hour           |
|                       | price of steel work per hour (EU) | 6,000 | EUR / ton            |
|                       | yard cost rate                    | 20    | EUR / hour           |
| tickets prices        | pax                               | 37.4  | EUR / person / trip  |
|                       | Car (3 pax / 4 m)                 | 52    | EUR / vehicle / trip |
|                       | Bus (30 pax / 15 m)               | 196   | EUR / vehicle / trip |
|                       | Lorry (1 pax / 15 m)              | 196   | EUR / vehicle / trip |
|                       | Trailer (2.5 m)                   | 33    | EUR / vehicle / trip |
| onboard sales         | car / bus pax                     | 5     | EUR / person / trip  |
|                       | lorry driver                      | 5     | EUR / person / trip  |
| operational cost      | fuel                              | 120   | EUR / ton            |
|                       | crew wages                        | 280   | EUR / day / person   |

<sup>2</sup> Assumption made in the risk model, see Annex II

Table 12: Reference Cost / Earning Profile for the Calculation of Marginal Costs

| season                 |                                 | winter              | spring / autumn | summer                         | annual sums                   |              |
|------------------------|---------------------------------|---------------------|-----------------|--------------------------------|-------------------------------|--------------|
| <b>revenue profile</b> | pax tickets sale / trip         | € 15,686            | € 25,770        | € 37,086                       |                               |              |
|                        | pax onboard sales / trip        | € 2,500             | € 3,750         | € 5,000                        |                               |              |
|                        | cargo revenue (vehicles) / trip | € 23,834            | € 22,727        | € 18,596                       |                               |              |
|                        | total revenue / trip            | € 42,020            | € 52,247        | € 60,682                       |                               |              |
|                        | revenue pax / season            | € 1,618,539         | € 5,254,486     | € 3,745,635                    | € 10,618,660                  |              |
|                        | revenue cargo / season          | € 2,121,239         | € 4,045,459     | € 1,655,067                    | € 7,821,765                   |              |
|                        | total annual revenue / season   | € 3,739,778         | € 9,299,945     | € 5,400,703                    | € 18,440,426                  |              |
|                        |                                 |                     |                 |                                | annual revenue per cabin      | € 42,475     |
|                        |                                 |                     |                 |                                | annual revenue per lane m     | € 4,117      |
|                        | <b>cost profile</b>             | total distance (nm) | 53400           | 106800                         | 53400                         |              |
| fuel consumption (MT)  |                                 | 10680               | 21360           | 10680                          | sum                           |              |
| fuel cost (EUR)        |                                 | € 1,281,600         | € 2,563,200     | € 1,281,600                    | € 5,126,400                   |              |
| crew wages             |                                 | € 2,990,400         | € 5,980,800     | € 2,990,400                    | € 11,961,600                  |              |
| maintenance            |                                 |                     |                 |                                | € 20,000                      |              |
|                        |                                 |                     |                 |                                | total annual cost             | € 17,108,000 |
|                        |                                 |                     |                 |                                | annual running cost per cabin | € 41,744     |
|                        |                                 |                     |                 | annual running cost per lane m | € 3,512                       |              |
|                        |                                 |                     |                 |                                | € 1,332,426                   |              |
|                        |                                 |                     |                 | annual profit per cabin        | € 731                         |              |
|                        |                                 |                     |                 | annual profit per meter lane   | € 605                         |              |

**CAF Calculation**

The results of cost-effectiveness calculations (GCAF) for RCO2a are illustrated in Figure 10. For RCO2b, the results are illustrated in Figure 11; the figures show sensitivity of GCAF to different assumptions related to risk reduction and cost. The figures indicate that if the Required Index A for the representative ship is increased from 0.78 to 0.9, the measure is **cost-effective** if the total marginal cost associated with the stability upgrade is less than US\$9M and US\$11M for RCO2a and RCO2b, respectively. NCAF values are also lower than US\$3M. Experience from Stockholm Agreement stability upgrades indicate that such cost can be significantly lower than US\$9M.

**CONCLUSIONS**

On the basis of the work presented in this paper on potential measures aimed at improving damage stability and survivability, and assuming that damaged ship survivability is ‘sufficiently’ reflected by the attained

subdivision index (A), then the required subdivision index (R) should be increased so that for the average size ferry (1,100 persons onboard), the R index is above 0.9. When a ship attains an A value of  $A > 0.9$ , it would mean that more than 90% of potential collisions would result in survival time of 30 minutes or longer. A high A value ( $> 0.9$ ) would also imply that there would be a larger number of damage cases with  $s=1.0$ , which, for a given damage case, implies infinite mean survival time ( $t \rightarrow \infty$ ).

In relation to this conclusion, the following points are noteworthy:

- Although the current formulation of the required index R is supposed to be a measure of safety in line with current expectations, it does not explicitly relate to risk; it has been established on the basis of the attained index from a sample of existing vessels; thus the R index may not reflect the level of safety to be expected in the

foreseeable future. An attempt to relate R more directly to safety would require the use of risk in its derivation.

- The formulation of the *s* factor should be urgently revisited for passenger ships, including RoPax vessels, using relevant reference ships (RoPax) and using available performance-based methods.

value associated with the introduction of measures to improve survivability in flooded conditions is going to be well below the current cost-effectiveness criterion (US\$3M), even for pessimistic assumptions of marginal costs. Hence it is strongly recommended that the required subdivision index R for RoPax vessels be increased to levels at least or above 0.9.

Finally, on the basis of cost-effectiveness considerations, it is expected that the CAF

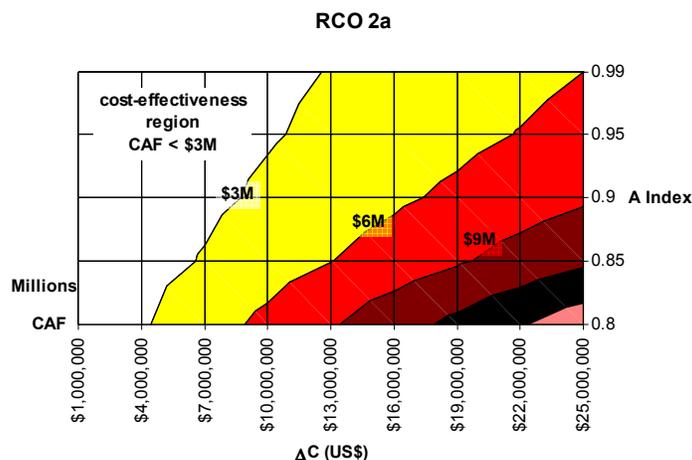


Fig. 10: GCAF sensitivity to Attained index A and cost implications RCO2a: measures improving damage stability (“stay afloat”)

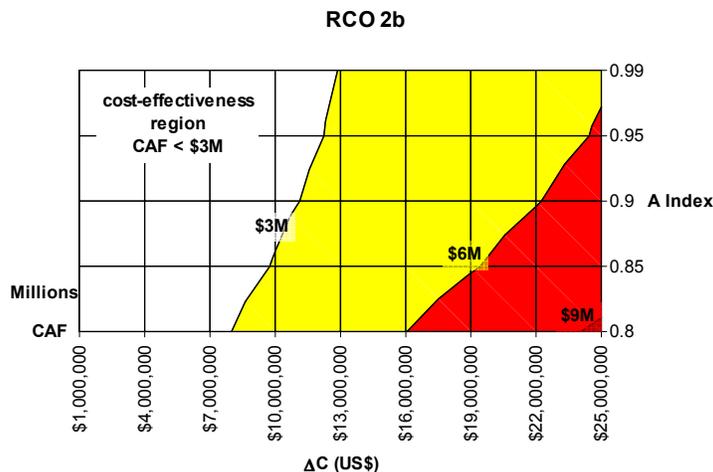


Fig. 11: GCAF sensitivity to Attained index A and cost implications RCO2b: measures improving damage stability and survival time (“stay afloat for longer”)

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