Conceptualising Risk

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ABSTRACT

Ever present jargon and colloquial notion of risk, coupled with obscuring of the simplicity inherent in the concepts of risk by the sophistication of computer software applications of techniques such as event trees, fault trees, Bayesian networks, or others, seem to be major factors inhibiting comprehension and systematic proliferation of the process of safety provision on the bases of risk in routine ship design practice. This paper attempts to stimulate consideration of risk at the fundamental level of mathematical axioms, by proposing a prototype of a comprehensive yet plain model of risk posed by the activity of ship operation. A process of conceptualising of substantive elements of the proposed risk model pertinent to the hazards of collision and flooding is presented. Results of tentative sensitivity studies are presented and discussed.

Keywords: *Risk; Attained Index of Subdivision, Probability; Safety, Survival Time*

1 INTRODUCTION

It is well recognised that the engineering discipline entails constant decision making under conditions of uncertainty, that is decisions are made irrespective of the state of completeness and quality of supporting information, as such information is never exact, it must be inferred from analogous circumstances or derived through modelling, and thus be subject to various degrees of approximation, or indeed, the information often pertains to problems involving natural processes and phenomena that are inherently random.

No better example of such decision making process in engineering can be invoked, than that of development of regulations for the provision of safety.

The process of rules development is well recognised to rely on both, (a) qualified “weighing” of a multitude of solutions derived on the basis of scientific research, engineering judgement, experiential knowledge, etc, and (b) debates accommodating the ubiquitous political agendas at play and governing societal concerns. The result of such complex and predominantly subjective pressures is often a simplistic compromise normally in the form of deterministic rules which does not reflect the underlying uncertainty explicitly.

Although such standards have formed the main frame of safety provision over a century or so, the acknowledgement of existence of these uncertainties, brought about by the occurrences of accidents with undesirable consequences on one hand, and realisation that economic benefit could be compromised by inbuilt but potentially irrelevant margins, on the other, have instigated a search such as [1] for better methodologies for dealing with the issues of safety.

Notably, such search has been enhanced, or possibly even inspired, by the tremendous progress in computational technologies, which by sheer facilitation of fast calculations have allowed for development of numerical tools modelling various physical phenomena of relevance to engineering practice, at levels of principal laws of nature. Such tools present now the possibility to directly test physical behaviour of systems subject to any set of input parameters, and thus also allow derivation of an envelope of the inherent uncertainty.

Existence of such methods, however, is not sufficient for progressing with the development of more efficient means of safety provision, without a robust framework for reasoning on the results of any such advanced analyses undertaken for safety verification processes.

Such means evolve naturally from the principles of inductive logic; a field of mathematics dealing with reasoning in a state of uncertainty, [11][10]. In particular the branch comprising probability theory forms a suitable framework for such reasoning in the filed of engineering.

However, while the concept of probability is known to engineers very widely, it does not seem that the many unresolved to this day subtleties associated with either, its fundamental principles or relevant linguistics, are recognised by the profession.

This is the situation especially when a special case of application of the probability theory, namely that of *risk*, is considered.

The uptake of risk assessment process, or more recently strife to develop and implement risk-based design paradigms, [1][3][4], are examples of a new philosophy that could alleviate the aforementioned problems of safety provision, if they can become suitable for routine practice. This in turn, can only be achieved if fundamental obstacles such as lack of common understanding of the relevant concepts are overcome.

Therefore, this paper sets to examine some lexical as well as conceptual subtleties inherent in risk, offer some suggestions on more intuitive interpretations of this concept, and put forward a proposal for risk modelling process as a contributory attempt to bringing formalism in this development.

2 THE RISK LEXICON

As has been the case with the emergence of probability in the last 350 years or so, [12], the terminology on risk has not evolved into anything that can be regarded as intuitively plausible lexicon, as neither have the pertinent syntax nor semantics been universally endorsed.

Any of tautological phrases, such as: *"level of safety standard"*, *"hazard threatening the safety"*, semantically imprecise statements such as: *"collision risk"*, *"risk for collision"*, *"risk from collision"*, *"risk of collision"*, *"risk from hazard aspects of …"*, simple misnomers such as *"safety expressed as risk"*, *"safety risk"*, or philosophically dubious slogans such as *"zero risk*[1]*"*, can be found in the many articles discussing or referring to the concepts of risk.

A few other, easily misconceiveable terms used in this field can be mentioned:

(a) likelihood, chance, probability
(b) frequency, rate
(c) uncertainty, doubt, randomness
(d) risk, hazard, danger, threat
(e) analysis, assessment, evaluation
(f) risk control measures, risk control options
(g) safety goals, safety objectives, safety functional statements, safety performance, relative safety

Although some preamble definitions of these and other terms are offered from article to article, lack of generic coherence in discussions of the risk concepts among the profession is not helpful in promulgating this philosophy as of routinely quality.

This article makes no pretence of having resolved all these subtleties. It merely attempts to adopt a scheme of thinking, which appears to allow for systematic understanding of the concepts of safety and risk.

[1] The Cournot's lemma stating that *"an event of small probability will not happen"* has been initially endorsed by many mathematicians, even acclaimed as the physical *"logic of probable"* by some, however, the concept has been dismissed for the latter part of the last century on the grounds of Bayesian interpretations of probability, i.e. that "zero" is subject to "personal" interpretation. Hence a statement of *"zero risk"* remains a philosophical conjecture with little, or indeed, no physical justification.

2.1 Safety

By way of introduction of this scheme, the term underlying all this discussion, namely safety, shall be presented to formally set the terms of reference.

Without going into intricacies of how complex the definition of the term "safety" can be, it is hereby emphasised that for all engineering purposes and currently emerging wider acceptance of risk concepts, the following definition of safety, [23], should be adopted widely:

<u>safety is the state of acceptable risk</u>

This definition is unambiguous and it is practical. It emphasizes explicitly that safety is a state. It thus cannot be calculated, it can only be verified by comparison of the actually established quantity of risk with the quantity of risk that is considered acceptable by relevant authoritative bodies; a criterion or standard, in other words.

Thus, it follows that statements such as *"higher safety"* are incompatible with this definition, as the safety is either attained or it is not and no grades of safety can be distinguished. Appropriate statement would be *"higher safety standard"*, which directly implies lowered levels of risk as acceptable. Also, expressions such as *"safety performance"* become semantically imprecise unless, contrary to intuitive perception, the word "performance" implies a binary mode of compliance / no compliance with the set standard, rather than a scale, which in turn, relates to risk not safety.

This definition also establishes clear distinction between risk and safety. Risk is the benchmark vehicle to demonstrate a state of safety or lack of it. Thus, safety cannot be *"expressed as risk"*.

What the definition does not resolve is the consistency of the relevant syntax which has come to be used in the every day communication on safety.

For instance, expressions such as *"fire safety"* and *"ship safety"* imply fundamentally different meanings despite use of the same syntax. While the interpretation analogous to that of the colloquial speech examples such as *"orange juice"* and *"baby juice"*, could be accepted or taken for granted, as it is done today, such subtleties should be addressed and resolved for avoidance of any ambiguities in engineering applications, especially when many new concepts such as safety goals or others are being introduced. This, however, is beyond the scope of the discussion of this article.

Another worthwhile note should be made here, that this definition is also fully compatible with the universally accepted in today's world mechanism of safety provision through compliance with regulations. Irrespective of the deterministic or more complex nature of the regulation, safety is said to have been attained, when an acceptable criterion has been met. Although the inherent risk is not disclosed, it is said to have been brought to an acceptable level. Very often expressions, such as *"relative safety"* or *"conditional safety"* are used to describe the limited scope of such regulations and undisclosed nature of the risk, though neither of the words "relative" nor "conditional" has any quantifiable explanation.

But, as mentioned earlier, since simplistic and disparate regulations could compromise commercial gain or undermine societal approval of the standards proposed for safety provision, when critical accidents happen, new methods are sought after.

The direct application of the concept of risk is one such method, especially since the above definition of safety implies the "presence of risks".

The key question now is what is risk?

2.2 Risk

An ISO 8402:1995 / BS 4778 standard offers the following definition of risk:

“Risk is a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence”

A similar definition is put forward at IMO, MSC Circ 1023/MEPC Circ 392:

“Risk is a combination of the frequency and the severity of the consequence”.

Although rather widely endorsed, these definitions are so ambiguous that they hardly qualify as useful for any engineering purposes. The ambiguity derives from the following: (a) the word “*combination*” is open to any interpretation whatsoever, both in terms of relevant mathematics as well as underlying physical interpretations (b) the words “*probability*” and “*frequency*” have, in common engineering practice, different physical interpretations, which itself can be arbitrary, (c) the words *“magnitude”* or *“severity”* are unspecific, (d) the *”consequence”* is again open to any interpretation.

For instance, the syntax of the above definition implies differentiation of the semantics of the phrases such as *“hazard”* and *“consequence”*, without any qualification how such differentiation is attained. Thus, the sinking of the vessel can be considered as a hazard, which can lead to the loss of human life, but it can also be considered as an ultimate consequence, or in other words as the loss. See here Figure 1 and the subsequent discussion.

While the merit of proposal of such definitions of risk could be its generic nature, overly lack of any specificity deprives it of practical significance.

The following alternative definition is suggested, which is equally generic yet it is comprehendible more intuitively and, apparently, more pragmatic:

<u>**risk is a chance of a loss**</u>

The word *“chance”* is one of the most fundamental phrases referring to, or being synonymous with the natural randomness inherent in any of human activities and which, in this case, can bring about events that are specifically undesirable, the *“loss”*. The engineering aspects of the concept of chance are effectively addressed by the fields of probability and statistics, both of which offer a range of instruments to quantify it, such as e.g. expectation, and hence there is no need for introduction of unspecific terms such as *“combination”*. These well known mathematical tools will be discussed in §3.

This definition of risk resolves also, to some extent, the manner of its classification. Namely reference to risk should be made in terms of the loss rather than in terms of any of the intermediate hazards in the chain of events leading to the loss, a nuance just mentioned.

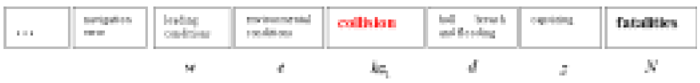

Figure 1 The concept of a chain of events in a sample scenario leading to the loss. Each of the events is a hazard after it materialises. A scenario can be identified by a principal hazard, see Table 1.

For instance, semantics of a statement *“risk to life”* or *“risk of life loss”* seem to indicate sufficiently precisely the chance that an event of “fatality” can take place, without much space for any other interpretations. On the other hand, a statement such as *“risk of collision”* can be interpreted as a chance of an event of two ships colliding; however, given a further set of events that are likely to follow, such as flooding propagation, heeling, capsizing, evacuation / abandoning and fatalities, see Figure 2, it becomes unclear what is the *“loss”*, and thus what is the risk?

Furthermore, the above definition supports lexically the recently more pronounced efforts to introduce the concept of holism in risk assessment. Namely, rather than imposing a series of criteria for acceptable risk levels in a reductionism manner, whereby separate criteria pertaining to different hazards are introduced, such as e.g. criteria on fire hazards or criteria on flooding hazards (e.g. probabilistic concept of subdivision, [14]), a unique criterion should be proposed that standardises the acceptable risk level of the ultimate loss, e.g. criteria for loss of life, environmental pollution, etc, and which risks account for each hazard that can result in the loss, a view already mentioned in [5] or [19].

This concept underlines the risk model proposed in the following §3.

3 RISK MODELLING

As mentioned above, the fields of probability and statistics provide all the essential instruments to quantify the chance of a loss.

3.1 Frequency prototyping

To demonstrate the process of application of these instruments for risk modelling, perhaps it will be useful to stress the not necessarily trivial difference between the concepts of probability and frequency. Namely, to assess a *"probability of an event"*, a relevant random experiment, its sample space and event in question on that sample space must all be well defined. The relative frequency of occurrence of this event, whereby relative implies relative to the sample space, is a measure of probability of that event, since such relative frequency will comply with the axioms of probability.

In the case of *"an experiment"* of operating a ship, however, whereby events involving fatalities can occur, the sample space is not definable. For this reason the rate of occurrence of these events per unit time cannot be referred to as probability. Thus, also use of the term *"likelihood"* would seem to be displaced here since it is synonymous with probability rather than frequency.

Therefore, application of the term *frequency per ship per year* is customary, also since its quantification relies on the historical data for the whole fleet.

Lack of a well defined sample space, however, does not prevent one from using concepts of probability, such as e.g. distribution, expectation, etc, in analyses and analytical modelling.

Thus, following from this preamble, it is proposed here that for the purpose of risk modelling the following assumptions are made:

(a) The loss is assumed to be measured in terms of an integer number of potential fatalities among passengers that can occur as a result of activity relating to *ship operation*
(b) The loss is a result of occurrence of a set of scenarios which can lead to this loss
(c) Scenarios are intersections of a set of events (all must occur) and are identified by principal hazards[2], e.g. fire
(d) The scenarios are disjoint (if one scenario occurs then the other does not)

These assumptions are shown graphically in Figure 2 below.

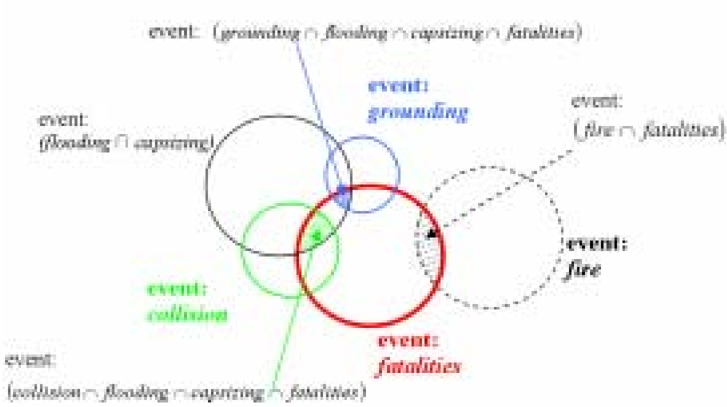

Figure 2 Illustration of the concept of a compound event referred to as "fatality" by Venn's diagram, [18], which is a union of

[2] an event of a loss scenario is a hazard that materialised

mutually exclusive scenarios, whereby each scenario is an intersection of a set of relevant events and is identified by principal hazards, such as collision, fire, etc.

Deriving from the above, it is hereby proposed that the frequency $fr_N(N)$ of occurrence of exactly N fatalities per ship per year is modelled as follows:

$$fr_N(N) = \sum_{j=1}^{n_{hz}} fr_{hz}(hz_j) \cdot pr_N(N|hz_j) \quad (1)$$

Where n_{hz} is the number of loss scenarios considered, and hz_j represents an event of the occurrence of a chain of events, (a loss scenario), identifiable by any of the following principal hazards:

Table 1 Principal hazards

j	Principal hazards, hz_j	Average historical frequency of its occurrence, $fr_{hz}(hz_j)$
1	Collision and flooding	2.48e-3 , ref [6]
2	Fire	
3	Intact Stability Loss	
4	Systems Failure	
	… etc	

Furthermore, $fr_{hz}(hz_j)$ is the frequency of occurrence of a scenario hz_j per ship per year, and $pr_N(N|hz_j)$ is the probability of occurrence of exactly N fatalities, given loss scenario hz_j occurred.

In principle, there is nothing new to this proposal, except, perhaps, for the emphasis of the need to estimate the probability of exactly N fatalities, $pr_N(N|hz_j)$, conditional on the occurrence of any of the principal scenarios j, an essential element, conceived during [20], and often unaccounted for in risk concept proposals, such as e.g. [19].

Modelling of either of the elements of the equation (1) requires an in-depth analysis of historical data as well as thorough analytical considerations of all real-life processes affecting them, practical attainment of which far exceeds the capacity of any one institute. It is for this reason that efforts integrated among a sizeable consortium of specialist partners are undertaken, [1], to derive essential elements, expectedly complementing model (1), collectively.

It is impossible to describe all of these efforts in this article, however for demonstration a prototype model of the probability of an event of occurrence of exactly N fatalities conditional on the occurrence of a scenario of $collision \cap flooding$, that is scenario corresponding to $j = 1$ in Table 1, will be discussed. Namely, it can be shown that $pr_N(N|hz_{j=1})$ can be expressed as (2), [20].

$$pr_N(N|hz_1) = \sum_{i}^{3} \sum_{j}^{n_{flood}} w_i \cdot p_j \cdot \sum_{k}^{n_{Hs}} e_k \cdot c_{i,j,k}(N) \quad (2)$$

Where the terms w_i and p_j are the probability mass functions of the 3 specific loading conditions and n_{flood} the number of flooding extents, respectively, calculated according to the harmonised probabilistic rules for ship subdivision, [14], [8]. The term e_k is the probability mass function derived from (15) for the sea state Hs_k, where $0 < Hs_k \le 4m$, $Hs_k = k \cdot 4 \cdot n_{Hs}^{-1}$ and n_{Hs} is the number of sea states considered. The term $c_{i,j,k}(N)$ is the probability mass function of the event of capsizing in a time within which exactly N number of passengers fail to evacuate, conditional on events i, j and k occurring, and can be tentatively estimated from (3).

$$c_{i,j,k}(N) = \left(-\ln(\varepsilon_{i,j,k}) \cdot (\varepsilon_{i,j,k})^{\frac{t_{fail}(N)}{30}} \right) \cdot \frac{|\partial t_{fail}(N)|}{30} \quad (3)$$

The term $\varepsilon_{i,j,k}$ (with σ_r) represents the phenomenon of the capsize band shown in Figure 3, that is the spread of sea states where the vessel might capsize. These can be estimated as follows:

$$\varepsilon_{i,j,k} = 1 - \Phi\left(\frac{Hs_k - Hs_{crit}(s_{ij})}{\sigma_r\left(Hs_{crit}(s_{ij})\right)}\right) \quad (4)$$

$$\sigma_r(Hs_{crit}) = 0.039 \cdot Hs_{crit} + 0.049 \quad (5)$$

Where $\Phi(.)$ is the cumulative standard normal distribution. The $Hs_{crit}(s)$ is calculated from equation (16) of Appendix 2. The s_{ij} is the probability of survival, calculated according to [14]. Its interpretation is discussed in Appendix 2.

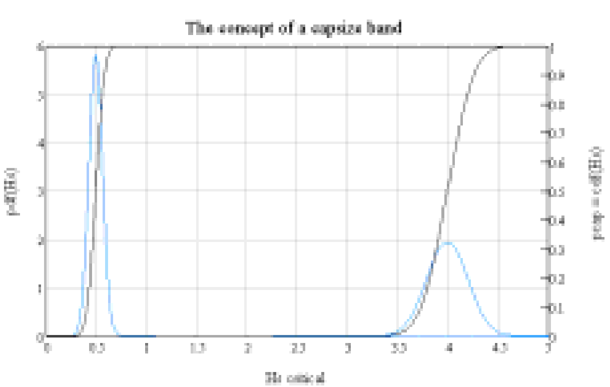

Figure 3 The concept of “capsize band”, [17], for critical sea states of 0.5 and 4.0m.

$$\partial t_{fail}(N) = t_{fail}(N) - t_{fail}(N-1) \quad (6)$$

$$t_{fail}(N) = N_{fail}^{-1}(t) \quad (7)$$

$$N_{fail}(t) = N_{\max} - N_{evac}(t) \quad (8)$$

Finally, the term $N_{evac}(t)$ is the number of passengers evacuated within time t, and is referred to as an “evacuation completion curve”, see Figure 4. Such a curve can effectively be estimated on the basis of numerical simulations, [22].

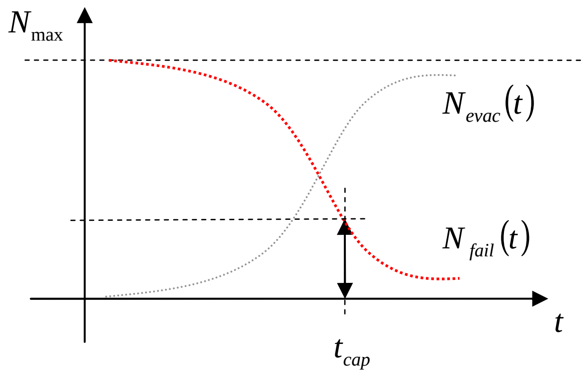

Figure 4 Evacuation completion curve

Details of the reasoning process followed in deriving the model (2) to (8) will be published elsewhere, as soon as the remaining elements of the modelling, not mentioned here, as well as the verification studies to be undertaken in [1] and [20] are complete.

However, it is worthwhile to offer discussion of some preliminary results from a sample case studies demonstrating risk sensitivity to some key input parameters. The study is discussed in §4, after introducing of the final elements of the risk model in the next section §3.2.

3.2 Risk as a summary statistic

The frequency of occurrence of exactly N fatalities per ship year, that is the information provided by the model (1), once all its elements are calculable, allows for direct application of fundamental concepts of statistics for describing the statistical properties of the random events in question, in this case fatalities.

The most obvious one is use of a graphical plot of a relationship of this frequency with the number of fatalities. For example, it is very common to graphically plot the cumulative frequency of N or more fatalities, so referred to FN plot, given by equation (9).

$$F_N(N) = \sum_{i=N}^{N_{\max}} fr_N(i) \quad (9)$$

Where $N_{\max}$ is the total number of persons considered (e.g. number of crew, or number of passengers, or both).

An example of such relationship derived on the basis of historical data, rather than analytical/numerical modelling, is shown in Figure 5 below.

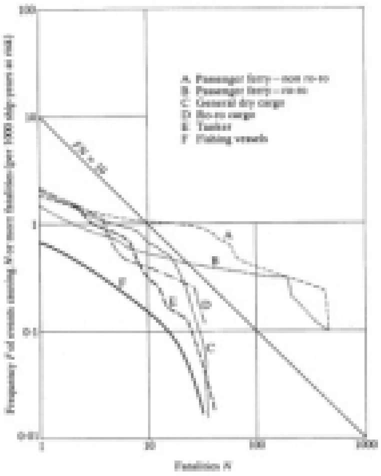

Figure 5 Example of an FN plot derived from historical data, [21].

However, while conceptually useful and, indeed, accepted widely as an expression of risk especially when plotted together with related criteria lines, [5], it has been well known that for the purposes of any consistent decision making, [15], some form of aggregate information, derived on the basis of such distributions, is required.

Commonly used summary statistics, such as expected value, are examples of such aggregate information.

It is hereby emphasised that this form of information be used to quantify the "chance" of a loss, or the risk. Unsurprisingly, the expected number of fatalities, $E(N)$, given by (10) and often referred to as the potential loss of life, PLL, has been used among the pertinent profession routinely. See Appendix 1 on the form of equation (10).

$$Risk_{PLL} \equiv E(N) \equiv \sum_{i=1}^{N_{\max}} F_N(i) \qquad (10)$$

As it is known in the field of statistics, it is always desirable to find a statistic which is not only consistent and efficient, but ideally is sufficient, as then all relevant information is contained in one such number. In case of a statistic which is not sufficient, additional information is required to convey the characteristics of the underlying random process.

Since it is well known that the expectation is hardly ever a sufficient statistic, it is necessary to examine what additional information is required additionally to (10) to quantify risk sufficiently comprehensively.

Namely, it is well known that the public tolerability for large accidents is disproportionally lesser than the tolerance for small accidents even if they happen at greater numbers. This tendency is not disclosed in the model (10), as simply the same expected number of fatalities can result from many small accidents or a few larger ones. It is for this reason, that model (10) is also referred to as a risk-neutral or accident-size-neutral, [15]. Thus, public aversion to large accidents cannot be built into any relevant criteria based on PLL.

Although there are strong suggestions negating such a need and supporting the view that a risk-neutral approach is sufficient, e.g. [5], it does not seem that the above simple fact of real life can be ignored. Indeed, recently proposed criteria for stability based on the so called "probabilistic concept of subdivision" defy this risk-neutral philosophy, as ships with more passengers are required higher index of damage stability.

Therefore, a proposal by [16] shown as equation (11) seems worth serious consideration as an alternative to (10), as it allows for controlled accommodation of the aversion towards larger accidents through stand. dev. $\sigma(N)$ and a risk-aversion index k.

$$Risk_{\sigma} = E(N) + k \cdot \sigma(N) \qquad (11)$$

Which form of a statistic is to be used to quantify risk should be the important next step in research in this field.

To summarise this chapter, as one can see, risk can be shown to be a *statistic of the loss*, which can be systematically modelled and used for better informed decision making during any design process.

To demonstrate potential benefits of some elements of the concept of a holistic approach to risk modelling and contained in model (1) and (10), simple case studies are discussed next.

4 SENSITIVITY STUDIES

As has been mentioned earlier, there are no readily available elements relating to even a handful of loss scenarios listed in Table 1 and necessary to complete model (1). However, since it is known that collision and flooding is one of the major risk contributors, a sample study aiming to demonstrate the usefulness of the proposed risk model is undertaken here based on only this loss scenario.

Consider a RoRo ship, carrying some 2200 passengers and crew, and complying with the new harmonised rules on damage stability by meeting the required index of subdivision of 0.8 exactly, see Figure 6. Consider also that the evacuation arrangements allow for two different evacuation completion curves, as shown in Figure 7. The question is what is the effect of given evacuation curve on risk to life posed by this ship?

The risk is calculated for $n_{hz} = 1$ in (1), using constant $fr_{hz}(hz_1) = 2.48 \cdot 10^{-3}$ per ship year. Element (2) is estimated based on the information shown in Figure 6 and Figure 7.

Figure 8 demonstrates the effect of the evacuation completion curve on the conditional probability $pr_N(N|hz_1)$. It seems that the majority of this scenario variants are either no fatalities at all or a very large number of fatalities. Note that because of this trend, the function estimates at these limits determine the ultimate risk, and that the impression of higher overall frequencies for 60-min evacuation curve seen in Figure 8, must be viewed with care.

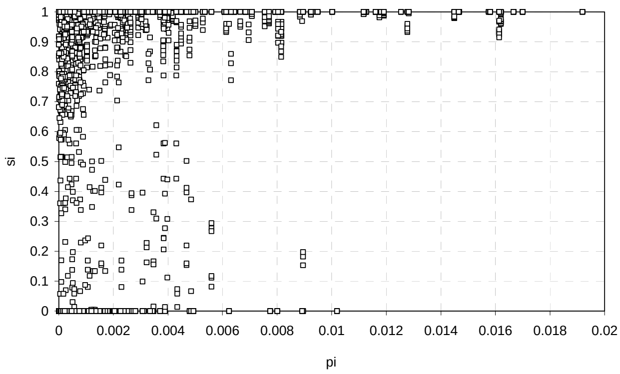

Figure 6 Elements of index A, sample case.

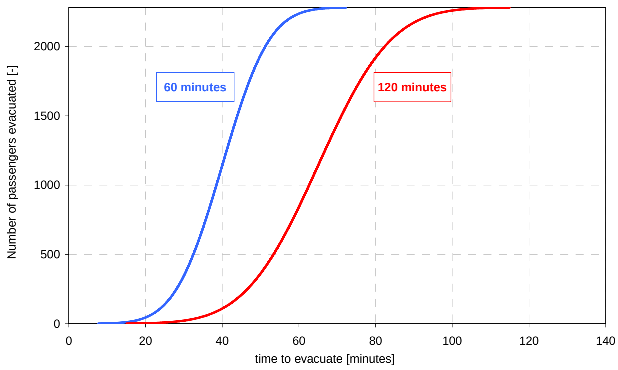

Figure 7 Hypothetical evac. completion curve

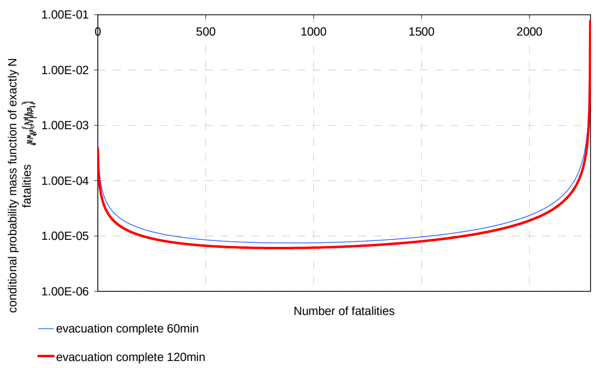

Figure 8 Prob. $pr_N(N|hz_1)$ for sample case

The resultant FN curve derived on the basis of (9) can be seen in the Figure 9. It seems that the distribution is not affected significantly by different evacuation completion curves, though when comparing the risk of 0.881 and 0.939

fatalities per ship year, estimated according to equation (10) for 60 minutes and 120 minutes evacuation completion curves, respectively, a difference of some 6% can be seen as a considerable design/operation target worth achieving.

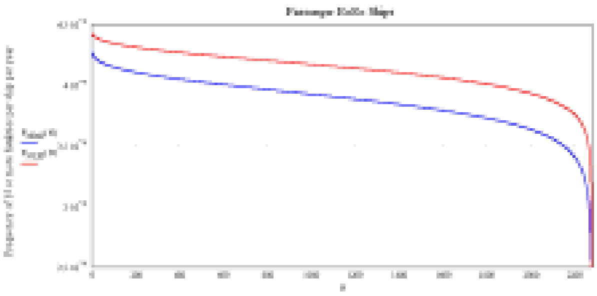

Figure 9 FN plot, effect of evacuation completion characteristics on risk

Another interesting test was undertaken, whereby a hypothetical ship with only two flooding extents possible was used together with the 60minutes evacuation completion curve shown in Figure 7. Two cases were assumed for the characteristics of flooding extents, such that in both cases the resultant index A remained the same. Namely in case 1, $p_1^1 = 0.1$, $s_1^1 = 0.3000$, $p_2^1 = 0.9$, $s_2^1 = 0.8560$, and for case 2, $p_1^2 = 0.2$, $s_1^2 = 0.6000$, $p_2^2 = 0.8$, $s_2^2 = 0.8505$, were assumed. The resultant FN curves are shown in Figure 10 below.

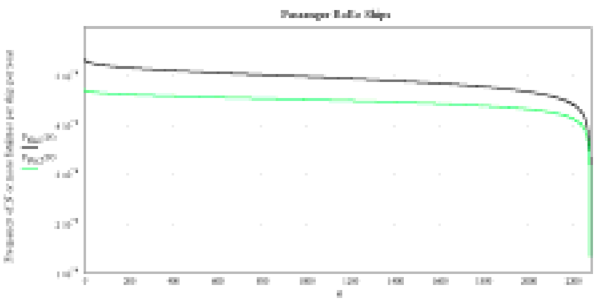

Figure 10 FN plot, effect of subdivision on risk, 60-min evacuation completion curve

As can be seen, contrary to the commonly expressed view, two ships with different subdivision but the same index A, seem unlikely to have the same level of risk.

5 FURTHER WORK

The process of conceptualising risk discussed in this article is one of the many needed before the vision of Risk Based Design, a design paradigm utilising the concept of risk for the purpose of safety verification, can become a reality. The fundamental elements that need to be in place are (a) an explicit risk model capable of accommodating a number of loss scenarios, sufficient to meaningfully quantify risk, and (b) the criteria, which will reflect both, the societal risk tolerability, and as importantly, the epistemic and the aleatory uncertainties of the proposed risk model. Hopefully some elements of these will be achieved through the recently mobilised international efforts of [1].

6 CONCLUSIONS

This paper discussed the concepts of safety and risk. Many lexical issues, often ignored in the communication on these concepts, have been pointed out. Some suggestions on more intuitive definitions have been made. A process of risk modelling has been explained to some extent, and a simple yet comprehensive model has been presented. A tentative model for probability of exactly N fatalities and conditional on the occurrence of a $collision \cap flooding$ loss scenario has been presented, with the derivation process yet to be published. Results of calculations of contribution to risk from this scenario have been presented. Preliminary results seem to indicate that the common notion that two different ships with the same index of subdivision correspond to the same level of risk is not justified.

7 ACKNOWLEDGEMENTS

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Appendix 1 A note on the expected rate of fatalities

It can be shown that the area under the FN curve represents the expected number of fatalities per ship year, [16]:

$$\sum_{i=1}^{N_{\max}} F_N(i) = \sum_{i=1}^{N_{\max}} \sum_{j=i}^{N_{\max}} f_N(j) = \sum_{i=1}^{N_{\max}} \sum_{j=1}^{i} f_N(i) = \sum_{i=1}^{N_{\max}} i \cdot f_N(i) \equiv E(N) = PLL \qquad (12)$$

Appendix 2 <u>A note on the interpretation of the probability of survival</u>

The survival factor "s_i" in [14], represents the probability of an event that a vessel *survives* after flooding of a set of compartments i due to a collision with another vessel and subsequent flooding.

The question is what does "*survive*" mean? The following is the proposed interpretation.

The relationship between the survival factors, considering only the final stage of flooding, and the ship parameters are:

$$s_{i,\,final} = K \cdot \left[\frac{GZ_{\max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}} \qquad (13)$$

This has been derived from (14), i.e. the relationship between the parameters $GZ_{\max}$ and $Range$ and the critical sea state[3], Hs_{crit}, established through physical model experiments, [13]; and the cumulative distribution function $F_{Hs_{collision}}$ of the sea states recorded at the instant of collision and given by equation (15), see also Figure 11. Note, that for the purpose of derivation of (13), it was implied that $Hs_{crit} \sim Hs_{collision}$, whereby the relationship between (14) and (15) was obtained through regression analyses rendering directly formula (13).

$$Hs_{crit} = 4 \cdot \left(\frac{GZ_{\max}}{0.12} \cdot \frac{Range}{16} \right) \qquad (14)$$

$$F_{Hs_{collision}} = e^{-e^{0.16 - 1.2 \cdot Hs_{collision}}} \qquad (15)$$

It is worth now offering the form of hard numbers in explaining the meaning of the probability (13), given the underlying relationships (14) and (15). One such form could read as follows: should the vessel suffer 100 collision incidents, say in her lifetime, always leading to flooding of the same spaces "i" with a survival factor of, say, $s_{i,\,final} = 0.9$, then 90 of these incidents will take place in a sea state with significant wave height below $Hs(s_{i,\,final}) = 2m$, see equation (16), with the vessel remaining afloat for at least 30minutes at a relevant damage-state equilibrium (in other words the vessel will "*survive*"). The remaining 10 of these incidents will take place in a sea state with the significant wave height above $Hs(s_{i,\,final}) = 2m$, and the vessel will not be able to sustain this for the 30 minutes after collision (the vessel will not "*survive*"), see the note on critical sea state[3].

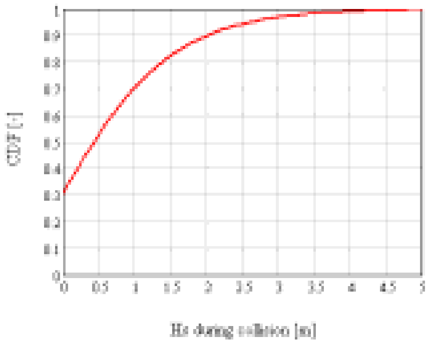

Figure 11 CDF of significant wave heights at instants of collisions, eq. (15), [13].

This interpretation follows the "philosophy" behind the formulation for the $s_{i,\,final}$, discussed in [13], currently underlying the new harmonised Chapter II Part B of the SOLAS Convention, [14].

The relationship between the significant wave heights at the instant of collision, here equal to the critical sea state[3], and the "s" factors is given by equation (16), [13], which is derived from equation (15).

$$Hs_{crit}(s) = Hs_{collision}(s) = \frac{0.16 - \ln(-\ln(s))}{1.2} \qquad (16)$$

The aforementioned time of 30 minutes derives from the re-scaled model test duration assumed during the campaign of physical model experiments of the HARDER project, [13], which underlines the relationship between ship parameters and the sea states[3] leading to capsize.

[3] a sea state causing the vessel capsizing during about half of the 30minutes scaled model tests, the damage opening modelled was that known as SOLAS damage