Risk-Based Design for Fire Safety – A Generic Framework

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ABSTRACT

SOLAS Ch. II-2 objective is to contain, control and suppress the fire in the space of origin. However, the regulatory rationale follows a vulnerability approach, i.e. assessment for a handful of the worst case scenarios and allows little flexibility to explore the much needed innovative arrangements of modern passenger ships. Drawing from the mature risk-based ship design methodology in damage stability, this rather stiff approach to the quantification of fire risk can be remedied by the development of a probabilistic framework, where the probability of ignition and the severity of a fire event will be quantified and aggregated in the form of an Attained fire index. As in SOLAS Ch. II-1, compliance with the regulation will be achieved when the attained index is equal to or larger than a Required index (standard), which will be derived on the basis of past experience and the investigation of a large set of fire scenarios. Considering that flooding and fire comprise 90% of ship accidents, it was opted to use this formulation so that compatibility with the existing damage stability framework can be achieved and taken into consideration in future amendments of SOLAS Ch. II. The work reported here describes a high level framework for the quantification of fire risk analysis and it is developed in the course of the FIREPROOF project (www.fireproof-project.eu), which is partially funded by the 7th Framework Programme of the European Commission.

INTRODUCTION

The SOLAS convention is the main regulation derived by IMO with the explicit focus on the safeguard of human life in all maritime-related activities. Among the hazards faces in the course of these activities, fire has proven to be the most frequent, albeit the less catastrophic one in nature compared to collision and grounding. This fact is established with analysis of past accidents statistics as presented in Figure 1.

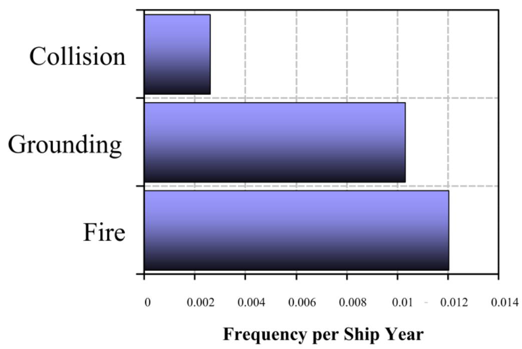

Figure 1: Fire, collision and grounding accidents according to the study of Nilsen (2007)

The SOLAS convention is a "live" instrument of IMO in the sense that that it expected to be regularly amended to reflect the most up-to-date needs of the industry and, as a consequence, the expectations of the society with respect to the safety levels of the services offered by it. However, it is widely appreciated that the amendment process of SOLAS is generally time-consuming and, more often that it would be expected, it is overtaken by major developments in the industry. At the same time, it is further acknowledged that SOLAS regulations are largely governed by past experience, therefore reflecting the safety of past or existing ships with little effort to cater for future, more advanced and innovative designs.

A development that initiated a step change in the passenger ship sector is the recent delivery of the *Oasis of the Seas* cruise liner, with capacity to accommodate passengers and crew in excess of 8,000. This project signified a step change in the way the engineering community, the maritime industry and the society at large perceive the unprecedented operation of a single platform with such large number of people onboard. Among other challenges that were posed by this development, the weaknesses of the SOLAS convention to cope with such a ship, and those that will follow, was highlighted in the course of the SAFEDOR project (www.safedor.org), and Guarin et al, (2007).

This paper elaborates on the establishment of a generic framework for the rationalisation of the fire risk assessment onboard passenger ships according to the mature risk-based design methodology. The proposed formulation is compatible with the probabilistic damage stability regulation (SOLAS, Ch. II-1) and considering that flooding and fire comprise 90% of all pertinent accidents, it is believed that this choice will facilitate a holistic treatment of both hazards in the future.

THE PROBABILISTIC FRAMEWORK FOR DAMAGE STABILITY AND THE RISK-BASED DESIGN APPROACH

The existing probabilistic framework for damage stability is based on the ideas proposed by Wendel (1960), and it is implemented by the calculation of the Attained Index of Subdivision (A):

$$A = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j \cdot p_i s_{ji} \quad ; \quad A > R \qquad (1)$$

Where:

- R Required Index of Subdivision;
- j loading condition (draught) under consideration;
- J number of loading conditions considered in the calculation of A (normally 3 draughts);
- i represents each compartment or group of compartments under consideration;
- I set of all feasible flooding scenarios comprising single compartments or groups of adjacent compartments;
- w_j probability mass function of the loading conditions (draught);
- p_i probability mass function of the extent of flooding (that the compartments under consideration are flooded);
- s_{ij} probability of surviving the flooding of the group of compartment(s) "i", given loading (draft) conditions j occurred.

$$s_i \approx K \cdot \left[\frac{GZ_{\max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}} \qquad (2)$$

Where

GZ_{max}: is not to be taken as more than 0.12 m
Range: is not to be taken as more than 16 degrees

$$K = \begin{cases} 1, \text{ if } \theta_e \le \theta_{min} \\ 0, \text{ if } \theta_e \ge \theta_{max} \\ \sqrt{\dfrac{\theta_{max} - \theta_e}{\theta_{max} - \theta_{min}}}, \text{ otherwise} \end{cases}$$

θ_{min}: 7 degrees for passenger ships and 25 degrees for cargo ships
θ_{max}: 15 degrees for passenger ships and 30 degrees for cargo ships

This formulation is based on the statistical analysis of a large number of scenarios and builds on the conditions that a collision has occurred and a compartment is flooded. As such, the purpose of having a *probabilistic* regulation is defeated by conducting *vulnerability analysis* for a finite set of damage cases, corresponding to the layout of the ship (Figure 2), and aggregating the results. Any attempt to take into considerations the operational provisions for averting collisions, the crashworthiness of the struck ship, and the dynamics of the capsizing mechanism are disregarded.

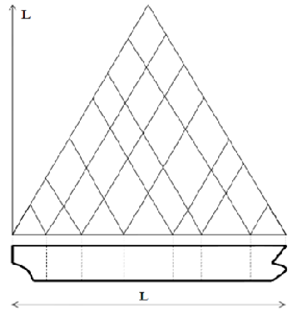

Figure 2: The probability of flooding of one of or more adjacent compartments functions as weight to the s-factors for the respective damage case

Notwithstanding this state of affairs, a risk-based design approach has been proposed by Vassalos, (2004), as an alternative to this formulation, where the collision risk is obtained by taking into consideration the elements that comprise the sequence of events that will lead to loss of stability and cause damage to property and environment, and loss of life:

$$R = P_c \times P_{w/c} \times P_{cap/w/c} \times C \qquad (3)$$

Where

- R: collision risk
- P_c: probability of collision
- $P_{w/c}$: probability of water ingress due to collision
- $P_{cap/w/c}$: probability of capsize due to water ingress and collision
- C: ensuing consequences of a collision accident

Formulations (1) and (3) are not necessarily incompatible to each other: they both build on the fundamental definition of risk as the product of probability of occurrence of an unwanted event and its ensuing consequences should it occur. In this manner, equation (1) could be developed further to include in the p-factor the elements of probability, i.e. $P_c \times P_{w/c}$, that should be taken into account (in the form of a large number of collision scenarios sampled by Monte Carlo simulation for example) in order to calculate the effect on the ship's stability, as it is demonstrated by Mermiris and Vassalos, (2010). Moreover, the stability loss and the loss of lives, i.e. $P_{cap/w/c} \times C$, could be accommodated in the s-factor as it has been shown by Jasionowski and Vassalos, (2006).

The above approach rationalises the way collisions are treated as the operational profile of the ship (in terms of traffic patterns, area of operation, speed, passengers onboard, etc.) and its inherent characteristics (length, layout, manoeuvrability, structural configuration of the side shell, etc.) are taken into consideration in the calculation of flooding risk. The benefit of this approach is the explicit consideration of safety as a design objective alongside more conventional design objectives like low resistance, sufficient strength, etc., which allows more thorough search of the design space and caters for innovation from the outset. For example, the crashworthiness of the side shell can be a major design objective if frequent operation in congested waters is pursued. The treatment of the side shell performance in collision loading imposes its own weight on the local strength of the ship and the design configuration in general. More thorough description of the risk-based design methodology and its applications can be found in (Vassalos, 2009).

A RISK-BASED DESIGN FRAMEWORK FOR FIRE SAFETY

The line of thought presented in the previous section will be followed for the establishment of a fire safety framework for passenger ships. This development is currently taking place in the course of the FIREPROOF project. The subsequent sections will elaborate on the specifics of the framework and will demonstrate the similarities with the existing damage stability framework.

Database and data mining

The frequent occurrence of fires onboard ships has naturally motivated maritime companies to collect and process the available data for setting up strategies and procedures in emergency situations, and crew training in general. In the course of the proposed framework, the fire-related data is processed with the *data mining* technique as it is discussed in Vassalos et al, (2009).

Data mining is the process of discovering meaningful correlations, patterns, and trends by sifting through stored data, using pattern recognition technologies, and statistical and mathematical techniques. The process is described at high level in Figure 3.

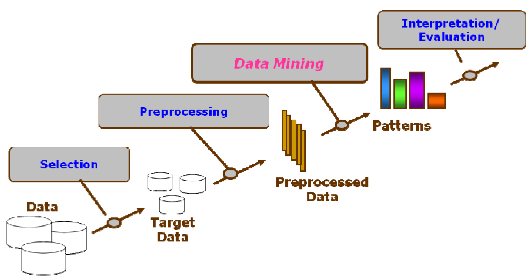

Figure 3: The data mining implementation in the course of interpreting and evaluating data related to fire incidents / accidents

Following this, the extracted data is used to define the structure of a Bayesian Network (BN). BN are directed acyclic graphs that build on the Bayes theorem. In the current context, a BN is built in terms of (i) selection of nodes that represent discreet parameters of the database (i.e. fields), (ii) the connections among the dominant parameters representing cause-and-effect relationships, and (iii) their population with the required conditional probability tables. An example BN is presented in Figure 4. The advantage of deploying BN in the current context is that once the network is populated, then a large number of scenarios can be generated by assigning 100% occurrence to a set of nodes and examining their effect at the end nodes of interest, in this case the "Fire escalation out of the space of origin". The approach is very similar to the development of a very extensive event tree but the added value is that the BN can be summarized on a single page and reviewed fast, contrary to the former case.

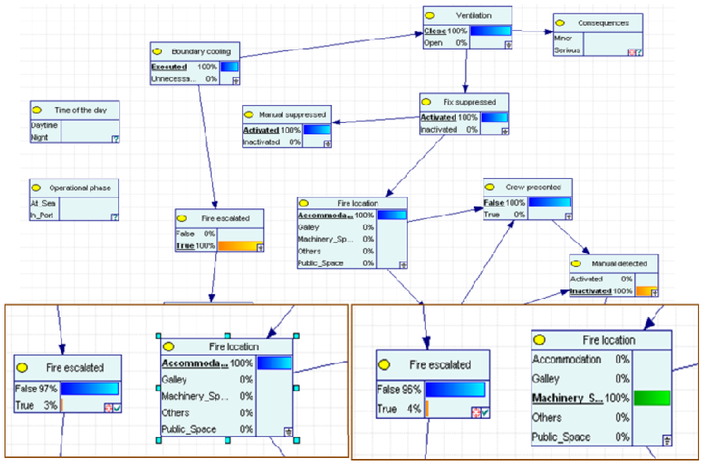

Figure 4: Example BN for the needs of FIREPROOF project

The choice to deploy the data mining technique in combination to a BN aims to rationalise the generation of a large number of scenarios and ensuing variations, and at the same time to build on existing experience with respect to the initial conditions of a fire incident / accident as it will be discussed next.

Fire specifics

In the study of fire occurrences, there is a series of parameters that needs to be taken into consideration as it is discussed next. This information will complement the scenarios that will be addressed in the framework.

- *Fire specifics*: for every space onboard it is necessary to poses information related to the contained fire load (amount and type) and potential heat release rate (HRR), the type of its boundaries (e.g. A60), the type and amount of the fire effluents, etc. The proposed framework builds on the 14 SOLAS categories as defined in Ch. II-2.
- *Geometry*: the dimensions of the space and its location with respect the general layout have a definitive character with respect to the potential size of the fire and the escape routes of passengers and crew in its vicinity.
- *Topology*: the amount of air supplied in the fire will define its potential to develop. As a result it is important to know the dimensions of various ventilation ducts, windows and doors.

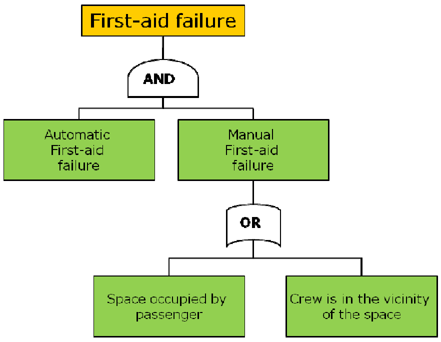

Figure 5: High level fault tree for first-aid-failure following ignition in a space

- *Conditions*: the development of a fire will depend on the activation of the fire extinguishing systems, the opening status of doors / windows, the operation of ventilation systems and the presence of passengers and/or crew in the vicinity, Figure 5.

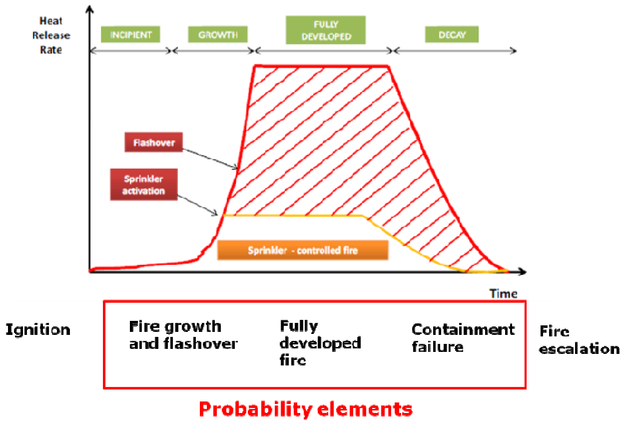

Figure 6: The phases of scenario generation based on fire specific information and data base initial conditions

<u>Scenario generation</u>

A fire scenario related with the fire type, size and development in a space is represented by the HRR curve (Figure 6), which describes the main fire stages, namely the *incipient*, the *growth*, the *fully developed* and the *decay* stage. A physically rational model that generates probabilistically HRR curves based on key parameters like fire load, incipient time, growth potential and others has been developed and presented in (Themelis et al, 2010).

The expected variation of layouts and contents of spaces of the same SOLAS category among ships leads to uncertainty with respect to the amount and type of the combustible material for example. As a result, the model addresses this and similar parameters as random variables and a number of HRR curves are produced probabilistically, top and bottom of Figure 7 respectively, which are utilised as input in terms of fire characteristics in the scenario generation methodology, as well as in the numerical tools for fire modelling.

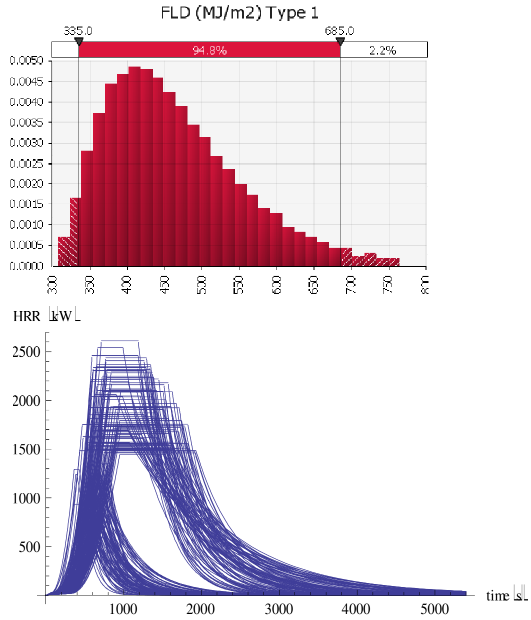

Figure 7: Generation of information for fire specifics (fire load density and HRR curves respectively)

In this respect, the outcomes of fire scenarios and their variations will be assessed with analytical models for the estimation of fire products (e.g. for calculating upper layer temperatures) (i) a hybrid model, Figure 8, between Computational Fluid Dynamics (CFD) and zone models that combine the advantages of both models by reducing the computational time (in order to simulate a larger number of scenarios) and (ii) the appropriate use of a societal consequence model (based on the coupling of initial occupancy of various spaces, evacuation behaviour and fire growth simulations).

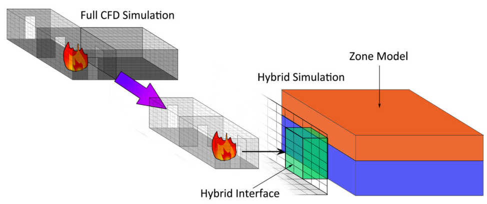

Figure 8: High level schematic description of the hybrid model for fire simulation

For the purposes of FIREPROOF, the integrated fire model will use CFD modelling for complex geometries and areas beyond the reliable application of empirical zone models and the zone models will be applied in areas where the empiricism can be consistently applied, (Burton et al., 2007).

<u>Fire regulatory framework</u>

Consolidation of all the derived information will be formulated as follows:

$$A_{\text{fire protection}} = \sum_{i=1}^{N} w_i \times p_i \times s_i \geq R \qquad (4)$$

Where:

A / R:	attained / required fire safety index
i:	counter for the number of spaces onboard
p_i:	probability of fire ignition in space i
s_i:	probability of fire protection in space i
N:	number of spaces under consideration
w_i:	weighting factor addressing the space criticality with respect to fire effluents, occupancy rate, proximity to escape routes, etc.

In this context, fire protection should be understood as the "contain, control and suppress" objectives described in SOLAS Ch. II-2.

The framework can be implemented for all spaces onboard. That is, for every space of a main vertical zone and for all zones, Figure 9. In this manner, a clear picture of the fire risk can be drawn during the approval process. It should be stressed that the large number of spaces on board a passenger ship can deem this exercise very time consuming. For this reason, a product model with the required information and integration of all the necessary tools for fire risk analysis will be elaborated upon in the process of FIREPROOF.

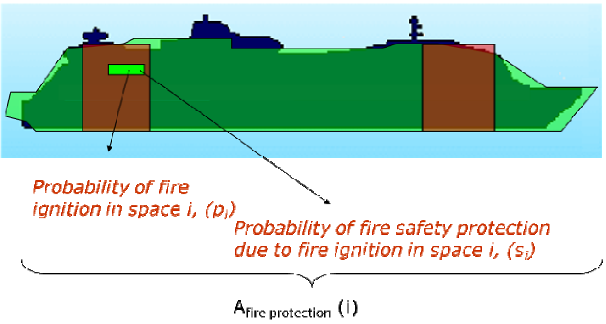

Figure 9: Application of the proposed framework for all spaces onboard a passenger ship

Finally, as it was discussed at the beginning of this paper, the similarity of equations (1) and (4) is obvious. However, as it was stressed earlier, the new development builds from the outset on the risk-based design methodology thus extending the potential of application to existing and new ships.

FUTURE STEPS

The framework outlined in this paper, and its presentation to IMO are the objectives of the FIREPROOF project. The project has almost reached the middle of its duration and it is now elaborating on the fine-tuning of the scenarios that will be simulated for the derivation of the required index R. The establishment of the fine details of equation (4) will be addressed in the last six months of the project. Further information will be regularly become available in the project web site.

CONCLUSIONS

Drawing from large experience in the area of damage stability regulation and considering that fire and flooding constitute 90% of all pertinent hazards of passenger ships, the framework for the probabilistic fire risk assessment is proposed. The elements of the framework build on the risk-based design methodology, i.e. a rationalised way in treating fire incidents / accidents and at the same time cater for the largely innovative arrangements and size of modern ships.

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