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Towards risk—based fire safety assessment of passenger ships

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ABSTRACT: In the paper is outlined a fire safety assessment framework for passenger ships, developed as one of the tasks for the European project FIREPROOF (www.fireproof-project.eu). The framework can yield the safety level attained by a candidate passenger ship design, with respect to fire incidents. The methodology is driven by a fire risk model, governed by explicitly stated principles and assumptions. A function characterizing fire severity is defined. To risk's calculation contribute all onboard spaces by means of: the associated probability of ignition, the reliability of the installed fire suppression systems; and the incurred fatality "cost" that is determined from the consequences of several "loss scenarios" considered. As a case study, risk is calculated with respect to an ignition incident in a cabin balcony, with fire effluents spreading towards deck's interior. Results are presented as fatalities per ship year, as probability of zero fatality and in the form of *F-N* curves.

1 INTRODUCTION

Could there be a reliable and transparent risk-based fire safety assessment methodology suitable for ship application? The question is not new and one might even consider it as superseded, given that procedures of fire safety assessment going beyond the prescriptive requirements of SOLAS are already applied in the design of large passenger ships. As well known, this key development was enabled by Reg. 17 of Chapter II-2 of SOLAS (IMO 2009) in combination with MSC 2002 (IMO 2001a). Nonetheless, to our knowledge, a coherent risk model allowing calculation of safety level while taking into account the breadth of choices faced by designers, has not appeared yet in the literature. The objective of the current work was to develop conceptually such a risk model, in essence taking one step beyond the probabilistic formulation recently proposed by the authors and integrating it with performance—based assessment tools of fire evolution, effluent spreading and evacuation (Themelis and Spyrou 2012).

The underlying concept of fire risk calculation is in harmony with the concept applied for damage stability assessment. Analogies exist also with the other probabilistic framework of ship design, the calculation of oil outflow in case of a random damage, especially on the definition of risk metrics. More specifically, the current concept is based on the summation of risk contributions of all spaces onboard, considering combinations of scenarios of fire development and evacuation. Compared to the two existing frameworks however, the problem here is considerably more multifaceted, affected by several uncertainties (Themelis et al. 2011a). Individual ignition incidents within a zone can evolve quite dissimilarly, producing consequences differing by orders of magnitude. Moreover, a fire incident can produce a multitude of threats to human life. The need to use advanced simulation tools for predicting fire evolution, effluents' spreading and their effect on the evacuees ("agents") appears here quite prevalent, since simple empirical models are not up to these tasks. Usually, the issue of "uncertainty" of deterministic predictions is kept to a low profile during applications. During the FIREPROOF project several tools have been used, sometimes in comparative manner [see for example Burton et al. 2011 and Themelis et al. (2011b)]. However, given the incurred computational cost, one still needs to be selective concerning the "loss scenarios" that are submitted to detailed processing, retaining only the likely "non-negligible" risk contributors. By "loss scenario" is meant a sequence of events imposing threat to human life, from the instance of ignition to the end of evacuation. It is basically one realization of a complex random process. To run a loss scenario, values should be specified for several parameters. These are grouped into four categories: location of fire ignition, fire specifics, ventilation conditions, and evacuation settings.

The method of risk calculation and the various conditions introduced to ensure the consistency of the framework are described below in section 2. The constituents of the fire risk model, analyzed in section 3, include the probability of fire ignition for each examined space, the reliability of the installed fire safety systems and the incurred "cost", with respect to human loss. Ignition probability is determined from available statistics. Random fire incidents are generated and they are subsequently ranked in terms of their severity. To achieve this ranking, an objective function is created, on the basis of the shape of the associated heat release rate curve. The median and the 95th percentile are selected respectively as the representative "moderate" and "extreme" scenarios. Results are presented for these two fire severity levels, in the form of: probability of zero fatality; risk indices based on the mean fatalities; and *F-N* curves.

A case of fire in a cabin balcony is included in section 4, for demonstrating a partial application of the risk model. Fire's evolution is affected by the prevailing wind condition and its effluents are considered to spread to the entire accommodation area of the same deck. Scenarios with and without fire extending to the interior of the ship are considered.

2 FIRE RISK FUNCTION FORMULATION

2.1 *Principles*

As a ship's first line of defense, the fire safety systems installed should effectively control and promptly extinguish any fire ignition accidentally occurring onboard. Should these systems be kept perfectly functional at all times, fire risk should be zero. No fire spreading should take place and there should be no fatalities owed to ignition events. This implies a "zero tolerance" principle.

On the other hand, one should recognize that fire safety systems may, in rare instances, not function to their specification level. Even then, the risk of human loss should still be controlled by design and it should be kept minimal. This principle introduces a second line of defense for a ship against ignition incidents. The safety level associated with a certain design, given failure of the fire safety systems installed in the vicinity of the ignition, will be determined on the basis of the risk model. As a matter of fact, it is imperative the risk model to be sensitive to a designer's choices, including objects' geometrical characteristics and arrangements, type and amount of ignited materials as well as design factors affecting the evacuation process (like escape routes and exits).

The risk formulation should take into account several uncertainties that influence the outcome of such an evaluation concerning for example: intensity of fire growth; fire location, size and duration; and agents' distribution onboard. The prediction of consequences should be based on mathematical models offering verified accuracy.

2.2 *Concept*

The main idea behind the current fire risk formulation is to calculate the risk contribution of every space onboard, by considering clusters of loss scenarios and their probability of occurrence. A loss scenario is based on a fire incident in some ship space. The standard SOLAS space categorization has been used. A passenger ship fire incidents database was created in the FIREPROOF project and it was used for building a fire ignition model (for a description of this development see Mermiris et al. 2012).

A design's fire safety performance can be captured by systematically subjecting the numerical ship to several scenarios of fire, with different level of severity. Risk indices can be created, reflecting performance in terms of human loss, with respect to fire events with non-negligible effects (these should normally be associated with scenarios characterized by "moderate" and "extreme" fire severity). Risk can be expressed as number of fatalities per ship-year (s-y). A companion index is the probability of zero fatality. The choice of a simple mean or of other statistical indices (like various power means) should be a matter of investigation. In general, such choices reflect safety priorities.

The outcomes of loss scenarios are investigated by evacuation simulation. This is a key element of the calculation procedure since, numerical tools applied for modeling fire effluents' spreading are used also for predicting their effect on the agents during the evacuation process. However, consequences are dependent on population's distribution in the space of consideration; as a matter of fact, to each fire simulation should be clustered several evacuation simulations. Each loss scenario is run with deterministic input, thus producing a single number of fatalities. Uncertainties in the input parameters should result in a probability distribution of expected fatalities.

2.3 *Assumptions*

The following key assumptions lie behind the current fire risk formulation:

- Any considered fire is the result of a single initial ignition event onboard and therefore, simultaneous ignitions are excluded.
- Every ignition occurrence, in any onboard space, lies within the area of coverage of at least one installed onboard fire suppression system.
- The loss scenarios retained for quantitative investigation are associated with "failure to operate" of the appropriate fire suppression system.
- In the investigation of the consequences of a loss scenario by evacuation simulation, the agents located in the Main Fire Zone (MVZ) where the ignition occurred are assumed to be safe as soon as they reach an adjacent MVZ.

2.4 *Mathematical model*

Fire risk is calculated by the next generic formula:

$$R = \sum_i p_i(1 - r_i)C_i(N) \tag{1}$$

where:

- R: is the calculated risk in terms of human loss, from accidental fires onboard a ship.
- p_i: is the probability of ignition in space i per ship—year.
- r_i: is the reliability of the type of suppression system that is associated with space i.
- $C_i(N)$: is the "cost" in terms of fatalities due to ignition in space i.

The value of the cost function $C_i(N)$ for each space i is calculated on the basis of a multitude of associated loss scenarios j. More specifically, it is determined from the weighted summation of fatalities N_j yielded by each scenario j. Two risk indices are calculated, relating to a moderate and an extreme scenario, in terms of the fire intensity. Therefore, two values of risk contribution are calculated per space i. For the cost function, the following generic formula is used:

$$C_i(N) = \sum_j w_{i,j} N_{i,j} \tag{2}$$

where $w_{i,j}$ is the % contribution of a loss scenario j to the cost function of space i. It should hold:

$$\sum_j w_{i,j} = 1 \tag{3}$$

The weighting factors j can be specified from statistics. Here they were considered as equal.

In MSC. 1238 (IMO 2007) are specified population demographics (age, gender) and agent speeds that should be used in evacuation simulations. A number m of evacuation realizations are carried out, per loss scenario j of space i. As representative number of fatalities is taken the weighted average obtained from the m realizations:

$$\bar{N}_{i,j} = \frac{1}{m}\sum_{k=1}^{m} w_{i,j,k} N_{i,j,k} \tag{4}$$

A F-N curve can also be obtained, considering the probability to have exactly N fatalities for each scenario j. This is calculated using the output of the m runs.

$$fr_i(N) = p_i(1 - r_i)\sum_j pr(N_{i,j} | j) w_{i,j} \tag{5}$$

$$F_i(N) = \sum_{k=\mathrm{N}}^{N_{\max}} fr_k(k) \tag{6}$$

3 ELEMENTS OF THE RISK CALCULATION PROCEDURE

3.1 *Probability of ignition*

This is calculated by a model combining the historical frequency data and the floor area of the considered space. The fire ignition model incorporates frequency data for each type of the SOLAS space category obtained from the FIREPROOF fire incidents database.

3.2 *Reliability of fire safety systems*

In principle, smoke and heat detection sensors should be activated in every onboard ignition. Activation should lead to automatic and/or manual suppression. Extinguishment should be prompt for any location of ignition. The reliability of fire safety systems determines whether an ignition has potential to develop to fire. In summary, if fire safety systems are promptly activated and function as intended, then their effectiveness should be absolute and any ignition should be extinguished before producing any consequences. The issue of reliability, i.e. the probability that the system will function on demand, becomes however critical (Spyrou et al. 2013).

3.3 *Calculation of the cost function*

3.3.1 *Loss scenarios*

To obtain the value of the cost function in connection with some onboard space i, a set of loss scenarios j are run. To initialize a loss scenario, the values of several parameters innate to the fire and evacuation processes need to be introduced in the involved numerical tools. Fire effluents' spreading and their effect on agents during egress are the objectives of these simulation efforts.

Design characteristics, but also uncertainties, should be taken into account, particularly those that could affect the number of fatalities. A fire's evolution is affected by the type and amount of the ignited material, the ignition source and the ventilation conditions. In fire engineering, the Heat Release Rate (HRR) curve describes the stages of fire development. Furthermore, materials' heat of combustion and the yields of fire effluents (CO, CO_2 and soot) affect agents' egress. The location of fire ignition affects the fire and smoke propagation within the zone and ultimately the number of fatalities. A grip on the latter should be held also by the time of the evacuation call, the agents' responsiveness, space's capacity and the associated population demographics.

3.3.2 *Ventilation conditions*

A ventilation opening (door, window) can supply the necessary oxygen for sustaining fire growth. On the other hand, it allows for the spreading of fire effluents outside or in the wider area of the space of fire origin. Since loss scenarios feature an environment with life threatening conditions, doors and windows will be treated as open. For open spaces the wind should be considered (defined by its velocity and direction) since it is very likely to affect fire effluents' propagation.

3.3.3 *Fire specifics*

The critical input to the fire and smoke spreading simulation codes is the HRR curve, the heat of combustion and the yields of fire effluents (CO, CO2 and soot). The type, amount of combustibles and the ignition source apparently affect the values of these parameters.

Per loss scenario two HRR curves are produced, corresponding to two levels of fire severity: the "moderate" and the "extreme" fire. The authors have developed a mathematical model for the generation of design HRR curves of various sizes, in terms of the fire load consumed, considering in probabilistic manner the parameters affecting fire development (Themelis and Spyrou 2012). Nominally, a fire's development can be split into the incipient, the growth, the full development and the decay stage. In Figure 1 is presented an example of a design HRR curve. It corresponds to a fire in a passenger cabin with total involvement of the combustible material. An experimental curve corresponding to the same conditions is also shown. However, here the main issue is to derive HRR curves which correspond to different severity levels, with consideration of the uncertainty (epistemic and aleatory) in the values of the parameters defining them. These are affected by some design selections, such as the type and amount of combustible materials. Moreover, consequences are sensitive to the size and duration of the fire, both determined by the amount of fire load that can be consumed. On the other hand, the intensity of fire development, expressed by the growth rate α, determines the rate the fire effluents are spread in the considered space, thus affecting the duration of agents' exposure to fire hazards.

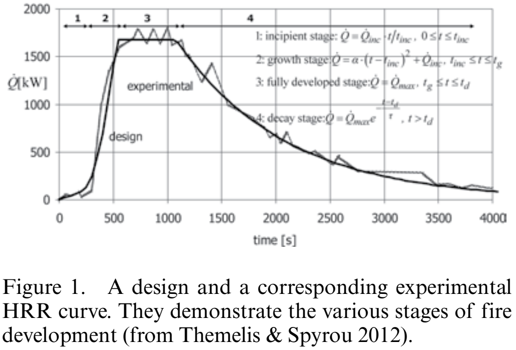

Figure 1. A design and a corresponding experimental HRR curve. They demonstrate the various stages of fire development (from Themelis & Spyrou 2012).

In order to quantify the severity of a fire scenario, a function f is built having as input normalized values Q_i', a_i' of the fire load and the growth rate, respectively. We tentatively assumed of equal importance for fire's evolution the fire load and the growth rate. Then, the procedure for the selection of the "moderate" and "extreme" scenario is described as follows:

- Generation of the probabilistic set of HRR curves.
- Identification of max values $Q_{\max}$ and $\alpha_{\max}$ in set.
- Normalization of Q_i, a_i by dividing respectively by $Q_{\max}$, $a_{\max}$.
- For each scenario, the "severity" function $f_i \in [0,1]$ is calculated (primes indicate normalized values):

$$f_i = s_1 \cdot Q_i' + \left(1 - s_1\right) \cdot a_i' \qquad (7)$$

- The f_i values are ranked in ascending order.
- The "moderate intensity" scenario is based on the median of the f_i values.
- The "extreme" scenario is identified with the 95th percentile of the f_i values.

The deterministic input required for some space under consideration is as follows:

- Geometry of the space and definition of its ventilation openings (dimensions).
- The total mass of combustibles that are available in the space, normalized by the area (this is known as fuel load density—[kgr/m^2]). This parameter is mentioned in MSC. 1003 (see IMO 2001b).
- Considering that combustible materials can be categorized in generic groups, an estimation of the percentage contribution of each group to the total combustible mass is required.

Furthermore, each generic group is determined by the mean values of several parameters (see Themelis & Spyrou 2012):

- The heat of combustion [kJ/kgr]. Knowing the fuel load density and the floor area of the space, the total fire load Q [KJ] of the space is known.
- The yields of fire effluents [g/g] (CO, CO_2 and soot).

- The thermal response parameter (TRP—[kW $s^{1/2}/m^2$]) and the critical heat flux (CHP—[kW/m^2]). These are related with the incipient phase, expressing material's resistance to ignition and to fire propagation.

Some other parameters however need to be treated as uncertain. These are mentioned next and characteristic ranges where they obtain values appear in Themelis & Spyrou (2012).

- The strength of the ignition source $\dot{q}_e''$, since it affects the duration of the incipient phase t_{inc}[s].
- The threshold HRR value, $\dot{Q}_{inc}$[kW], for achieving "established" burning.
- The fire growth coefficient a[kW/s^2]. In principle, every space, depending on the type of its combustible materials, could be characterized by a range of fire growth rates (e.g. slow to medium rates).
- The fire size, determined as fraction k of the total fire load Q.
- The ratio b of fire load that will have been consumed by the time fire decay begins.

3.3.4 *Location of fire ignition*

A fire incident's location affects the propagation of fire effluents. In addition, fire location might affect agents egress as evacuation routes or exits possibly become blocked. We think that the definition of location for some fire ignition should be related to the distance from the evacuation exits. In general, two locations of fire are examined: one nearest to an exit and one most distantly located from any one of the available exits. Each location participates to the risk function with equal weight.

3.3.5 *Evacuation settings for the loss scenarios*

3.3.5.1 Parameters of a loss scenario

An onboard space's occupation varies during the 24 hours. For example, a passenger cabin could be assumed as full at night; but for a large restaurant something similar may hold in certain hours during daytime while it is empty at night. Moreover, the time of the call affects agents' response time. According to MSC.1238 (IMO 2007), "response times are intended to reflect the total time spent in pre-evacuation movement activities, beginning with the sound of the alarm and include issues such as cue perception, provision and interpretation of instructions, individual reaction times, and performance of all other miscellaneous pre-evacuation activities. Therefore, the readiness of agents could affect significantly the number of fatalities.

Furthermore, possible unavailability of escape routes and exits should be considered as it can significantly affect the number of fatalities during evacuation, due to the possible congestion at the exits remaining available. Loss scenarios, where for each deck within the MVZ one of the available exits is blocked, are considered. Specifically, unavailability of both aft and fore side exits, with their mean fatality cost effect, are taken into account.

In MSC.1238 are found recommended population demographics and walking speed ranges in corridors and in stairways per population category (IMO 2007). These values were adopted in the current simulations. Walking speeds were uniformly distributed between the minimum and maximum values, per demographic category.

3.3.5.2 Fatality indices

In principle, a large number m of evacuation simulations are needed per loss scenario j in order to have confidence on the statistical result. In MSC. 1238 it is recommended to perform, at minimum 50 simulations. Then the question arises what are the appropriate statistical indices (based on the number of fatalities), that could be used in a process of design performance assessment. Below, the mean fatality value produced by the m simulations (see eq. 4) will be used for the calculation of risk indices.

4 A CASE STUDY: A FIRE ORIGINATING FROM A CABIN BALCONY

4.1 *Scenario description*

A case study will be presented for clarifying, through application, the previously described methodology of fire risk calculation. A fire originating from a cruiser's cabin balcony is considered. The effluents spread through the openings to the entire cabin area of the MVZ (in Fig. 2 is shown the accommodation deck). We mention that results regarding the number of fatalities are based upon data generated in Task 3.3 (Breuillard et al. 2012) and used in Task 4.1 (Spyrou et al. 2013) of the

Figure 2. The cruise ship accommodation deck showing the cabin (with balcony) of fire origin, the exits and the stairwells.

Table 1. Generic groups of combustible materials in cabin.

Materials	% contribution	Average heat of combustion [MJ/kgr]	Yield CO [g/g]	Yield CO_2 [g/g]	Yield soot [g/g]
Textiles	28.0%	22.5	0.051	1.420	0.065
Wood based	34.0%	17.33	0.004	1.280	0.015
Plastics	38.0%	24.81	0.046	1.832	0.081
Average	100%	21.62	0.0331	1.5290	0.0541

FIREPROOF project. Details of the utilized tools are provided in Pawling et al. (2012).

Cabin's characteristics and the generated HRR curves will be presented in the next section. Briefly, in the "moderate" severity fire scenario the fire is confined only to the balcony, burning some amount from the available fire load. For the "extreme" scenario on the other hand, the fire spreads from the balcony towards the interior of the cabin, consuming the total available fire load (in balcony and in cabin).

We assumed two scenarios of relative wind direction and speed: a) parallel to the ship, with wind's relative velocity 20 knots; b) vertically against the ship side, with velocity 5 knots. The two directions are equally contributing to the risk function. Evacuation routes and access to exits were not hindered. Night and day scenarios were studied, with equal weight. In the day scenarios, the cabins had 50% occupancy, with the other passengers located in public spaces within the zone. In the night scenarios the cabins were fully occupied. The total number of passengers within the zone was 580. The probability of fire ignition and the reliability of the sprinkler suppression system were 1.03×10^{-3} per s-y and 93.7% respectively (Spyrou et al. 2013).

4.2 *Fire specifics*

This passenger cabin was used also in Themelis and Spyrou (2012). Materials' groups, including materials in cabin's balcony, and their characteristics are shown in Table 1. Moreover, in Table 2 and in Table 3 are shown, respectively, the values of the fixed and random parameters participating in the fire scenarios. 100 HRR curves have been generated (see Fig. 3). In Figure 4 are shown the fire load and growth rate values of each generated scenario, in dimensionless form using the maximum fire load (1816 MJ) and growth rate (0.01674 kW/s2) respectively.

The empty triangles corresponds to the scenarios where fire has been spread to the cabin and therefore the total fire load available was involved, while the black squares correspond to scenarios where a limited amount of fire load was ignited. The "severity" function is calculated for each scenario. The corresponding median and

Table 2. Fixed parameters of fire scenarios.

Parameter	Value
Fuel load density [kg/m^2]	6.54
Fire load density [MJ/m^2]	141
Total fire load Q [MJ]	1816

Table 3. Random parameters of fire scenarios.

Parameter	Value
$\dot{Q}_{inc}$ [kW]	20–30
$\dot{q}''_e$ [kW/s^2]	25–45
α [kW/s^2] (slow to medium rates)	0.003488–0.01688
b (%)	40–80
k (%)	15–35

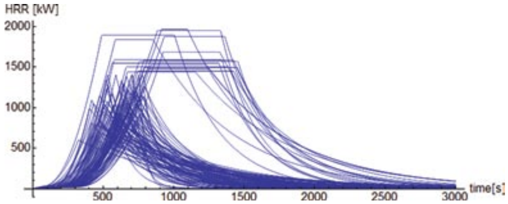

Figure 3. The generated HRR set.

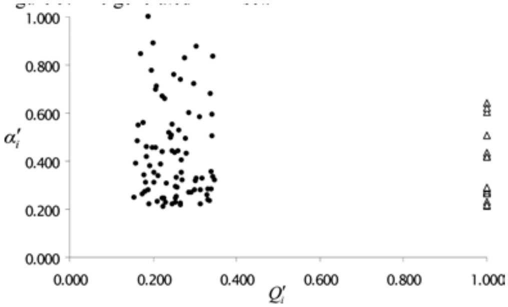

Figure 4. Fire load and growth rate for the examined scenarios, in dimensionless form.

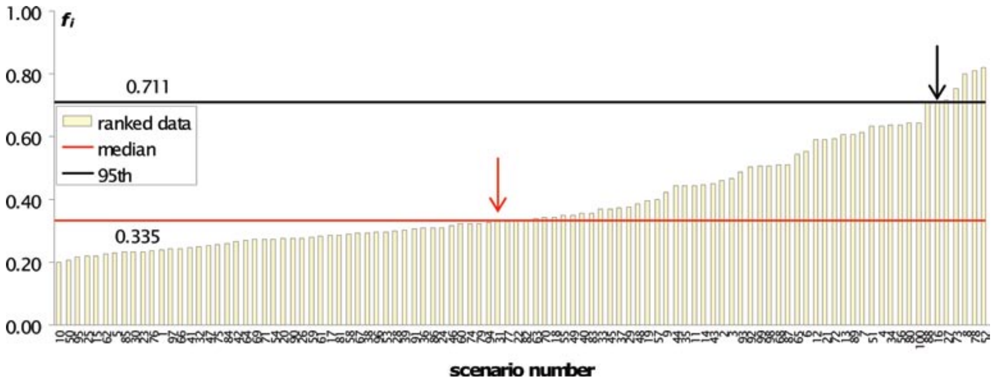

Figure 5. Ranking of fire scenario severity in ascending order, indicating also the median and the 95th percentile values.

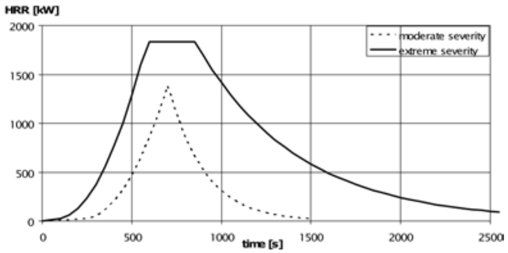

Figure 6. The selected moderate and extreme fires.

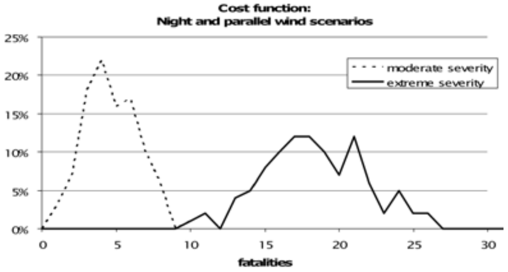

Figure 7. Fatalities for two night scenarios of balcony fire. Wind assumed parallel to ship side.

Table 4. Mean and range of fatalities for night and extreme severity scenarios.

Wind direction	Mean fatalities	Range of fatalities
Transverse	32.96	24–44
Parallel	18.36	10–26

95th percentile values are, respectively, 0.335 and 0.711. In Figure 5 are shown the achieved scores of severity and the scenarios that are closest to the median (scenario 82) and the 95th (scenario 16). In Figure 6 are shown the HRR curves of these two characteristic scenarios that form the basis of the evacuation simulations.

4.3 *Results*

Several evacuation simulations per fire scenario and severity level were carried out. In Figure 7 is shown the calculated fatality cost, in the form of probability mass function. As expected, day scenarios produced far fewer fatalities. Characteristically, for the extreme fire severity scenarios, zero fatalities occur in the 91% and 95% of the evacuation simulations, for the transverse and parallel wind direction respectively. Actually, the maximum number of fatalities was one. This is attributed to the fact that, in the day evacuation scenarios, the egress process begins immediately with the fire alarm (according to the MSC.1238 time line sequence).

On the other hand, for the extreme severity scenarios referring to night conditions, significant wind in direction transversely to the ship appears to result in more fatalities than wind acting parallel to the ship side. The mean and the range of the fatality values obtained are presented in Table 4. The probability of zero fatality was also calculated on the basis of the various considered scenarios. This was obtained by dividing the number of evacuation simulations producing no fatality, to the total number of performed simulations.

In Table 5 is shown, per fire severity, the probability of zero fatality, as well as the calculated risk index. The corresponding *F-N* curves appear in Figure 8. Whilst night and day scenarios participate with equal weights in the risk formulation, night scenarios are much more costly in terms of consequences.

Table 5. Probability of zero fatality and value of risk index.

Severity	Probability of zero fatalities	Risk index (fatalities/(s-y)
Moderate	75%	7.59×10^{-5}
Extreme	46.46%	8.32×10^{-4}

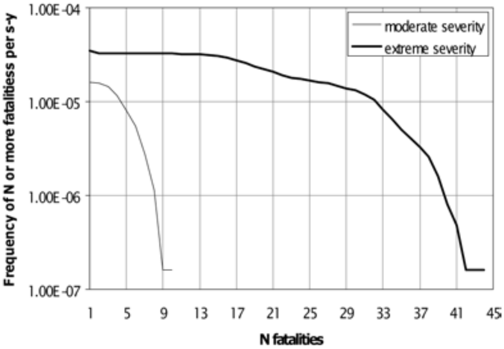

Figure 8. F-N curves per fire severity scenario.

5 CONCLUDING REMARKS

A novel methodology for assessing a design's performance against fire incidents has been described. The formulation is based on two lines of ship defense against fire incidents. Given absolute reliability in the installed fire safety systems, no fatalities should be produced from any ignition event onboard. Such a principle implies a zero tolerance philosophy. On the other hand, should some systems fail at the critical time, a second line of defense should be present by design, minimizing the human loss.

By using the presented methodology for the quantification of ship safety against fire incidents, a rational basis is supplied for developing risk—based fire safety criteria. The safety level achieved by a candidate ship design should be compared against the required safety level. For the definition of the latter, the options are as follows:

- A prescriptive threshold value could be selected by IMO, reflecting an acceptable risk level obtained by considering risks within the transportation sector.
- Alternatively, the required value can be based on the analysis of a number of existing SOLAS ships. Specifically, the examined ships will be subjected to the presented methodology in order to quantify their achieved level of safety.

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