Towards Building an Attained Index of Passenger Ship Fire Safety

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Abstract. Protection against fire is one of the pillars of maritime safety. In particular for passenger ships, experience has shown that a fire onboard can incur catastrophic consequences. Although the maritime fire safety legislation requires compliance with prescriptive regulations of fire prevention, protection and extinction, the concept of "safety equivalence" has enabled substantial innovations in the design of some passenger ships. The assessment framework could be strengthened by introducing a probabilistic formulation. The present study is an attempt for a step forward, aiming to develop the elements and the structure of a probabilistic attained fire safety index. The probability of fire ignition, the reliability of the installed suppression systems and the expected loss due to fire growth, are key elements contributing to the novel assessment which is sensitive to design detail, such as the space layout and the interior design materials used. The distribution of fatalities has been selected as the most appropriate "loss" function. As an application, two adjacent fire zones accommodating passenger spaces will be examined. The loss function distribution is derived from a batch of fire and evacuation simulations. The method is extendable to address the entire ship.

Keywords. Passenger ship design, fire safety, risk index, risk function, loss distribution, fire dynamics simulation, evacuation

1. Introduction

Despite the substantial increase in the stringency of ship fire safety regulations since the early nineties, the fire on the passenger ship Norman Atlantic in December 2014 indicated that loopholes still exist, allowing for catastrophic accidents to occur. One problem is, arguably, the deterministic framework of the existing regulations. Currently, fire safety is addressed either through statutory means deriving from established design solutions; or through performance-based approaches for alternative designs and arrangements [1, 2]. Their qualitative differences besides, both approaches rely in essence on a limited number of representative fire scenarios, i.e. they are intrinsically deterministic.

In the field of ship design, a modern trend is to develop quantitative expressions of the safety level of a vessel, with regard to individual hazards, using probabilistic

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methods. As risk is the most accepted notion for quantifying safety, such methodologies employ (directly or indirectly) risk indices. IMO' Resolution A265 (VIII) had introduced, as early as 1973, an alternative (to the standing deterministic) probabilistic subdivision method for passenger ships. According to it, a calculated attained index *A* reflecting the safety level for all possible flooding scenarios resulting from collisions, should be found greater than a set "standard", represented by the required index *R* [3]. In 2009, IMO adopted a similar method more universally, in order to cover also dry cargo vessels [4]. On the other hand, an oil pollution prevention index, introduced in the mid-nineties, constituted the first regulatory environmental risk index for the shipbuilding industry, estimating statistical values of oil outflow resulting from collisions and groundings and comparing against a similar performance index of a standard "acceptable" design [5]. More recently, new promising fields of implementation of risk-based methodologies have emerged in ship design and most prominent among them is fire safety [6, 7].

In the present paper the objective is to expand further on our earlier efforts for composing a risk framework of ship fire safety that can be used in ship design [6, 7]. The methodology uses probability theory in order to form risk indices addressing the entire ship. Three are the main elements for building such indices: the probability of fire ignition, the reliability of the installed suppression systems; and the expected human loss due to fire growth. Significant is that all fourteen categories of standard SOLAS spaces, classified according to their fire risk, can be addressed; and that, space layout and the interior design materials used, contribute to the assessment. Hence, design choices are well reflected in the calculated risk function and in the stemming from it risk indices. Potential losses are represented via appropriate probability distribution functions deriving from a systematic massive simulation campaign. In this paper we demonstrate the method through simplified examples. Two adjacent fire zones accommodating large public spaces of a cruise vessel will be examined. A theater, a casino, a bar, a restaurant, a galley, a gallery and shop areas are involved in the considered geometries. Such large public spaces of cruise ships have been extensively designed and approved in the past by utilizing the alternative design and arrangement regulatory framework of SOLAS [1, 2]. FDS and PyroSim codes will be used for simulating the fire scenarios, while Pathfinder will be used for simulating the respective evacuation scenarios [8, 9]. In this way, characteristic fire safety indices are presented for the two considered zones of the reference vessel.

The structure of the paper is as follows: in section 2 the risk formulation is presented, including a proposed approach for components' calculation. In section 3, an application of the model is described and some discussion of the obtained results is presented. Finally, conclusions are drawn in section 4.

2. Risk Formulation

An objective manner for determining the safety level in the maritime industry is through the risk assessment process which has been described, in the context of rule-making, by the Formal Safety Assessment (FSA) guidelines [10]. Risk is usually defined as the probability times the consequences of undesirable events and it provides the means for identifying, analyzing and evaluating maritime risks. Although risk analysis has been applied several times in maritime studies, concern is raised about the way the consequences are evaluated since these involve uncertainties that should be taken into consideration in the formulation. Therefore, a correct risk formulation should have providence for uncertainties both in events' occurrence and in the consequences, evaluated through the probability and statistics theory.

2.1. Mathematical Framework

In the proposed formulation three main events, assumed as independent of each other, are supposed to influence the attained risk: fire ignition; onboard systems' failure to suppress the ignition; and the human loss if an ignition develops into a fire. The probability of occurrence of these three events are examined for all possible ignition locations onboard (in horizontal, transverse and vertical extend). Moreover, they are examined for all fourteen SOLAS space categories, specifying the materials' fire properties and the available combustible mass. The mathematical equation that provides a risk function is presented in Eq. (1).

$$F_R = \sum_{i=1}^{\infty} \sum_{j=1}^{n} P_{i,j}^{ign} \times \overline{P}_{i,j}^{sup} \times L_{i,j} \tag{1}$$

$P_{i,j}^{ign}$ is the probability of ignition in ship location *i* and category of SOLAS space *j*; $\overline{P}_{i,j}^{sup}$ is the probability of failure of suppression systems in location *i* and SOLAS space *j*; $L_{i,j}$ is the distribution function of human loss due to a fire originating in location *i* and SOLAS space *j*; and *n* is the number of SOLAS space categories that determine the appropriate fire intensity standards to be applied [4].

Obviously, given the infinity of possible fire locations on a ship, the fire scenarios to be considered are, at first sight, also infinite. To deal with such countless scenarios, a nominal position in the reference area could be specified assuming one fire event (or a few for large spaces) per space. Then, different fires in the same space can be accounted by considering fire intensity as a probabilistic quantity expressed through a distribution. Obtaining a reasonable number of discrete values from this distribution, the calculation of risk can be formulated taking into account *m* fire locations according to the number of separate spaces onboard; and *l* values of fire intensity with their weighting (Eq. 2). For each scenario of fire intensity (represented by *k*), a distribution for human loss is calculated.

$$F_R = \sum_{i=1}^{m} \sum_{j=1}^{n} P_{i,j}^{ign} \times \overline{P}_{i,j}^{sup} \times \sum_{k=1}^{l} L_{i,j,k} \tag{2}$$

The percentiles of the calculated risk function should be used for deriving practical risk indices. The lower the percentile, the higher is the stringency for fire safety. Actually, here one has the option of using a variety of indices, some deriving also directly from the distribution of losses (Eq. 3).

$$F_N = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{l} L_{i,j,k} \qquad (3)$$

2.2. Estimation Process

Historic frequency data can be used in order to estimate the first two probability factors: $P_{i,j}^{ign}$ and $\overline{P}_{i,j}^{sup}$ [11, 12]. Subsequently, the locations of the fire scenarios and the involved categories of SOLAS space are specified. The probability distribution of fire intensity is set and the discrete fire scenarios which will participate in the risk function estimation are extracted. Lastly, simulation evacuation scenarios are conducted, for the selected fire intensity values, in order to derive the distribution function of possible human loss. A detailed description of fire and evacuation scenarios estimation follows.

Fire Scenarios: Representative fire intensity scenarios should be chosen from a set of probabilistically generated Heat Release Rate curves (HRR). A HRR curve is composed by the different levels of Heat Release across the 3 phases of the development of a fuel controlled fire event: incipient, growth and decay. The shape and the size of the curve depend on the total mass of combustible materials available in the space, which in turn determines the amount of fire load consumed, the growth coefficient that affects exposure duration to fire hazards, the materials' heat of combustion, the effluents' yields, the materials' thermal response parameter and the materials' critical heat flux affecting the fire incipient phase [7, 13 and 14]. Based on the complexity of these curves, parameters can be separated into those for which fixed values can be assumed; and those whose values are taken to vary randomly within a range. On this basis, HRR curves can be generated, which are then distributed and classified depending on the intensity of fire growth. In this way, the distribution function for the fire intensity is exported.

Evacuation Scenarios: Several evacuation scenarios should be run for each selected fire intensity scenario so as to calculate the fire products concentration (heat, smoke, toxicity) affecting human health. The simulation results should be compared to IMO' life safety performance criteria for maximum temperature, minimum fractional effective dose and minimum visibility [2]. On this basis, the distribution function for the human losses can be constructed.

3. Application

3.1. Scenario Description

The main designed geometry is a two fire zone model based on a cruise vessel. The actual length is 95m, height 6.4m and width of 33.2m, consisted of two decks containing public areas. For simplification reasons we excluded some connection spaces and the considered geometry has a length of 67.9m.

On the left side and lower deck there is a casino, a bar-restaurant area, a galley and a small shop. In the upper deck (left side) there is a restaurant, an internal gallery room, a galley, a corridor and two external decks open in the outer ambient. On the right side there is a theater whose height covers both deck levels. The theater is connected through an internal corridor and stairs with the other two decks. The considered occupants' capacity is 190 visitors and 40 passing passengers for the lower deck, 170 visitors and 30 passing passengers for the upper deck and 400 spectators and 20 actors for the theater.

The general arrangement of the considered accommodations is illustrated in Figure 1. To demonstrate the method, a limited number of fire scenarios is considered. As shown, fire breaks out on the restaurant area of the lower and upper decks, and on the stage of the theater area.

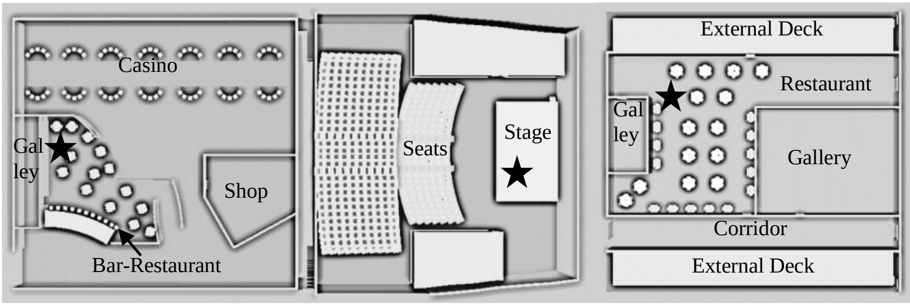

Figure 1. General arrangement of cruise vessel accommodations. Left: lower deck, Middle: theater area and Right: upper deck. (★Location of fire ignition)

3.2. Parameters' Specification

In the present study, the examined areas are three and belong to public accommodation spaces. Public spaces containing furniture and furnishings of other than restricted fire risk and having a deck area of $50m^2$ or more belong to the category 8 of SOLAS space, namely the accommodation spaces of greater fire risk. Taking into consideration two fire intensity events, the risk function is formed as presented in Eq. (4).

$$F_R = \sum_{i=1}^{3} P_{i,8}^{ign} \times \overline{P}_{i,8}^{sup} \times \sum_{k=1}^{2} L_{i,8,k} \tag{4}$$

3.2.1. Fire Scenarios

100 fire scenarios, in terms of HRR curves, have been produced for each area. A specific burning area, which is equal to $18m^2$ for the lower deck, $12m^2$ for the upper deck and $24m^2$ for the theater has been considered, along with the average of combustible materials [15, 16]. Both the contribution of each group material to combustion, and the material properties are given in Table 1.

The combustible materials, the fuel load density and the total fire load parameters are assumed to have fixed values. In more detail, the knowledge of the material quantities and their properties contribute to determining both the fuel load density and the total fire load values. In the past, the assumption was made that these two parameters follow the gamma distribution [7, 17]. In the example, their fixed values have been obtained from the 95th percentile of the respective distribution. As far as the random parameters are concerned, these are: the value of HRR at the end of the incipient stage; the ignition source heat flux; the growth coefficient (considering fires with medium to fast growth); the percentage of fuel load consumed before decay starts; and the percentage of total fire load. The specific values (or ranges) that were used for the fixed (or respectively random) parameters in the simulated fire scenarios are given in Tables 2 and 3. With these, all required information for producing the probability distribution function for fire intensity, in terms of growth, is available.

In Figure 2, HRR curves for the lower deck are illustrated, along with the fire intensity function that follows the Log-Normal distribution [18].

Table 1. Combustible material properties.

Area	Material	Contribution	Heat of Combustion (MJ/kg)	Yield CO (g/g)	Yield CO_2 (g/g)	Yield Soot (g/g)
Theater	Natural	25%	13.88	0.012	1.378	0.015
[15]	Synthetic	75%	22.38	0.049	1.672	0.097
	Average		**17.88**	**0.0305**	**1.525**	**0.056**
Restaurant	Textiles	3.8%	22.5	0.051	1.42	0.065
[16]	Plastics	5.2%	24.81	0.046	1.832	0.081
	Wood/Paper	84%	17.33	0.004	1.28	0.015
	Misc.	7%	31.7	0.036	1.829	0.013
	Average		**23.655**	**0.03425**	**1.59**	**0.0435**

Table 2. Fixed parameters for fire scenarios.

Fixed Parameter	Gamma Distributed	95th percentile values
Fuel load density [kg/m^2]	3.37, 3.44	23.55
Total fire load: Lower deck [MJ]	3.371, 746.462	5110.59
Total fire load: Upper deck [MJ]	3.369, 497.767	3407.1
Total fire load: Theater [MJ]	3.373, 1058.37	7246.91

Table 3. Random parameters for fire scenarios.

Random Parameter	Values [Min-Max]	Distribution
HRR at the end of incipient stage [kW]	20-30	Uniform
Ignition source heat flux [kW/s^2]	30-40	Uniform
Medium to fast growth coefficient [kW/s^2]	0.0177-0.0466	Log-Normal
Percentage of fuel load consumed for decay to start [%]	45-60	Uniform
Percentage of total fire load [%]	15-35	Uniform

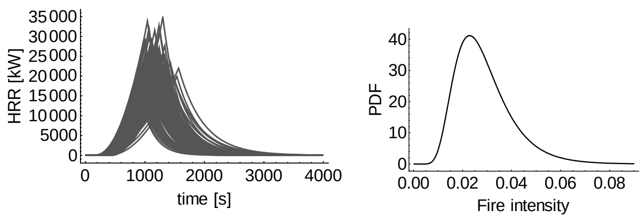

Figure 2. The 100 generated HRR curves (left) and the fire intensity probability density function (right) for the lower deck fire scenarios.

3.2.2. Probability of Ignition

The probability of fire ignition is considered based on a previous developed method and depends both on the historical frequency of ignition per ship-year, based on the SOLAS space category, and the floor area [11]. The calculations are shown in Table 4.

Table 4. Calculation of probability of ignition.

Probability factor	Area	Area A_i	Historical frequency γ_i	Probability of ignition $A_i \times \gamma_i$
$P_{1,8}^{ign}$	Lower deck	1158.68	1.007 E-05	1.167 E-2
$P_{2,8}^{ign}$	Upper deck	816.66	1.007 E-05	8.224 E-3
$P_{3,8}^{ign}$	Theater	1019.48	1.007 E-05	1.027 E-2

3.2.3. Probability of Failure of Suppression Systems

As far as the probability of failure of suppression systems is concerned, it is derived from the probability of proper sprinkler operation, which is equal to the mean of the reliability function that is based on the exponential distribution and is given by Eq. (5).

$$\overline{P}^{sup} = 1 - P^{sup} = 1 - \frac{1}{t_{max}} \int_0^{t_{max}} e^{-\lambda t} dt \tag{5}$$

Where, t is the time in days, t_{max} is the maximum time duration between maintenances, and λ is the failure rate per days. Assuming a yearly reference period and a failure rate of a sprinkler system, $3.6\ 10^{-4}$ per days [12], the probability of failure is 6.3%.

3.2.4. Loss Distribution

In order to define the loss distribution, and since only the demonstration of the method is intended here, a small number of fire intensity scenarios have been selected from the respective distribution: the 5th and 95th percentile values corresponding to medium and fast fire growth (it is recalled that a distribution covering the medium to fast growth range has been used. Slow growth gives ample time for response and usually it does not produce consequences). PyroSim software has been chosen to construct the arrangement and simulate the fire scenarios [8]. PyroSim is, actually, a graphical user interface for the Fire Dynamics Simulator (FDS) which simulates fire scenarios using computational fluid dynamics (CFD) optimized for low-speed, thermally-driven flows. The software solves numerically a large eddy simulation (LES) form of the Navier-Stokes equations, with an emphasis on smoke and heat transport from fires. Thereafter, 50 evacuation scenarios, at 80 percent occupancy, are conducted, using the Pathfinder program [9]. Pathfinder is also a graphical user interface that is used to create and run evacuation simulation models, able to take into consideration fire simulation effluents (i.e. temperature, fractional effective dose and visibility).

The random parameters of evacuation scenarios are: the distribution in space, the speed and the response time of occupants. IMO' recommended values for occupant gender and speed are used as an input for each scenario [19]. Especially for the occupant response time, the Log-Normal distribution functions illustrated in Figure 3, are advocated. In more detail, the response time distribution for the lower and upper deck is based on data generated from a cruise vessel evacuation study for public spaces onboard [20], while the response time distribution for the theater is derived from data recorded for a theater area [21].

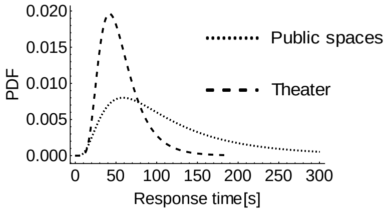

Figure 3. Probability Density Function for the occupant response time.

Results from all fifty evacuation simulations provide the loss distribution function for each fire scenario. Assuming that fire scenarios equally affect the losses in a specific area, the loss distribution in location *i* derives from the mixture of loss distributions of each fire scenario given an assigned weight which, here was taken 0.5. The human loss distribution is basically a complementary cumulative distribution function (CCDF) [22]. The CCDF is set on a logarithmic scale and shows the frequency of at least *N* human losses, which is actually a FN curve. In Figure 4, both the probability density function and the FN curve for human loss are presented, in the case of the fast growth scenario considered, for all areas participating in the current assessment.

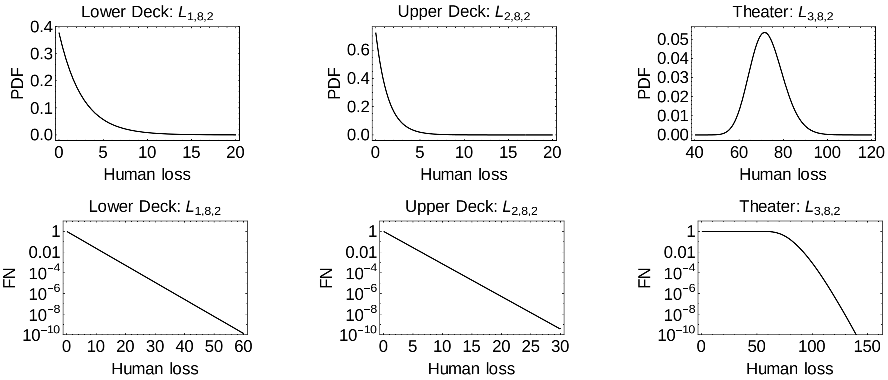

Figure 4. The Probability Density Function (up) and the FN curve (down) for all areas.

3.3. Indices Estimation

The estimated risk function and FN curve for the entire considered geometry, are presented in Figure 5. The FN curve constitutes the probability of at least *N* human losses given the occurrence of a fire event on board and the failure of the suppression systems. From such a curve, various attained indices can be deduced. We have selected as such: a) the probability of zero fatalities; b) the median value of the fatalities, and c) the extreme fatalities. Specifically, the extreme fatalities calculation is based on the median value above the 90th percentile. Corresponding indices could be calculated also for the risk function, which incorporates the probabilities of ignition and suppression.

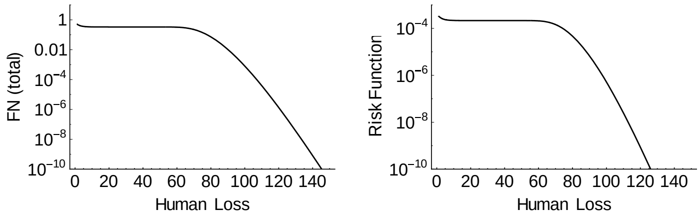

Figure 5. The FN curve (left) and the Risk function (right) for the considered geometry.

In Table 5, the values of the proposed indices are presented. As shown, the number of extreme fatalities in the considered restaurant fires (lower and upper deck) is quite low, in contrast to the theater fires. Indeed, in the area of the theater, the smoke is concentrated in the upper level where the two of three exit doors are placed, hence there is increased number of fatalities for all scenarios examined. This is also inferred from analysis of the risk function, demonstrated in Table 6.

Table 5. Indices given the fire occurrence.

Area	Probability of zero fatalities	Median fatalities	Extreme fatalities
Lower deck	0.658	0	4
Upper deck	0.758	0	3
Theater	0.000	73	88
Entire	**0.472**	**2**	**82**

Table 6. Indices based on risk function.

Area	Risk of more than 1 fatality	Risk of 1 to 10 fatalities	Risk of 10 to 100 fatalities	Risk of more than100 fatalities
Lower deck	2.513 E-4	2.430 E-4	8.313 E-6	1.301 E-20
Upper deck	1.253 E-4	1.252 E-4	1.844 E-7	8.754 E-36
Theater	6.461 E-4	0.000 E 0	6.446 E-4	1.556 E-6
Entire	**3.409 E-4**	**1.227 E-4**	**2.177 E-4**	**5.186 E-7**

4. Conclusions

In the current paper we reported ongoing work intended to construct innovative attained risk indices of fire safety that could be used in ship design. These indices take into consideration all possible locations of a fire ignition onboard and all existing categories of SOLAS space. The described method is performance-based and several fire development and evacuation simulations have provided the data for calculating a risk function, from which attained fire safety indices can be deduced. Such indices can be very useful for comparing alternative design solutions.

The new methodology for fire safety has been evaluated through an application to public spaces found onboard a cruise vessel, showing that it can produce meaningful results. A step forward would be to apply and evaluate the proposed mathematical framework to the entire vessel.

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