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Article

Fire Risk Model for Fires in Ro-Ro Ship Ro-Ro Spaces

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Abstract: In recent years, fire accidents on Ro-Ro ships have led to numerous fatalities and significant economic losses. The response of the crew and the ship's protection systems are crucial in managing these incidents and mitigating their consequences. To assess fire safety improvements, this study has focused on developing and quantifying a risk model that captures the dynamics of a fire starting in a Ro-Ro space. Various risk modelling techniques were reviewed to construct the model, which was then quantified using historical data, simulations, and expert judgments. A Delphi-based, fully digital approach to expert elicitation was introduced, utilizing Microsoft Teams and Microsoft Excel-based questionnaires. This method ensured full anonymity for the experts, reducing the risk of group bias and eliminating the need for travel. To enhance understanding and verify the results, uncertainty and sensitivity analyses were performed. They revealed that the potential loss of life deviated, with 90% confidence, from the calculated mean value by less than 26%. Overall, the questionnaire-based method proved effective for expert elicitation and for quantifying nodes in the risk model, demonstrating its utility in the risk assessment process.

Keywords: Fire Risk Model; Ro-Ro Ships; Quantification; Expert Judgement; Questionnaire

1. Introduction

Ro-Ro (roll-on/roll-off) ships transport vehicles and passengers across the seas, loading and unloading cargo such as personal cars, lorries/trucks, recreational vehicles, trains, forest vehicles, and other wheeled cargo. Ro-Ro ships are categorized into three types: Ro-Ro passenger (Ro-Pax) ships, general Ro-Ro cargo ships, and vehicle carriers. Ro-Pax ships carry more than twelve passengers, while Ro-Ro cargo ships do not. Vehicle carriers are a specific type of Ro-Ro cargo ship designed to transport unoccupied and unloaded motor vehicles. Onboard Ro-Ro ships, cargo is stored in large areas known as Ro-Ro spaces, which usually extend either to a substantial length or the entire length of the ship without any subdivisions [1]. In the event of a fire in a Ro-Ro space, the crew and the ship's protection systems are crucial in managing the situation and mitigating the consequences. Although external assistance may be available, it cannot be relied upon, and Ro-Ro ships must be capable of handling fires independently. If a fire cannot be controlled, evacuation becomes necessary, which is risky, particularly in harsh weather conditions. According to Vanem and Skjong, 7% of all fires on Ro-Pax ships result in unsuccessful evacuations, leading to the loss of one or more lives [2].

Several fire incidents on Ro-Ro ships have had severe consequences. For instance, the Felicity Ace fire in 2022 resulted in the total loss of almost 4 000 cars and the ship itself, with estimated losses exceeding 500 MUSD [3]. The Euro Ferry Olympia fire in 2022 led to the disappearance of eleven passengers, the loss of 153 vehicles, and the ship, while 292 people were evacuated [4]. The Norman Atlantic fire in 2014 resulted in 23 lives lost or missing [5]. The most tragic incident was the Al Salam Boccaccio 98 fire in 2006, where 1,031 people lost their lives [6].

Due to the potentially severe consequences and high frequency of fires in Ro-Ro spaces [7, 8], the fire risk onboard Ro-Ro ships demand heightened attention from a risk management perspective. Two previous formal safety assessment studies, FIRESAFE [9] and FIRESAFE II [10], addressed the risk of Ro-Ro space fires on Ro-Pax ships to evaluate the cost-effectiveness of measures aimed at reducing the incidence and consequences of these fires. One outcome of these studies was a risk model designed to quantify the risk of a fire in a Ro-Ro space. Such a risk model must be capable of capturing fire protection actions and the dynamics of a fire. Initially, a Ro-Ro space fire is relatively small, with good visibility. However, over time, if fuel and oxygen remain available, the fire will grow and become increasingly difficult to control. In the FIRESAFE studies, the risk model was structured using an event tree, complemented by numerous fault trees to calculate the probabilities of different branches of the event tree. This is a standard risk model structure used in maritime formal safety assessment studies [11]. While event trees can consider multiple scenarios, they are binary models, which limits their ability to fully capture the dynamic properties of a fire. To address this limitation, the concepts of ‘early’ and ‘late’ detection, as well as ‘early’ and ‘late’ decision, were introduced, allowing the model to better capture the dynamics of a fire event.

The primary objective of the current study was to establish a risk model that could assess the effectiveness of risk-reducing actions and installations. To achieve this, various risk modelling techniques were reviewed and assessed. Examples of these models, in addition to the FIRESAFE studies' risk model, include Petri nets [12-14], Bayesian networks [15-17], and time-dependent event trees [18]. While these models allow for risk estimation at any point during a fire event, they can be complex, may require specialized software, and can be challenging to quantify. Once the risk model was selected, the work proceeded with quantification. When adequate historical data and statistics were available, these were the preferred sources. However, for several reasons, statistical data may not always be available, necessitating alternative means for quantifying the nodes in the risk model. These alternatives include calculations, data from literature, and expert judgments. According to Skjong and Wentworth, an expert is someone with a background in the subject area and recognized by others as qualified in that field [19]. In expert elicitation, the choice between a single expert or a group of experts must be made. A group of experts can provide more accurate responses but may suffer from group bias [19, 20]. Ioannou et al. suggest a minimum of four experts [21], while Mannan recommends at least five [20]. The optimum number, according to Ioannou et al., is eight, whereas Mannan suggests nine, balancing the need for diversity and manageability. The numbers correspond approximately to the minimum needed to obtain diversity and to the maximum that can be readily handled, respectively [20]. During the present study, quantification took place during the peak of the Covid-19 pandemic, which required digital tools and a new way of thinking about managing the expert group.

2. Materials and Methods

The following sections describe the process of selecting a risk modelling technique, establishing a risk model structure, and the quantification process. Additionally, the methods used to validate the risk model are outlined. A graphical summary of the work is illustrated in Figure 1.

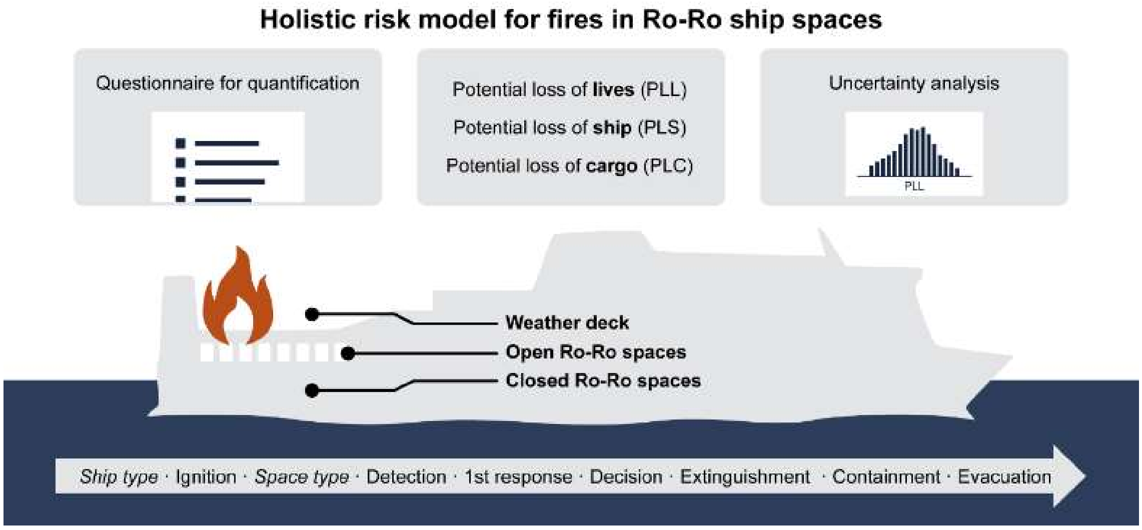

Figure 1. Graphical illustration of the conducted work.

The overall fire risk assessment followed a process outlined by Mannan [20]. In the current work, emphasis was placed on defining the study scope, understanding, and describing the process (referred to as the chain of events) and the surrounding environment, as well as estimating failure frequencies and probabilities. A schematic overview of the process from start to achievement of a final risk model structure is presented in Figure 2 Initially, two activities were carried out in parallel; literature was reviewed to identify suitable fire risk models and methods of quantification, and a hazard identification (HazId) workshop was held to identify fire hazards and to gain an understanding of the development of a fire onboard a Ro-Ro ship.

The three different Ro-Ro ship types (Ro-Pax, general Ro-Ro cargo, and vehicle carriers) were covered by the current study. One risk model was created and quantified for each ship type. General Ro-Ro cargo and Ro-Pax ships have three Ro-Ro space types: closed Ro-Ro space (CRS), open Ro-Ro space (ORS) and weather deck (WD). Vehicle carriers were assumed to have only closed Ro-Ro spaces. A weather deck is a space which is completely exposed to the weather from above and from at least two sides [1]. An open Ro-Ro space is a space open in at least one end and provided with adequate natural ventilation through permanent openings along the sides. It can also be a space that is open at both ends [1]. A closed Ro-Ro space is per definition any ro-ro space which is not an open ro-ro space or a weather deck, typically a space with no or very limited openings.

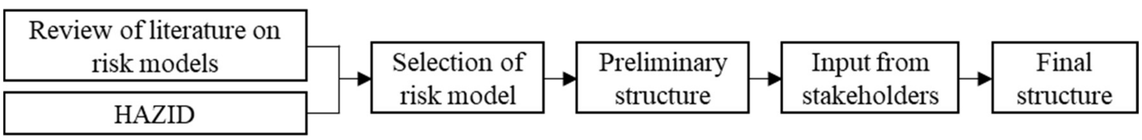

Figure 2. Schematic summary of work towards a risk model structure.

The materials and methods part of the paper is quite lacking in the experimental report we usually write. This part accounts for a large proportion in the paper, especially the analytical and experimental research papers, which can be introduced clearly only after accounting for about 30% of the full text. The material mainly introduces experimental objects and data, and the method refers to the experimental design or data collection method.

An important reason why the materials and methods of the paper need to be introduced in detail is to ensure the repeatability of the experiment, which is convenient for peers and readers to detect and quote your experimental results, which is also an important argument to ensure the reliability of your data. The material part of the paper should introduce the selection method of the experimental object and the source and characteristics of the experimental object, which can not only estimate the sampling error, but also let the readers understand the content of the article and the scope of use of the conclusion. In addition, we should clearly introduce the sample number and grouping method of the research object, and do not use a sentence of random grouping to describe it. In the method, the experimental design scheme should be introduced clearly, such as "randomized controlled trial", "nonrandomized controlled trial", "cross controlled trial", "pre post controlled trial", "double-blind" and other methods, and then the setting or laboratory facilities should be introduced clearly. According to the type of article, the intervention measures, blind methods, measurement indicators and criteria for judging the results should also be introduced.

The materials and methods in the paper must be realistic and explained one by one, to prove the accuracy of the data in your article and the reliability of the experiment.

2.1. Generic Ships

To better understand the situation onboard (design, evacuation routes, location of life saving appliances, etc.), three generic ships were selected. The selection was made by three ship owners, one generic ship was selected for each of the ship types. The ship owners were all partners in the LASH FIRE project and the generic ships were selected from their fleets. The ships were selected based on the ship owners' experience and to be a fair representation of the world fleet. A summary of some of the ships' properties is given in Table 1. The lane meters presented in the table were used to in the first branch of the event tree (addressing the different deck types, cf. Section 2.2.2) while the total numbers of people onboard (passengers and crew members) were used to estimate consequences in terms potential loss of life (PLL). The generic ships were also used to calculate other input needed to the risk model e.g., the probability of flames or smoke exiting through openings and affecting lifesaving appliances.

Table 1. Data for the three generic ship types.

Parameter	Ro-Ro cargo	Ro-Pax	VC
Maximum number of passengers [person]	12	852	0
Average passenger fill rate [%]	100	62.5	N/A
Number of crew members [person]	14	28	24
Lane meters [m]	3 3830	2 255	6 400
Share of lane meters in closed spaces [%]	45	65	100
Share of lane meters in open spaces [%]	30	23	0
Share of lane meters on weather deck [%]	25	11	0

2.2. The Fire Risk Model

2.2.1. Review of Fire Risk Models

As outlined in the introduction, a fire is a dynamic event, i.e., the risk of a fire and the potential of successful fire mitigation changes over time. Early detection and early first response are examples of factors significantly improving the probability of successful extinguishment of a fire. Other factors that affect the fire risk are the type of fire source, ventilation conditions, available fire protection, actions taken by the crew and passengers, as well as the surroundings, e.g., geometry and materials.

The review of risk models was made with the desire to capture the dynamics of a fire while still being possible to quantify with data from literature, statistics, simulations or expert estimates. In the two FIRESAFE project studies [7, 9], event trees were used to quantify the risk of a ro-ro space fire. To capture fire dynamics, branches for 'early and late detection' as well as 'early and late decision' were incorporated into the event tree. While early detection should be understood as a situation allowing first response to potentially be carried out successfully and safely, early decision refers to whether the decision to activate the fixed fire-extinguishing system has been taken early enough to have a chance to extinguish the fire, not only to suppress it. Petri nets (PNs) were identified as a modelling technique promising to capture time-dependent, i.e., dynamic risks; it has been demonstrated in multiple studies. Kamil et al. for example used PNs to predict the risk of a domino tank fire scenario [12] and Lee and Lu applied the PN technique on the airlock system of a Canada Deuterium Uranium reactor [13]. The main identified drawbacks were that PNs are still relatively unknown for many, especially outside of the risk engineering environment (this may cause reduced acceptance of the result) and potential challenges in the quantification of the nodes. Further, PNs require dedicated software. The time-dependent event tree has been suggested and demonstrated by Korhonen et al. [18] to be an alternative to the more static event tree. They demonstrated the technique's strength in a case study with a property-loss risk analysis for a fire in a one-storey industrial hall. Overall, the time-dependent event tree was found to be better handle fire dynamics but suffered from the same drawbacks as the PNs. Bayesian networks have been proposed to quantify dynamic risks. For example, Xu et al. studied underground gas storage facilities [17], and Konovessis et al. proposed the use of Bayesian networks for a risk-based ship design [16]. Challenges with Bayesian networks are e.g., hidden/unknown dependencies, the need of a dedicated software, the quantification (especially in the case of dynamic Bayesian networks) [22].

Among the reviewed risk models, the model consisting of a combination of event trees and fault trees was selected. This model was found to be anchored in the maritime industry [9, 10], which was considered important to gain a wide acceptability of the result. Furthermore, the breakdown into early and late detection and early and late decision was considered to provide enough dynamic properties of the model. To avoid an unnecessary complex model, the simplest model still able to fit the need of the project was selected, following criteria were considered in the selection.

- *Requirements:* The risk model must be able to address fires in Ro-Ro spaces, match the project needs, be possible to quantify without an unreasonable amount of work, and produce a result that can be backtracked and accepted by stakeholders and be within available resources.
- *Established method:* Risk modelling techniques, which previously have been used in the same, or potentially a similar, field, were awarded.
- *Fire dynamics:* The risk model should be able to capture the dynamics of a fire.

2.2.2. Description of the Risk Model

The risk model used in the current study was a combination of a risk contribution tree, an event tree and fault trees. The structures of the risk models for the three ship types are available in the supplementary material (S1-S3). The structures are also fully outlined in previously reported work (cf. reference [23] and [24] by Lewandowski, De Carvalho and Cassez). An illustration of the risk model is shown in Figure 3. A risk contribution tree was used to quantify causes of ignition in the left part of the bow tie. The frequency of ignition (FIRE) was established by analysis of available statistics [8]. Following ignition, possible events were detailed by an event tree. The probability of each event was estimated by fault trees. Statistics, calculations and expert judgements were used to quantify the probability of failure of the basic events (or bottom nodes) in the fault trees.

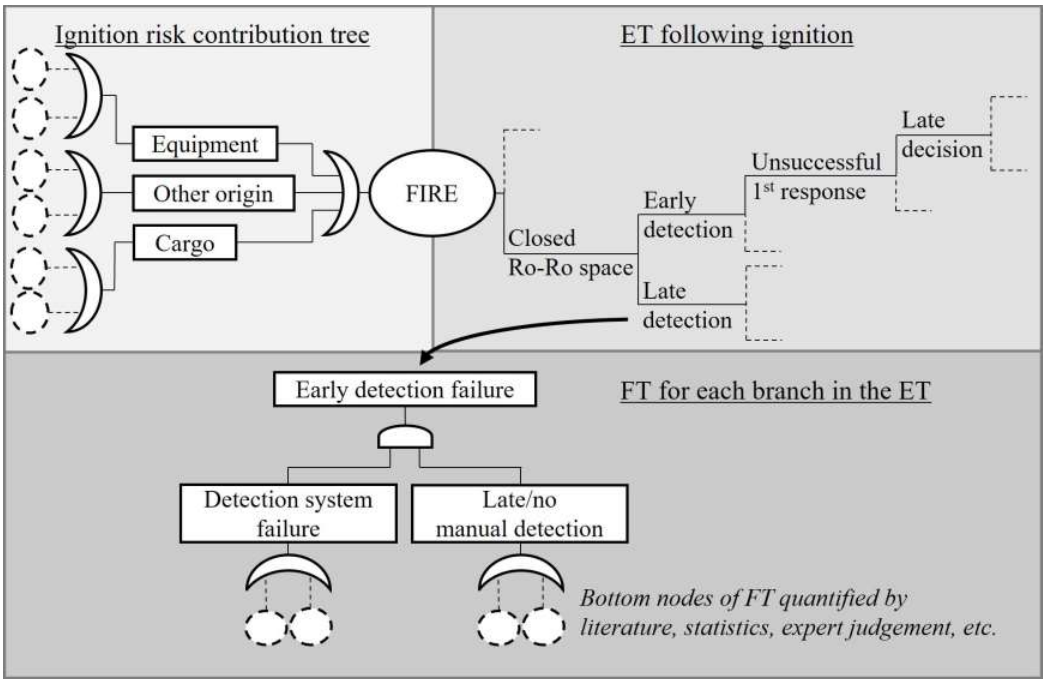

Figure 3. Top half: The risk model is a combination of a risk contribution tree and an event tree (sometimes referred to as a bow tie). Bottom half: The probabilities of the event tree branches were quantified by additional fault trees.

All the branches in the event tree ended up in different scenarios/consequences ranging from minor damages to total loss of the cargo and/or the ship as well as from injuries to multiple fatalities. For each of the three ship types (Ro-Pax, general Ro-Ro cargo and vehicle carrier), individual risk models were established. The risk models were similar in structure, although not identical (cf. supplementary material S1–S3). To quantify the consequences, six distinct scenarios were employed consistently across all analyses. These scenarios, labeled A through F in Table 2, are indicated at the terminal branches of the event trees (see supplementary material S1–S3). Detailed methodologies for consequence quantification are provided in the report by Lewandowski et al. [23]. For instance, fatalities associated with unsuccessful evacuation on Ro-Pax ships were estimated at 5% of the total number of people onboard. This estimation was derived from a review of prior studies and statistical data [2, 9, 23, 25, 26]. Previous research suggested a fatality rate of 5–8%, while a review of available statistics indicated a rate of 5.5%. To account for injuries and potential indirect fatalities (e.g., due to heart conditions), a baseline of one fatality was assumed even in cases of successful evacuation.

Table 2. Consequences for the terminal branches in the event tree.

ID	Scenario	Fatalities	Cargo loss	Ship loss
A	Small fire: The fire is extinguished by a portable extinguisher	Ro-Pax: 0 Ro-Ro cargo: 0 VC: 0	Damage to one vehicle, corresponding to 50% of its value, no damage to transported goods	No damage to the ship but sanitation needed, the ship can remain in service
B	Small fire: The fire is extinguished by firefighting	Ro-Pax: 0 Ro-Ro cargo: 0 VC: 0.05	Total loss of one vehicle, including damage on transported goods	Minor damage to the ceiling, the ship can remain in service, 0.5% loss of the ship's value
C	Medium fire: The fire is suppressed and contained	Ro-Pax: 0 Ro-Ro cargo: 0 VC: 0.05	*Drencher system:* Total loss of one vehicle (and transported goods) + 50% loss of four vehicles *CO_2-system:* Total loss of 13 vehicles (and goods) + 50% loss of 12 vehicles	Non-severe damage to the ceiling, structure and equipment, the ship is off service for several days, 5% loss of the ship's value
D	Fire on one deck: The fire is not suppressed, but contained	Ro-Pax: 0 Ro-Ro cargo: 0 VC: 0.05	Total loss of one vehicle, including damage on transported goods	Severe damage to the entire deck, the ship is off service for several weeks, 80% loss of the ship's value
E	Total loss: The fire is not contained, evacuation is successful	Ro-Pax: 1 Ro-Ro cargo: 0.01 VC: 0.05	Total loss of the cargo, assuming 70% of the total cargo capacity being used	Total loss of the ship, 100% loss of the ship's value
F	Total loss: The fire is not contained, evacuation is unsuccessful	Ro-Pax: 5% of POB Ro-Ro cargo: 0.35 VC: 0.35	Total loss of the cargo, assuming 70% of the total cargo capacity being used	Total loss of the ship, 100% loss of the ship's value

The chain of events laying the ground for the design of the event tree was based on the risk model developed in FIRESAFE II [10] and constituted the following tiers:

1. *FIRE:* Ignition/start of the fire.
2. *Space type:* The fire development, detection, and firefighting possibilities depend on the type of Ro-Ro space (ORS, CRS or WD). Fire in a certain space was in the current study considered as a separate event.
3. *Detection:* The detection can either be 'early' or 'late'. Early detection refers to enough time to succeed with first response, e.g., with a handheld fire extinguisher before the conditions become untenable in the direct vicinity of the fire.
4. *First response:* Firefighting with a handheld extinguisher. Can be successful or unsuccessful.
5. Decision: The terms 'early' and 'late' are used to describe if the decision to activate a fixed extinguishing system is early enough to extinguish the fire or if only fire suppression is possible.
6. *Extinguishment:* Only possible following an early decision. Following a late decision, only suppression of the fire was assumed to be possible.
7. *Containment:* Fire and smoke spread can be avoided, allowing safe stay on board.
8. *Evacuation:* In case of failure of extinguishment and failure of containment, evacuation of the ship is necessary.

As in FIRESAFE II [10], the terms 'early detection' and 'late detection' as well as 'early decision' and 'late decision' were included in the model. This was done to capture dynamics of a fire, i.e., the earlier detection and decision, the greater the likelihood of a successful response.

2.3. Quantification of the Fire Risk

To quantify the risk of a fire in a Ro-Ro space, statistics and data from previous studies were used as far as possible. When statistics were found, they were assessed by a team of experts and, if found relevant to the case at hand, directly implemented in the model. In some instances, the statistics were subject to slight adjustments, to be representable for the case at hand. In addition, some nodes were quantified through simulations or calculations. However, due to lack of data and computing limitations, this was not possible for most of the nodes. To quantify these nodes, a method based on expert elicitation was developed. A summary of the number of nodes quantified by the different methods of quantification is presented in Table 3.

Table 3. Number of nodes quantified by the different methods of quantification for the three risk models (Ro-Pax, Ro-Ro cargo and vehicle carrier).

-	Ro-Ro cargo			Ro-Pax			VC
-	CRS	ORS	WD	CRS	ORS	WD	CRS
Statistics	19	19	19	19	19	19	19
Calculations	3	5	3	3	5	3	3
Previous studies [9, 10]	43	42	5	62	61	17	10
Expert judgement	38	38	30	19	19	18	63
Total	103	104	57	103	104	57	95

Because of the Covid-19 pandemic, it was not possible to travel or to meet physically. Therefore, the expert elicitation had to be fully digital. The platform for all workshops and meetings was Microsoft Teams. Instead of physical workshops, a questionnaire-based approach was used. The expert elicitation process was designed based on the Delphi method [27], an established elicitation method. The conventional Delphi method involves a structured, anonymous process of multiple rounds of written surveys to aggregate expert opinions on anticipated events and trends [28]. Between the rounds of expert elicitations, a facilitator provides an anonymized summary of the experts' forecasts and (sometimes) reasoning, encouraging them to revise their answers based on the panel's collective feedback. By doing so, it overcomes the limitations of traditional group discussions, such as the influence of dominant voices and conformity pressures [29], resulting in more accurate and expedient outcomes compared to individual judgments [30, 31]. However, the current work was limited by having reduced iterations, occurring only between the facilitators and the participants, with no review of the aggregated results. This is a deviation from the Delphi method, which is an iterative method to elicit group judgements. In a Delphi exercise, experts provide estimates and are then allowed to review the aggregated results and update their estimates. This goes on for several rounds until consensus is reached or for a certain number of rounds [32, 33].

Once the experts were appointed and had agreed to participate in the study, the process of expert elicitation consisted of five steps (Figure 4). First, the risk model and complementary information in written form were shared with the experts. Secondly, a digital training session was held. During the training session, the experts were trained in quantification and common reasons for biases were discussed. The risk model was explained during the session, and there was room for questions. After the information and training session, a questionnaire was sent out by e-mail to all the experts. During the response time, which was several weeks, optional digital support sessions were organised on a regular basis. The support sessions were scheduled, open sessions, where the experts could raise any questions or ask for all kinds of support. Once all replies were collected, the response data were processed. In case of strongly deviating answers, the experts were given the opportunity to clarify their reasoning, change their response or keep their response without change.

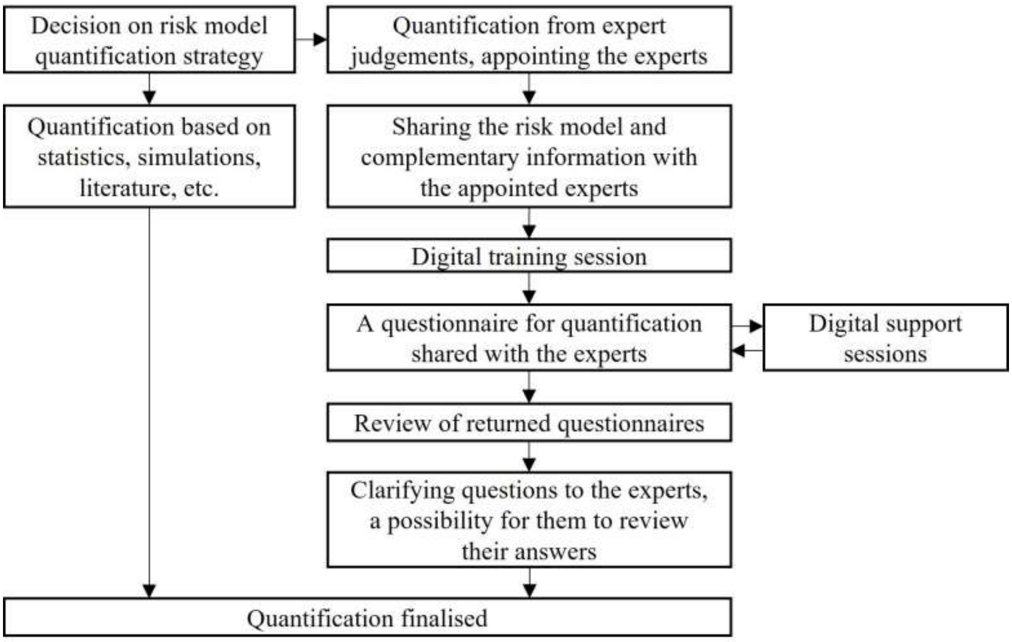

Figure 4. Schematic summary of the quantification process.

Since the risk assessment was part of a large project (LASH FIRE) the availability of experts was good. Experts from different areas and with different expertise were available. While there are several suggestions for a minimum number of experts [20, 21] involved, the maximum number is generally limited by what can be managed. As further discussed below, it was decided to make use of a larger select crowd of experts. A summary of the experts and their backgrounds is given in Table 4. To ensure confidentiality and anonymity, the experts were encouraged to communicate directly with the quantification facilitators. Furthermore, the individual questionnaire responses were only shared with the facilitators. Just as in a study by Ioannou et al. [21], this was made to encourage the experts to provide their individual judgement without fear of criticism.

Table 4. Number of experts participating in the quantification and their background/competence.

Roles	Ro-Ro cargo	Ro-Pax	VC
Researcher	2	3	2
Seafarer	10	6	2
Service provider	2	2	2
Surveyor	2	2	2
System provider	2	3	2
Total	18	16	10

The questionnaire sent to the experts was in Microsoft Excel format. The file contained nine sheets (sections). In the first worksheet, the respondent was asked to provide information on her/his experience. The second worksheet contained pictures and drawings of a generic Ro-Ro ship (either Ro-Ro cargo, Ro-Pax or vehicle carrier) and the third worksheet contained instructions on how to fill out the remaining worksheets, addressing the quantification. There were quantification worksheets for detection, first response, decision, extinguishment, containment and evacuation, respectively. The respondents were asked to provide their estimates of the average failure rate. For example, if experts estimated a 10% failure rate, this corresponds to 10 failures out of 100 occurrences, meaning the equipment operates successfully 90 times out of 100. After gathering the expert estimates, the average values for each node were calculated. These average values (of the responses) were then employed to quantify the risk model. The questions in the questionnaire were phrased in a way to assist the respondent and minimize bias; the topic of the question was put in context and examples were given when considered relevant.

2.4. Potential Loss of Life, Cargo and Ship

The result from the quantification was the frequency of each end branch of the event tree, representing a certain (fire) scenario. To quantify the consequences of each scenario, the main risk metric used in this study was PLL. It is an annual fatality rate, measured as equivalent fatalities per ship year. PLL was used in accordance with the definition in the International Maritime Organization's guidelines for formal safety assessment, i.e., as the expected value of the number of fatalities per year [11]. In addition to PLL, the two metrics 'potential loss of cargo' (PLC) and 'potential loss of ship' (PLS) were used. PLC and PLS are measured as monetary costs, expressed as Euros per ship year. All three metrics were calculated throughout the risk model so that each scenario was associated with a certain fatality rate and cost and a certain frequency. The fatality rate and cost times the frequency provided the risk of the fire scenario. Aggregating the risk of each fire scenario provided the PLL, PLC and PLS for each type of Ro-Ro ship.

2.5. Uncertainty and Sensitivity Analyses

To evaluate the robustness of the risk model and the precision of the risk quantification, sensitivity and uncertainty analyses were carried out. While the sensitivity analysis identifies which nodes of the risk model have the largest impact on the result, the uncertainty analysis demonstrates the overall uncertainty of the estimated risk.

2.5.1. Uncertainty Analysis

The analysis was performed using the add-in @RISK (by Lumivero) in Microsoft Excel. With the software, Monte Carlo simulations [34] were performed (5 000 iterations). Input to the model was each node's estimated probability distribution, and output from the model was a distribution of the PLL risk metric. To perform the Monte Carlo simulations, all nodes were assigned with a Beta probability distribution. The beta probability distribution was selected because of its flexibility and ability to provide many distributional shapes over a finite interval [35] and since it has been shown to be applicable in previous uncertainty analyses of risk assessments [9, 10, 35, 36].

The probability density function (PDF) is given in Eq. 1, and the beta function in Eq. 2. The parameters α and β must be greater than zero, and X (a continuous random variable) must be between zero and one. B is the beta function.

$$PDF = \frac{x^{\alpha-1}x^{\beta-1}}{B(\alpha,\beta)} \quad (1)$$

$$B(\alpha,\beta) = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}dt \quad (2)$$

The expected value (E), which was the probability of each node was, together with the variance (Var) used to define the parameters α and β. The correlation between α, β and the expected value is given in Eq. 3, and the variance calculated from α and β is given in Eq. 4.

$$E[X] = \frac{\alpha}{\alpha+\beta} \quad (3)$$

$$Var(X) = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} \quad (4)$$

To reflect the uncertainty associated with the different data sources (as is presented in Table 5), three sets of α and β parameters were used (Table 6). To assign the level of confidence (Table 5), following factors were considered: assumptions made in the modelling, the number of experts consulted, and the variance in the expert estimates. The authors, however, admit that assigning this type of confidence is not a precise science. The numbers presented in Table 6 were used in a previous study on maritime fire safety (FIRESAFE II) by Leroux et al. [10]. The authors did not provide an explanation for using these numbers, we have reflected on them and decided to use them in the current study, for consistency. From Table 6 and Eq. 4, it can be calculated that moving from high confidence to medium confidence increases the variance by a factor of 4.8, and moving from medium to low confidence increases the variance by a factor of 4.3. In other words, the variance was 21 times higher for data sources with low confidence compared to high confidence.

Table 5. Level of confidence assigned to the different data sources, where L = Low, M = Medium, H = High, SAP = Same confidence level as in the previous studies.

-	Ro-Ro cargo	Ro-Pax	VC
Statistics	M	H	H
Calculations	M	M	M
Previous studies [9, 10]	SAP	SAP	SAP
Expert judgement	M	M	L

Table 6. Formulas for calculation of the α and β parameters in the beta probability distribution, where P_{Node} = Probability of each specific node.

Level of confidence	α	β
Low	$11 * P_{Node}$	$11 * (1 - P_{Node})$
Medium	$51 * P_{Node}$	$51 * (1 - P_{Node})$
High	$251 * P_{Node}$	$251 * (1 - P_{Node})$

2.5.2. Sensitivity Analysis

To identify the nodes with the biggest impact on the PLL, a sensitivity analysis was performed. The analysis was carried out by decreasing the values (probabilities) of each node by 10% and recording the new PLL i.e., a deterministic approach was used [37]. Only one type of node was changed at a time. However, if the same node existed for different space types, all nodes (up to three) were changed simultaneously. The percentage of change in PLL was calculated according to Eq. 5.

$$PLL_{Rel.change} = 100 * \frac{PLL_{New} - PLL_{Ref.case}}{PLL_{Ref.case}} \quad (5)$$

3. Results and Discussion

Table 7. Result from expert estimations of probabilities of failure (in percentage) for nodes along the ET branch identified in Figure 5, where Q1 = first quartile, Q3 = third quartile, K = Knowledge, T = Technical, DT = Design: Technical, DO = Design: Operability, C = Cultural, O = Other.

-	-	-	Ro-Ro cargo			Ro-Pax			VC		
-	-	Type	Q1	Mean	Q3	Q1	Mean	Q3	Q1	Mean	Q3
Detection	Individual detector failure	T	2.0	7.6	10	1.0	7.1	10	1.8	7.4	11.3
	Detection system failure	T	2.0	4.8	8.0	1.0	5.6	13.8	1.8	4.4	5.0
First response	Accessibility problems	DO	-	-	-	15.0	25.9	30.0	27.5	48.1	71.3
	Tactical failure	K	-	-	-	7.5	16.2	25.0	10.5	31.8	46.3
	Equipment failure	T	-	-	-	1.0	5.7	9.3	-	-	-
Decision	Lack of relevant information	K	3.5	17.7	27.5	10.0	26.2	50.0	5.0	26.0	50.0
	Poor flow of information	K	2.0	14.4	21.5	5.0	27.4	43.8	4.0	30.4	50.0
	Insufficient competence	K	2.0	11.6	15.0	2.0	12.6	13.8	-	-	-
	Hesitation, due to fear or blame	C	1.5	12.9	20.0	-	-	-	1.6	5.8	11.3
Extinguish-ment	Reduced accessibility	DO	5.0	21.5	30.0	20.0	50.6	75.0	8.0	36.8	70.0
	Inefficient tactic	K	5.0	17.8	25.0	5.0	17.8	25.0	5.0	16.1	32.5
	Lack of personnel	DO	2.5	18.1	31.3	3.5	30.7	60.0	2.8	26.6	48.8
	Firefighting group equipment failure	T	2.0	7.5	10.0	5.0	14.4	14.0	5.0	11.1	14.3
Containment	Flame spread through permanent openings	DT	-	-	-	1.5	4.6	5.0	-	-	-
	Flame spread through open doors	C	-	-	-	0.5	1.6	2.5	0.8	1.5	2.0
	Flame spread through unsealed penetrations	C/DT	-	-	-	-	-	-	0.8	1.0	1.3
	Damages in fire insulation	O	-	-	-	-	-	-	1.8	2.8	5.0
	Failure of fire insulation (caused by the fire)	DT	1.3	7.7	10.0	-	-	-	2.0	7.0	10.5
	Heat bridges	DT	-	-	-	-	-	-	1.8	4.0	6.3
	No fire insulation	C/DT	-	-	-	3.0	5.1	7.3	4.8	5.8	7.0
	Failure of boundary cooling	DT/T	2.0	13.0	15.0	4.5	20.2	36.0	2.0	4.8	7.5
	Smoke spread through external openings	DT	-	-	-	5.0	9.9	10.0	4.5	12.8	21.3
	Unfavorable navigation of the ship	K/O	-	-	-	3.5	5.6	9.3	4.8	5.8	7.0
	Doors damaged prior to fire (gaps)	C	-	-	-	-	-	-	0.9	2.1	2.8
	Failure of smoke-tight doors	DT/T	-	-	-	2.0	5.2	8.5	3.5	4.0	5.0
	Door(s) left open	C	-	-	-	2.0	5.1	5.5	2.8	6.5	11.3
	Failure to create a pressure difference	DT/K	-	-	-	20.0	60.5	88.8	35.0	69.0	97.5
Evacuation	The ratio of failure at shore to at sea	-	4.3	7.7	11.5	4.5	10.0	15.0	2.0	4.4	5.0
	Communication failure	O	5.0	10.5	10.0	3.0	20.7	35.0	-	-	-
	Blocked evacuation route	C	2.3	6.7	11.5	2.8	12.9	16.3	-	-	-
	Evacuation route impacted by fire	DT	2.5	7.1	12.5	2.0	8.0	10.0	1.8	6.2	11.0

In this study, several assumptions and limitations were acknowledged. Regarding the risk model, a balance was necessary between capturing every phase of a fire scenario and maintaining the model's quantifiability. To achieve this, the terms 'early' and 'late' were introduced to represent detection and decision-making phases. While these terms allow for some distinction, the model does not fully account for the dynamic progression of a fire. Additionally, the model operates under the assumption of a linear sequence of events, without accounting for potential back-and-forth progression. For instance, if a fire begins in a closed Ro-Ro space, the model does not explicitly address the possibility of fire spreading to an open Ro-Ro space; instead, such scenarios are incorporated within the consequence definitions. It is important to emphasize that the results of the current study are derived from a model and, as such, cannot fully capture the complexities of real-world scenarios. Consequently, these results should be interpreted with caution. Particular attention should be given to the outcomes of the uncertainty analysis, which, rather than providing a single fixed value, offers a range of possible outcomes.

3.1. Quantification by Expert Judgement

As far as practicable possible, statistics, data from previous studies, and calculations were used to quantify the risk model. With that said, out of the total 623 nodes quantified in this study, 36% were quantified by expert judgement, as presented in Table 3. While interactive expert group elicitations can benefit from dynamic discussions, the results may be skewed by dominant voices or conformity pressures within the group. The Delphi-based method employed in this study mitigates the risk of such group biases but relies heavily on the careful selection of experts. To minimize the influence of any single expert's input, 10–18 experts were consulted depending on the ship type and expert availability. This is significantly more than the four or five experts recommended by Ioannou et al. [21], or the ideal eight or nine suggested by Mannan [20]. Given that all the experts were selected from project partners involved in a single project focused on enhancing fire safety onboard Ro-Ro ships, there is a possibility that their heightened awareness of risks and the crew's adherence to safety standards might be above the norm for the global fleet, introducing a potential bias that cannot be entirely ruled out. As further discussed below, the inclusion of a relatively large and diverse group of experts from various fields, with their responses averaged, is expected to improve the accuracy of the probability estimates by incorporating a broad range of experiences and knowledge.

Parts of the structure of the risk model were identical for all three ship types. However, even if the structure of, and nodes in, the risk models were identical, the probability of certain nodes differed between ship types. For example, the probability of discovering a fire in a Ro-Ro space could be assumed to depend on the number of crew and passengers onboard, ship type-specific routines, operations and the size of the Ro-Ro spaces. Therefore, the quantification was made by a different group of experts for each ship type. An example of the nodes quantified for closed Ro-Ro spaces is marked in Figure 5 by the thick black line, following the series of events CRS, early detection, unsuccessful first response, early decision, and successful extinguishment or suppression. The data quantified along the line for all three ship types is presented in Table 7. The table contains values for the lower and upper quartiles and the mean values by the expert judgements (i.e., the value used in the risk model).

To better understand and further analyze the results, the nodes were classified as 'technical', 'cultural', 'knowledge', 'design' or 'other'. The 'design' category was further subdivided into 'design: technical' and 'design: operability'. 'Technical' refers to the technical failure of a physical component or system (e.g., failure of an individual detector or a valve, not caused by poor design). While 'cultural' refers to things such as leaving doors open or being hesitant to start the drencher, 'knowledge' addresses actions the crew does not have sufficient knowledge to perform. The category 'design: technical' covers weaknesses in the ship design and arrangements (e.g., openings, lack of insulation), while the category 'design: operability' is a bit closer to 'cultural' but covers the operational balance of the different activities of the ship (e.g., navigation, safety, cargo handling, passenger care, etc.).

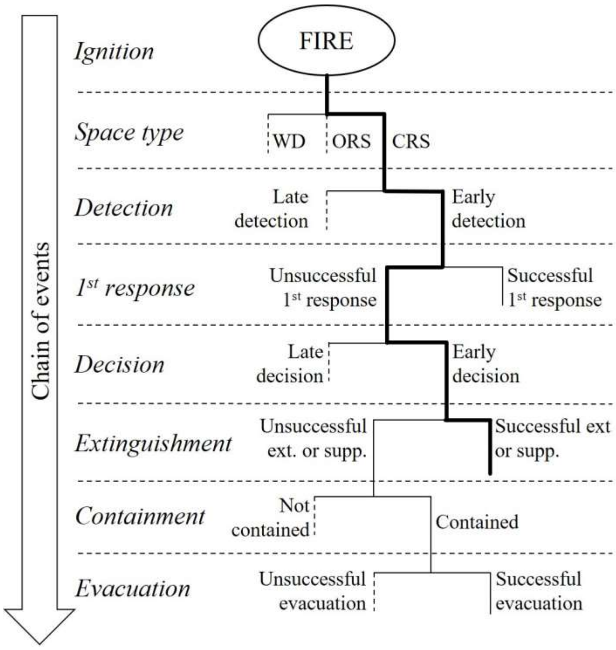

Figure 5. Illustration of the event tree. The probabilities presented in Table 7 come from nodes in the fault trees for the events along the thick line.

3.1.1. Technical Nodes

For all nodes identified as 'technical', the probabilities of failure (calculated as averages) were estimated to be 4–14%. Data in the literature, to compare with, is scarce. However, according to the authors, a probability of failure around 10% seems reasonable, particularly for aggregated systems. As an example, according to EN 61511 standard, a value greater than 10% must be used for a basic process control system [38]. Additionally, according to the Swedish Process Safety Association (IPS), the probability of failure of an automatic (without manual intervention) fixed fire protection system in land-based applications falls within the range of 0.5% to 10% [39]. At sea, with the presence of salt water, it is likely in the higher range due to corrosion issues.

When the two nodes 'individual detector failure' and 'detection system failure' are compared, there is a tendency that the estimated probability of failure of a complete detector system is slightly lower than the probability of failure for an individual detector. This indicates a belief among the experts that the system is more robust than a single detector. This could be interpreted as that the weakest point is a single detector and not the system itself.

3.1.2. Cultural Nodes

Nodes classed as 'cultural' are highly dependent on the experts' previous experience and the (safety) culture in their present company. By safety culture, we refer to norms, values, and routines related to risk and safety shared by a group [40, 41]. Seafarers from three shipping companies participated in the quantification, one shipping company per ship type. When the lower and upper quartiles are considered, the spread in the result is, for most nodes, relatively narrow and close to the average value. This indicates that, even though the experts may have different experiences, they have a shared perception of the risk. In the case of 'Hesitation, due to fear or blame', a somewhat larger spread in the replies is observed. We propose that this reflects personalities and the fact that subjective feelings are not solely influenced by culture.

For all cultural nodes, the estimated probabilities are in the interval 1–13%. The estimations are like, or slightly higher than, some generic probabilities for human error presented by Kirwan (0.3%–10%) [42], but they remain within the same order of magnitude. A potential explanation could be that the probabilities provided by Kirwan apply to single events (e.g., a single door is left open) while the current study investigated aggregated probabilities.

For the node dealing with partially or completely blocked evacuation routes, the result indicates this to be more common onboard Ro-Pax ships (compared to Ro-Ro cargo). It could be assumed that passengers are less aware of the risks than the stationary crew, but it could also be a result of the higher number of people onboard.

Finally, all shipping companies involved in the current study were based in the European Union. The safety culture around the globe may differ [43] and the result from the quantification may be biased towards the situation in Europe.

3.1.3. Design Nodes

When it comes to 'design: operability', a high probability of failure of the nodes addressing this topic is noted (18–51%). The nodes either address accessibility (to the fire) or lack of personnel. Both accessibility and personnel relate to profitability since less cargo will reduce the income, and more personnel will increase the expenses. Most of the nodes in the category 'Design: Technical' are estimated to have a probability of failure between 1% and 13%; this is in line with the failure of other technical protection measures (0.1% to 10% per device, according to [37]). One of the nodes in the 'Design: Technical' category addresses the failure to establish a pressure difference to prevent smoke from spreading to specific areas. For this node, expert judgments ranged widely from 1% to 100%. This variability could suggest either difficulty in understanding the question or significant differences in the experts' experiences.

3.1.4. Knowledge Nodes

The probability of failure of the nodes in the 'knowledge' category is generally estimated to be higher (averages range from approximately 10–30%) than nodes in many of the other categories ('Design: operability' is, however, significantly higher). The authors hypothesize that it could be due to a difficult environment onboard ship, ships being rebuilt, which adds complexity, and that seafarers are not professional firefighters. The relatively high probabilities associated with nodes related to knowledge suggest a significant opportunity to enhance fire safety onboard Ro-Ro ships through improved education and training programs.

3.2. Uncertainty Analysis

The result from the uncertainty analysis is presented in Figure 6. The figures show histograms of PLL, as a result of a fire in a Ro-Ro space. The two delimiters (in each figure) correspond to the interval in which the PLL is found with a confidence of 90%, i.e., PLL for Ro-Pax ships is, with a probability of 90%, between 0.0115 and 0.0172 fatalities per ship year (with an average of 0.0142 fatalities per ship year). In this work, expert judgment was used to quantify several of the nodes. To collect the expert judgements, a questionnaire-based approach was used. This approach helped mitigate the risk of group bias and saved resources by eliminating the need for travel [20]. With the current approach, the uncertainty analysis indicates that PLL for each of the ship types, with 90% confidence, deviates from the calculated mean value by ±19–26%.

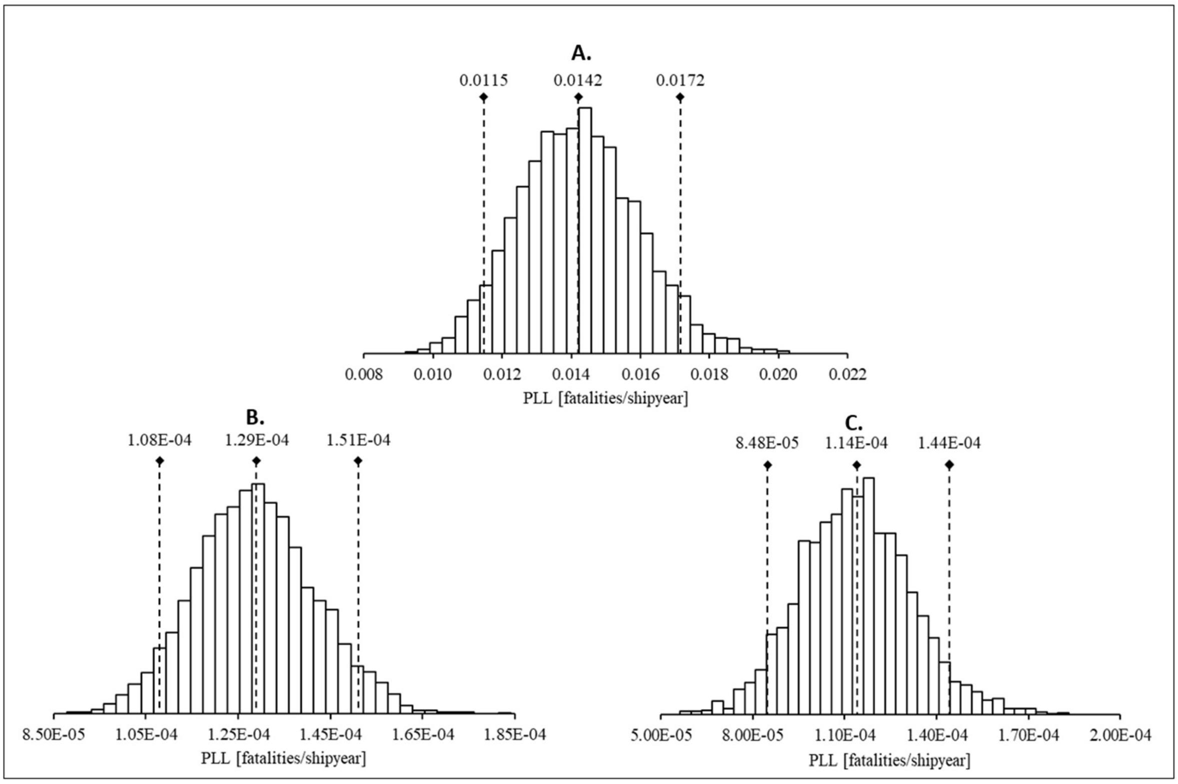

Figure 6. Result from uncertainty analysis of PLL for Ro-Pax ships (A. top center), Ro-Ro cargo ships (B. bottom left), and vehicle carriers (C. bottom right).

The extent of the deviation, in relative terms, is indicated by the confidence levels (cf. Table 5) and the number of nodes in each risk model. Additionally, it can be concluded that the potential loss of life (PLL) is notably higher for Ro-Pax ships compared to Ro-Ro cargo ships and vehicle carriers. This is reasonable due to the larger number of people onboard (passengers) Ro-Pax ships."

It should be mentioned that the uncertainty analysis addresses only the parameter uncertainty (imprecision and inaccuracies in probabilities) and not the complete uncertainty (all significant phenomena and all relationships considered) nor the modelling uncertainty (inadequacies and deficiency in various models) [44]. Another challenge with the uncertainty analysis is the generation of a probability density function. In this study, the beta type of distribution was selected for input variables. As previously discussed in Section 2.5.1, there is inherent uncertainty in assigning values to alpha and beta in Eq.1–Eq.4. While the selected values were based on a prior study, they are not beyond question and could be subject to further scrutiny [10]. The uncertainty analysis conducted does not alter the calculated average value of the PLL but affects the distribution of variance. Consequently, the upper and lower bounds of the 90% confidence interval should be considered indicative rather than definite.

Even though it offers advantages and has been used in previous studies, the use of the beta distribution and the selected parameters are assumptions affecting the outcome of the uncertainty analysis. It is recommended that future research focuses on the selection of alpha and beta parameters to reduce this uncertainty.

Markowski et al. highlighted the difficulty in generating or selecting a probability density function due to the limited availability of data [44]. In the current study, up to 18 experts (depending on ship type) participated in the quantification of some of the nodes. This exceeds the recommendations of at least four or five, or ideally eight or nine experts, as suggested by Ioannou et al. [21] and Mannan [20], respectively. For some of the nodes, the fit between the assumed beta distribution and the expert estimates was relatively good. For other nodes, there was no or only a very vague correlation between the assumed distribution and the expert judgements. This finding does not necessarily affect the quality of the uncertainty analysis but highlights the challenges with the selection of a probability density function (when not enough data is available). Therefore, the uncertainty analysis, together with the sensitivity analysis should be seen as tools to better understand the result from the risk assessment.

3.3. Sensitivity Analysis

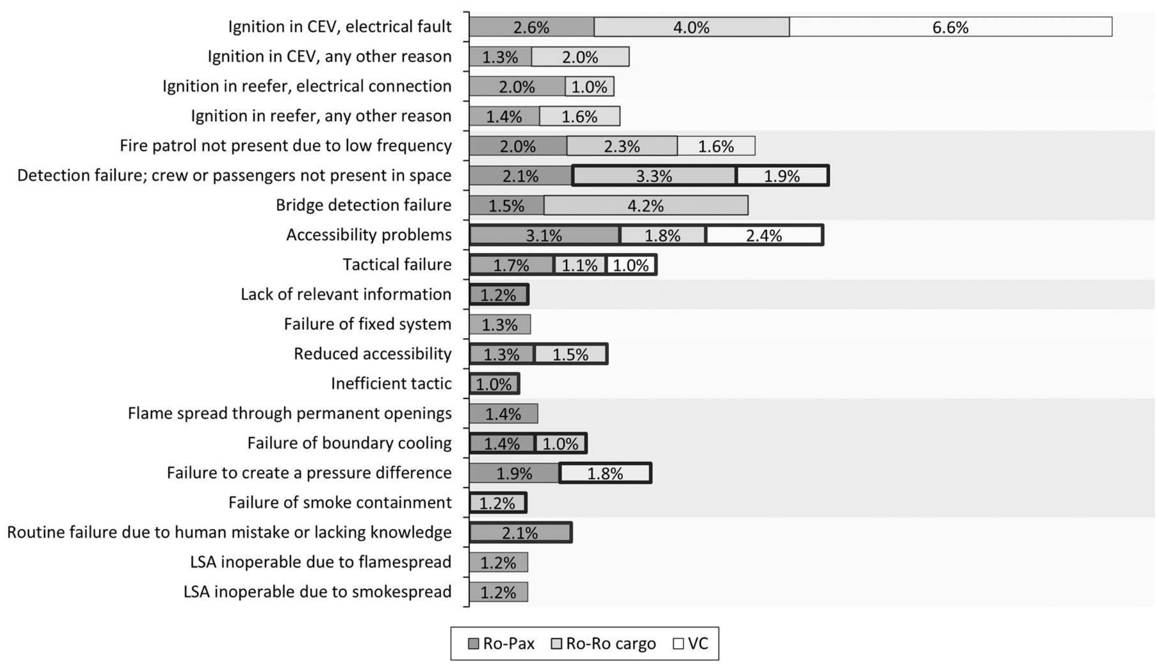

Figure 7. The nodes most sensitive to a 10% change in their values, as identified in the sensitivity analysis. The values correspond to the relative change in PLL (for a 10% change of the node). Boxes with thick lines were quantified by expert judgements. CEV = Combustion engine vehicle. LSA = Life-saving appliances.

The nodes for which a 10% change in their reference values resulted in more than a 1% change in the PLL are presented in Figure 7. The results show that the three ship types share many of the nodes with a, in relative terms, large impact on the PLL result. For Ro-Pax ships, there is a greater number of nodes with a notable effect on the PLL compared to general Ro-Ro cargo ships and vehicle carriers. As in the uncertainty analysis, this is explained by the higher number of people on board Ro-Pax ships. Nodes quantified by expert judgement are marked by a thick border in Figure 7. Out of the 12 nodes with the largest impact on the result (≥ 2% change in PLL), only three were quantified by expert judgements. Quantification by other means (e.g., statistics) is generally more reliable. It is thus considered that this finding contributes to the robustness of the result.

The nodes affecting the ignition node tend to have a large impact on the risk, according to the sensitivity analysis of the risk model. This is due to the structure of the risk model; the probability of ignition directly affects the probability of all outcome scenarios. Similarly, the earlier a node occurs in the event tree, the greater the sensitivity. This is because changes introduced early can propagate through the event tree and affect several branches. The more sensitive the predicted risk is, compared to a change in a certain node, the more important becomes the accuracy in the quantification. Further, it was also observed that nodes in fault trees with fewer nodes had a larger impact on the result.

3.4. Extended Result Discussion

3.4.1. Developed Risk Model and Future Utilization

The Formal Safety Assessment procedure was implemented in the IMO rule-making process over 20 years ago, to move away from subjectively focusing on publicized accidents stigmatized in media or politics [45]. The ambition was to facilitate a transparent decision-making basis, allowing clear comparison of different options, particularly for decisions with far reaching implications. Formal Safety Assessment applies a systematic and scientific cost-benefit assessment approach, where benefit is estimated as risk reduction. It requires a risk model which can both estimate the current risk level and the impact of the proposed improvements. Many activities have been carried out to establish relevant acceptance criteria and to develop risk models accounting for collision, grounding and fire for different ship types [46–48]. However, it was not until the FIRESAFE project that a model was made available to assess fires starting in ro-ro spaces. In the current study (the LASH FIRE project), the model was significantly expanded to cover all types of ro-ro ships, and it was also elaborated in several areas where FIRESAFE made conservative assumptions. The LASH FIRE risk model described above is published as a whole and explained in technical reports, including the many assumptions and expert estimations, further discussed subsequently [23,24]. The model is also based on the performance of different proposed solutions, as demonstrated in a multitude of fire tests [49]. In combination with the risk model, they provide a practical example to the maritime rule-makers and industry of how solutions and validating fire tests can be incorporated to improve the Formal Safety Assessment. The risk model also shows the holistic picture of how one safety improvement, e.g. integration of a new system or routine, affects the fire safety of the ship as a whole [50]. Thereby the risk model can also be used to identify the best candidates for recommendations for decision-making, by an objective comparison of different solutions. The risk model will hence be useful in future rulemaking for ro-ro ships, for any IMO Member State, but it will also be useful for classification societies and insurance companies for the development of their own rules.

3.4.2. The Strength of Using a Larger Crowd of Experts

While the development of a risk model was the primary objective of the study, it quickly became clear that expert elicitation and a process to attain the expert judgements would be key for the assessment. Different solutions have been proposed to quantify experts' estimates of risk, which is a complex issue since they are essentially intersubjective judgements which can be heavily differentiated [51]. Using a small group of experts may be more manageable but it also causes a large sensitivity to the selection of experts. Using a larger group is primarily limited by what can be readily managed [20, 21], but this limitation was alleviated by the digital tools required during the pandemic. An interesting solution to the consistency and uncertainty issues of large groups of experts is the wisdom of the crowd's phenomenon [52]. The basic principle behind the phenomenon is that the errors people make in their assessments seem to be normally distributed around the actual value. If there is not a systematic bias in the judgements, this implies that over and under estimations cancel each other out, while the mean value has proven to come astonishingly close to the actual value, as further explained by Surowiecki and revisited by Wallis [53,54]. Large differences in judgements or appraisals are often used as an argument against the use of expert judgements. However, if the purpose of the judgement is rather the collective appraisal than single values, Galton shows that also differentiated judgements can be very useful.

For engineering applications, the wisdom of the crowd's concept has been further explored by e.g., Georgalis & Marais and Mannes et al. [55,56]. Mannes et al. noted that it may be difficult and costly to collect the opinion of a crowd and that the public still rather relies on experts than on a crowd [57]. They therefore introduced "select crowds", using a selection of the top five knowledgeable judges, based on a cue to ability. This gave very accurate average appraisals and increased the strength of knowledge while relying on a smaller select crowd. The concept explored in this study was to use a larger select crowd of experts, involving 10–18 persons from the industry to estimate probabilities in the risk model. This limited the sensitivity to the selection of experts, while the Delphi-based approach mitigated group biases. This way involved many personnel familiar with the workplace in the analysis worked to manage knowledge uncertainties, at the same time as the result legitimacy and public acceptance increased [58,59]. It can therefore be recommended when carrying out Formal Safety Assessments but is likely to be appropriate for risk assessments applied in other areas.

4. Conclusions

Finding historical data for the quantification of all nodes in large and complex risk models is either impossible, too time-consuming, or too costly. Therefore, there will always be a need for expert judgements. In the current study, 225 of 623 nodes were quantified through expert elicitation. The process was carried out fully remotely using digital means. The experts were first introduced to the quantification, then asked to fill out a questionnaire. Support sessions were given meanwhile. Overall, the experts were overall engaged in the task, and it turned out well. The method is recommended to avoid group bias or when input from several experts is desired. The method is also a suitable alternative in situations when travelling must be avoided. The main drawback of the digital method is to obtain a shared understanding of a problem; attendance at the support sessions was optional and open discussions were kept to a minimum (to avoid group bias). To increase the robustness of the result, uncertainty and sensitivity analyses were performed. For all three Ro-Ro ship types, the uncertainty analysis showed the PLL to deviate, with 90% confidence, from the calculated mean value by less than 26%. The result from the sensitivity analysis indicates that nodes early in the chain of events have a larger impact on the result than nodes occurring later in the chain of events. Therefore, in case of limited resources, focus should be put on quantification of the nodes occurring early.

The number of experts consulted plays a role. The greater the number of experts, generally the better the precision of the probability estimation(s). By assigning different levels of confidence and using a distribution with a higher variance, this could be dealt with.

Supplementary Materials: The following are available request: S1 Risk model structure ro-pax, S2 Risk model structure ro-ro, and S3 Risk model structure VC.

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Declaration of AI-assisted technologies in the writing process: During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed.

References

[1] International Maritime Organization (IMO). (2014). Safety of Life at Sea (SOLAS) Convention, Consolidated Edition, as amended.

[2] Vanem, E., & Skjong, R. (2004, July 5-7). Fire and evacuation risk assessment for passenger ships [Conference session]. International fire science and engineering conference (INTERFLAM), Edinburgh, Scotland.

[3] Marine Casualty Advisory. (2022). Fire & Abandonment of Car Carrier Vessel. https://www.skytek.com/wp-content/uploads/2022/02/Skytek-Report-Felicity-Ace-Update-21022022.pdf

[4] Reuters. (2022). Passenger found alive on Greece-Italy ferry after blaze, 11 still missing. https://nypost.com/2022/02/20/greece-italy-ferry-fire-one-passenger-found-11-still-missing/

[5] Ministry of Infrastructure and Transport. (2014). Fire on board of the ro-ro pax NORMAN ATLANTIC. https://hbmci.gov.gr/js/investigation%20report/Final%20as%20Interested%20Authority/2014-NORMAN%20ATLANTIC.pdf

[6] Garibaldi, R., & Smith, N. (2006). Preliminary Investigation Report on the Sinking of M/V Al Salam Boccaccio 98. https://safety4sea.com/wp-content/uploads/2019/11/Panama-Maritime-Authority-Preliminary-investigation-report-on-the-sinking-of-Al-Salam-Boccaccio-98-2006_08.pdf

[7] Leroux, J., Mindykowski, P., Bram, S., Gustin, L., Willstrand, O., Evegren, F., Aubert, A., Cassez, A., Degerman, H., Frösing, M., Li, Y.Z., Lottkärr, J., Ukaj, K., & Vicard, B. (2018) FIRESAFE II Detection and Decision. https://emsa.europa.eu/projects/firesafe/#/download-reports

[8] Gadel, M., De Carvalho, E., & Lewandowski, L. (2020). D04.2 – Ro-ro space fire database and statistical analysis report. https://lashfire.eu/deliverables/

[9] Wikman, J., Evegren, F., Rahm, M., Leroux, J., Breuillard, A., Kjellberg, M., Gustin, L., & Efraimsson, F. (2017). Study investigating cost effective measures for reducing the risk from fires on ro-ro passenger ships (FIRESAFE). https://www.emsa.europa.eu/publications/reports/item/2931-study-investigating-cost-effective-measures-for-reducing-the-risk-from-fires-on-ro-ro-passenger-ships-firesafe.html

[10] Leroux, J., Evegren, F., Gustin, L., Ukaj, K., & Vicard, B. (2018). FIRESAFE II Combined Assessment. https://emsa.europa.eu/projects/firesafe/#/download-reports

[11] International Maritime Organization (IMO). (2018). Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process (MSC-MEPC.2/Circ.12/Rev.2).

[12] Kamil, M.Z., Taleb-Berrouane, M., Khan, F., & Ahmed, S. (2019). Dynamic domino effect risk assessment using Petri-nets. Process Safety and Environmental Protection, 124, 308-316. https://doi.org/10.1016/j.psep.2019.02.019

[13] Lee, A., & Lu, L. (2012). Petri Net Modeling for Probabilistic Safety Assessment and its Application in the Air Lock System of a CANDU Nuclear Power Plant. Procedia Engineering, 45, 11-20. https://doi.org/10.1016/j.proeng.2012.08.113

[14] Liu, T.S., & Chiou, S.B. (1997). The application of Petri nets to failure analysis. Reliability Engineering & System Safety, 57, 129-142. https://doi.org/10.1016/S0951-8320(97)00030-6

[15] Bobbia, A., Portinale, L., Minichino, M., & Ciancamerla, E. (1999, September 27-29). Comparing Fault Trees and Bayesian Networks for Dependability Analysis [Conference session]. International Conference on Computer Safety, Reliability and Security (SAFECOMP). https://doi.org/10.1007/3-540-48249-0_27

[16] Konovessis, D., Cai, W., & Vassalos, D. (2013). Development of Bayesian network models for risk-based ship design. Journal of Marine Science and Application, 12, 140-151. https://doi.org/10.1007/s11804-013-1179-9

[17] Xu, Q., Liu, H., Song, Z., Dong, S., Zhang, L., & Zhang, X. (2023). Dynamic risk assessment for underground gas storage facilities based on Bayesian network. Journal of Loss Prevention in the Process Industries, 82, 104961. https://doi.org/10.1016/j.jlp.2022.104961

[18] Korhonen, T., Hietaniemi, J., Baroudi, D., Kokkala, M.A. (2003). Time-Dependent Event-tree Method For Fire Risk Analysis: Tentative Results. Fire Safety Journal, 7, 321-332. https://doi.org/10.3801/IAFSS.FSS.7-321

[19] Skjong, R., & Wentworth, B.H. (2001, June 16-21). Expert Judgment and Risk Perception [Conference session]. International Offshore and Polar Engineering Conference (ISOPE). (pp. 537-544).

[20] Mannan, S. (2005). Lees' Loss Prevention in the Process Industries (3rd ed.) Elsevier.

[21] Ioannou, I., Cadena, J.E., Aspinall, W., Lange, D., Honfi, D., & Rossetto, T. (2022). Prioritization of hazards for risk and resilience management through elicitation of expert judgement. Natural Hazards, 112, 2773-2795. https://doi.org/10.1007/s11069-022-05287-x

[22] Ahl, A., Lindberg, A., & Stenerus, A.S. (2008). Att utforma Bayesianska nätverk: Diskussion, erfarenheter och metodik för tillämpningar av Bayesianska nätverk. https://www.foi.se/rest-api/report/FOI-R--2680--SE

[23] Lewandowski, L., De Carvalho, E., & Cassez, A. (2022). D04.05 – Development of holistic risk model report. https://lashfire.eu/deliverables/

[24] Lewandowski, L., De Carvalho, E., & Cassez, A. (2022) D04.04 – Holistic risk model. https://lashfire.eu/deliverables/

[25] Konovessis, D., Hamann, R., Eliopoulou, E., Luhmann, H., Cardinale, M., Routi, A.-L., Kujanpaa, J., Bertin, R., Harper, G., Pang, E., & Papanikolaou, A. (2015). Risk Acceptance Criteria and Risk Based Damage Stability, Final Report, part 2: Formal Safety Assessment.

[26] International Maritime Organization (IMO). (2008). Formal Safety Assessment, FSA - RoPax ships (MSC 85/INF.3).

[27] Brown, B.B. (1968). Delphi Process: A Methodology Used for the Elicitation of Opinions of Experts. https://www.rand.org/pubs/papers/P3925.html

[28] Linstone, H.A., & Turoff, M. (2011). Delphi: a brief look backward and forward. Technological Forecasting and Social Change, 78, 1712–1719. https://doi.org/10.1016/j.techfore.2010.09.011

[29] Rowe, G., Wright, G., & Bolger, F. (1991). Delphi: a reevaluation of research and theory. Technological Forecasting and Social Change, 39, 235–251. https://doi.org/10.1016/0040-1625(91)90039-I

[30] Davis, J.H. (1969). Individual-group problem solving, subject preference, and problem type. Journal of Personality and Social Psychology, 13, 362–374. https://doi.org/10.1037/h0028378

[31] Parente, F.J., Anderson, J.K., Myers, P., & O'Brien, T. (1984). An examination of factors contributing to Delphi accuracy. Journal of Forecasting, 3, 173–182. https://doi.org/10.1002/for.3980030205

[32] Dalkey, N. (1969). An experimental study of group opinion: The Delphi method. Futures, 1, 408-426. https://doi.org/10.1016/S0016-3287(69)80025-X

[33] Hasson, F., & Keeney, S. (2011). Enhancing rigor in the Delphi technique research. Technological Forecasting and Social Change, 78, 1695-1704. https://doi.org/10.1016/j.techfore.2011.04.005

[34] Heyes, K. (2011). Uncertainty and uncertainty analysis methods. CSIRO. https://doi.org/10.4225/08/585189e5f2360

[35] Johnson, D. (1997). The triangular distribution as a proxy for the beta distribution in risk analysis. Journal of the Royal Statistical Society Series D, 46, 387-398. https://doi.org/10.1111/1467-9884.00091
[36] Unal, R., Keating, C., Conway, B., & Chytka, T. (2004). Development of an Expert Judgement Elicitation and Calibration Methodology for Risk Analysis in Conceptual Vehicle Design. https://ntrs.nasa.gov/api/citations/20040016143/downloads/20040016143.pdf
[37] Kneifel, J., & Webb, D., (2020). Life Cycle Costing Manual for the Federal Energy Management Program. https://doi.org/10.6028/NIST.HB.135e2022
[38] EN 61511-1:2017. (2017). Functional safety - Safety instrumented systems for the process industry sector - Part 1: Framework, definitions, system, hardware and application programming requirements
[39] Fylking, T., & Bjursten-Carlsson, C. (2016). Skyddsbarriäranalys (LOPA) - Vägledning för val av numeriska data. IPS.
[40] Cooper, M.D. (2000). Towards a model of safety culture. Safety Science, 36, 111-136. https://doi.org/10.1016/S0925-7535(00)00035-7
[41] Pidgeon, N. (1998). Safety culture: Key theoretical issues. Work & Stress, 12, 202-216. https://doi.org/10.1080/02678379808256862
[42] Kirwan, B. (1994). A Guide to Practical Human Reliability Assessment. CRC Press https://doi.org/10.1201/9781315136349
[43] Noort, M.C., & Reader, T.W. (2016). The relationship between national culture and safety culture: Implications for international safety culture assessments. Journal of Occupational and Organizational Psychology, 89, 515-538. https://doi.org/10.1111/joop.12139
[44] Markowski, A.S., Mannan, M.S., Kotynia (Bigoszewska), A., & Siuta, D. (2010). Uncertainty aspects in process safety analysis. Journal of Loss Prevention in the Process Industries, 23, 446-454. https://doi.org/10.1016/j.jlp.2010.02.005
[45] International Maritime Organization (IMO). (2002). Guidelines for formal safety assessment (FSA) for use in the IMO rule-making process (MSC/Circ.1023 MEPC/Circ.392).
[46] Vanem, E, & Skjong, R. (2006). Designing for safety in passenger ships utilizing advanced evacuation analyses—A risk-based approach. Safety Science, 44, 111-135. https://doi.org/10.1016/j.ssci.2005.06.007
[47] Skjong, R. (2002). Risk Acceptance Criteria: current proposals and IMO position, Surface transport technologies for sustainable development.
[48] Vassalos, D. (2010). Probabilistic Framework for Onboard Fire Safety – FIREPROOF. http://shipdynamics.ntua.gr/publications/Design4Safety2011_Vassalos_et_al.pdf
[49] De Carvalho, E. (2022). D04.9 – Preliminary impact of solutions and related testing and demonstrations plan. https://lashfire.eu/deliverables/
[50] Andersson, S., Dahlbom D., & Pramanik R. (2023). D04.10 – Consolidation of performance assessment and solutions' impact on safety. https://lashfire.eu/deliverables/
[51] Möller, N., Hansson, S.O., & Peterson, M. (2006). Safety is more than the antonym of risk. Journal of Applied Philosophy, 23, 419-432. http://www.jstor.org/stable/24354864
[52] Galton, F. (1896). Application of the Method of Percentiles to Mr. Yule's Data on the Distribution of Pauperism. Journal of the Royal Statistical Society, 59, 392-396. https://www.jstor.org/stable/2979780
[53] Surowiecki, J. (2005). The wisdom of crowds: why the many are smarter than the few. Abacus.
[54] Wallis, K.F. (2014). Revisiting Francis Galton's Forecasting Competition. Statistical Science, 29, 420-424. https://www.jstor.org/stable/43288519
[55] Georgalis, G., & Marais, K. (2019). Can We Use Wisdom-of-the-Crowd to Assess Risk of Systems Engineering Failures?. INCOSE International Symposium, 29, 620-635. https://doi.org/10.1002/j.2334-5837.2019.00624.x
[56] Mannes, A. E., Soll, J. B., & Larrick, R. P. (2014). The wisdom of selecting crowds. Journal of Personality and Social Psychology, 107, 276-299-299. https://doi.org/10.1037/a0036677
[57] Breyer, S.G. (1993). Breaking the Vicious Circle: Toward Effective Risk Regulation. Harvard University Press.
[58] Morgan, M.G., Henrion, M., & Small, M. (1990) Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press.
[59] Slovic, P. (2001). The risk game. Journal of Hazardous Materials, 86, 17-24. https://doi.org/10.1016/S0304-3894(01)00248-5

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