Horizon 2020

Project acronym:	**LASH FIRE**
Project full title:	**Legislative Assessment for Safety Hazard of Fire and Innovations in Ro-ro ship Environment**
Grant Agreement No:	**814975**
Coordinator:	**RISE Research Institutes of Sweden**

Deliverable D04.05

Development of holistic risk model report

February 2022

Dissemination level: **Public**

Abstract

The Formal Safety Assessment (FSA) carried out in LASH FIRE requires the development and quantification of a holistic risk model describing the fire growth and response in ro-ro spaces. The objective is to compute the risk levels in term of life, cargo and ship loss for the three generic ships, as well as to assess the impact of each solution proposed by the D&D WPs on these safety levels.

For this purpose, the FIRESAFE studies and more particularly their risk model were reviewed, as well as several other modelling techniques. The FIRESAFE risk model structure was adapted to LASH FIRE's scope and objectives, to take into account ro-ro cargo ships and vehicle carriers, as well as some failure modes not yet present in the FIRESAFE risk model but necessary for the study of proposed solutions. Once the structure was established, the risk model was quantified using values from FIRESAFE models, when relevant, historical data and expert judgement. The quantification was verified. Based on this risk model, several safety levels were computed and assessed, and several analyses (i.e. sensitivity and other verification) were performed to verify the model.

As a result, several types of risk models were analysed and their strengths and weaknesses were described. For numerous reasons it was decided to keep as much as practicable the same risk model structure as FIRESAFE II. Similarly, it was decided to keep as much as practicable of the probabilities used in FIRESAFE II to quantify the risk model. Historical data, calculations and expert judgement were used to quantify the parts of the risk model where this was not deemed suitable. As far as possible, consequences associated to the determined scenarios were computed using numerical simulations performed in T04.5, and ship operators were contacted to provide data when necessary. Last, but not least, this completed risk model was used to compute safety levels for the different reference cases, but also to determine the most sensitive nodes with regard to the safety levels. Other analyses were also performed, for example to determine the top risk contributor ro-ro spaces in terms of loss of life for each generic ship.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 814975

Document data

Document Title:	D04.05 – Development of holistic risk model report		
Work Package:	WP04 – Formal safety assessment		
Related Task(s):	T04.4		
Dissemination level:	Public		
Deliverable type:	R, Report		
Lead beneficiary:	8 – BV		
Responsible author:	Léon Lewandowski		
Co-authors:	Eric De Carvalho, Antoine Cassez		
Date of delivery:	2022-02-28		
References:	D04.2, D04.3, D04.4		
Approved by	Bernard Porterie on 2022-02-03	Stina Andersson on 2022-01-28	Maria Hjohlman on 2022-01-21

Involved partners

No.	Short name	Full name of Partner	Name and contact info of persons involved
1	RISE	Research Institutes of Sweden	Stina Andersson – stina.andersson@ri.se Kujtim Ukaj Sixten Dahlbom – sixten.dahlbom@ri.se
8	BV	Bureau Veritas Marine & Offshore Registre International De Classification De Navires Et De Plateformes Offshore	Eric De Carvalho – eric.de-carvalho@bureauveritas.com Léon Lewandowski – leon.lewandowski@bureauveritas.com Antoine Cassez – antoine.cassez@bureauveritas.com

Document history

Version	**Date**	**Prepared by**	**Description**
01	2020-06-18	Eric De Carvalho	Draft of structure
02	2022-01-04	Léon Lewandowski	Draft of final report, circulated to reviewers
03	2022-02-28	Léon Lewandowski	Final report

Content

1 Executive summary

1.1 Problem definition

The LASH FIRE project aims to develop solutions to enhance fire safety in ro-ro spaces by the development of innovative technologies as well as by the modification of operations and applications. An evaluation of each solution, in line with IMO Formal Safety Assessment (FSA) procedures, will be carried out within the project. This implies the creation and quantification of a risk model, which will be used to compute the safety levels in terms of life, cargo and ship loss for the three generic ships. The risk model will also be used to assess the impact of each solution proposed by the D&D WPs on these safety levels.

The main challenges were to select the best type of risk model amongst all existing ones, and then to quantify it with the most accuracy possible. As requested by the IMO FSA guidelines [1], the quality and validity of the information and data used to build the model are a paramount. Furthermore, as stated in the LASH FIRE Grant Agreement [2], the development should benefit from the risk model developed in the EMSA-funded FIRESAFE studies.

1.2 Technical approach

To address the described problems above, the D04.5 report was built around four major axes:

- Review of the FIRESAFE studies and selection of the type of risk model. The risk model used in the FIRESAFE studies was studied as well as several other techniques (e.g., time dependent event tree, Petri net, etc.);
- Adaptation of the FIRESAFE risk model structure to LASH FIRE's scope and objectives. Unlike FIRESAFE, LASH FIRE addresses ro-ro cargo ships and vehicle carriers. Hence, the risk model was enhanced to include these two ro-ro ship types, as well as some failure modes not yet present in the FIRESAFE risk model but necessary for the study of proposed solutions;
- Quantification of the risk model. Once the structure was established, the risk model was quantified using values from FIRESAFE models, when relevant, historical data and expert judgement. Historical data came mainly from the WP04 Casualty database summarised in LASH FIRE deliverable D04.2 [3]; and
- Computation of the different safety levels (Potential Loss of Life, of Cargo, of Ship), analysis of these results to provide useful findings, as well as sensitivity and other analyses to verify the model.

In addition, the LASH FIRE deliverable D04.4, "Holistic risk model" [4] provides a detailed description of the risk model.

1.3 Results and achievements

Several types of risk models were analysed and their strengths and weaknesses were described. With regard to the requirements settled by the Grant Agreement, the lessons learnt from the FIRESAFE studies, as well as other considerations, it was decided to keep the same risk model structure as in FIRESAFE II, i.e. a Risk Contribution Tree.

The risk model structure was based on the one from the FIRESAFE studies, and its probabilities were used in LASH FIRE as far as practicable. Historical data, calculations and expert judgement were used to quantify the parts of the risk model where this was not deemed suitable. The privileged communication that WP04 had with ship operators and experts from the maritime world allowed to refine numerous failure modes with a greater precision (e.g. the operational oriented ones). The results of the quantification were analysed and verified.

As far as possible, consequences associated to the determined scenarios were computed using the simulations performed in T04.5. Ship operators were contacted to provide necessary data related to the costs of cargo and ship loss.

Finally, this completed risk model was used to compute safety levels for the different generic ships for the reference case (i.e., without any proposed solution implemented), but also to determine the most sensitive nodes with regard to the safety levels, which shall be addressed to select the most impactful solutions in terms of risk reduction. Other analyses were also performed, e.g. to determine the top risk contributor ro-ro spaces in terms of loss of life for each generic ship, or the position of the generic ships' PLL amongst the whole fleet's PLL distribution. However, all these results have to be taken with caution: they are theoretical and based on a model developed to be a good representation of the fleet. Hence, they cannot be applied to one specific ship (e.g. to compute its actual PLL) and they shall be used with the limitations of the model in mind.

1.4 Contribution to LASH FIRE objectives

The IMO strategic plan for 2018-2023 highlights the importance of integrating new and advancing technologies in the regulatory framework. One of the objectives of LASH FIRE is to support the aforementioned strategic plan, in part through this deliverable. This deliverable will furthermore lay the groundwork for achieving the LASH FIRE objective 3:

> LASH FIRE will provide a **technical basis** for future revisions of regulations by **assessing risk reduction and economic properties of solutions**.

This deliverable is the last step to fulfil the action 4-A:

> **Development of a holistic ro-ro ship fire risk assessment** model and tool for consequence quantification of fires originating in ro-ro spaces.

1.5 Exploitation and implementation

The risk model will be used within LASH FIRE first to determine the most promising solutions in terms of risk reduction, and then, with the help of cost inputs from Work Package 5 (WP05), to assess more precisely their cost-effectiveness, as requested by the IMO FSA guidelines [1].

This deliverable can be used by external parties at different levels:

- The deliverable provides an overview of existing risk model techniques, their strengths and weaknesses. This information can be exploited by anyone who needs to build a risk model, whether as part of an FSA or not;
- The deliverable provides an explanation of the expert judgement techniques: basic principles, when to use it, principal biases to avoid, but also the template from the questionnaire used during this study. Expert judgement can be used in many situations, and is obviously not limited to FSAs. Thus, this overview can be used by any actor who needs to quantify or select elements without having enough data available;
- The deliverable also provides a way to compute the level of agreement amongst experts when the one explained in the IMO FSA guidelines is not applicable; and
- Finally, the analyses in this deliverable provide several pieces of information about safety levels on board ro-ro ships: the top risk contribution ro-ro spaces, the distribution of the PLL amongst the whole fleet, etc. These results can be used by decision bodies to have a better understanding of the issues of fires on board ro-ro spaces.

2 List of symbols and abbreviations

AB	Able seaman
APV	Alternatively Powered Vehicle
ATSFR	Available Time for Safe First Response
BNN	Bayesian Network
BSc	Bachelor of Science
BV	Bureau Veritas
CBI	Can Be Implemented
CEU	Car Equivalent Unit
CFD	Computational Fluid Dynamics
CI	Confidence Intervals
CO	Carbon monoxide
CO_2	Carbon dioxide
CV	Conventional Vehicle
D&D	Development and Demonstration
DZ	Drencher Zone
EJ	Expert Judgement
EMSA	European Maritime Safety Agency
ET	Event Tree
EV	Electric Vehicle
FDS	Fire Dynamics Simulator
FP	IMO sub-committee on Fire Protection (now, sub-committee on Ship Systems and Equipment (SSE))
FSA	Formal Safety Assessment
FSI	IMO sub-committee on Flag State Implementation (now, sub-committee on Implementation of IMO Instruments (III))
FSII	FIRESAFE II
FT	Fault Tree
GA	Grant Agreement
GPV	Gas-Powered Vehicle
GT	Gross Tonnage
H2020	Horizon 2020
HazId	Hazard Identification (workshop)
HRR	Heat Release Rate
IACS	International Association of Classification Societies
IMO	International Maritime Organization
LM	Lane meter
LOPA	Layer Of Protection Analysis
LNG	Liquefied Natural Gas
LSA	Life-Saving Appliance
MOAG	LASH FIRE's Maritime Operators Advisory Group
MS	Magnolia Seaways
MSC	IMO Maritime Safety Committee
MSc	Master of Science
N/A	Not Applicable

PGM	Probabilistic Graphical Model
PLC	Potential Loss of Cargo
PLL	Potential Loss of Life
PLS	Potential Loss of Ship
PM	Project Month
PN	Petri Net
POB	Persons on Board
PRV	Pressure Relief Valve
PVC	Polyvinyl chloride
RCM	Risk Control Measure
RCO	Risk Control Option
RCT	Risk Contribution Tree
RISE	Research Institute of Sweden
RTSFR	Required Time for Safe First Response
SF	Stena Flavia
SOLAS	International Convention for the Safety Of Life At Sea (IMO)
SSE	IMO sub-committee on Ship Systems and Equipment
SY	Shipyear
TDET	Time-Dependent Event Tree
VTT	Technical Research Centre of Finland
WP	Work Package
WP04	Work Package on Formal Safety Assessment
WP05	Work Package on Ship Integration
WP10	Work Package on Extinguishment

3 Introduction

Main author of the chapter: Eric De Carvalho, BV.

3.1 Scope and objectives

The first objective of the risk model developed in the context of LASH FIRE is to estimate the current safety level of the three types of ro-ro ships (reference cases): ro-ro passenger ships, ro-ro cargo ships and vehicle carriers. The model should focus on fires originating in ro-ro spaces and cover each part of the fire protection chain (ignition prevention, detection, decision-making, extinguishment, containment and evacuation).

The risk model should address the three generic ships defined by the Work Package 05 (WP05) as starting point but, as far as practicable, be representative of any ro-ro ships of the LASH FIRE fleet (defined in LASH FIRE deliverable D04.2, "Ro-ro space fire database and statistical analysis report" [3]). The model should reflect fire risks for a ship compliant with the IMO regulations, operated with standard industry practices and with a geometry and arrangement the most representative of the world fleet. Indeed, the risk model is a significant feature in the "technical basis for future revisions of regulations" (LASH FIRE's specific objective 3) and should reflect the fire risks common to all ships targeted by the regulations.

Later in the project, another objective of the risk model will be to allow assessment, in quantitative values, of the effects on probabilities and consequences of additional preventing and mitigating measures addressing the fire risks.

The main limitations of the developed risk model are the following:

- The risk model is built on an analytical approach and fed with available data at the time of the study. It is not an exact picture of the real world. It provides general level of safety, i.e. relative comparisons but not absolute numbers;
- The impact on environment of fires originating in ro-ro space is not considered;
- External help, e.g. rescue vessels or shore support, is out of scope; and
- The risk model does not consider future trends, e.g. alternative fuelled ro-ro ships or ro-ro spaces filled with 100% alternatively powered vehicles (APVs). It provides a picture at the time of the study of fire risks originating in ro-ro spaces.

3.2 Background

The risk assessment constitutes the step 2 of a Formal Safety Assessment (FSA) [1]. A risk assessment is a "systematic process to comprehend the nature of risk, express and evaluate risk, with the available knowledge" [5]. The IMO FSA guidelines [1] defines risk as: "The combination of the frequency and the severity of the consequence" [1]. In order to estimate the frequency and consequence of each important accident scenario identified in hazard identification, a risk model needs to be developed using suitable techniques.

From 2016 to 2018, the EMSA-funded FIRESAFE studies [6], [7] and [8] investigated cost-effective measures for reducing the risk from fires on ro-ro passenger ships using a risk model developed specifically for this purpose. The FIRESAFE studies and its risk model were reviewed and commented by the IMO FSA Experts Group [9].

Starting in 2019, the LASH FIRE project funded by the European Union's Horizon 2020 research and innovation programme is the logic continuation of FIRESAFE. The risk models developed in FIRESAFE and FIRESAFE II should be used as input for LASH FIRE.

In addition to LASH FIRE's specific objective 3, i.e. "providing a technical basis for future revisions of regulations by assessing risk reduction and economic properties of solutions", LASH FIRE is a research and innovative project. Therefore, while developing the risk model, new modelling techniques should be investigated.

3.3 Methodology

In order to achieve the objectives described above, the different steps described in Figure 1 were followed:

1. **Review of the FIRESAFE studies:** The purpose was to review the risk model developed in the FIRESAFE studies in order to build the LASH FIRE model upon the knowledge from FIRESAFE. This step is summarised in chapter 4;
2. **Definition of conditions for risk model:** The purpose was to define the objectives and the main features for the future LASH FIRE risk model and prepare the method of assessment of the new modelling techniques. This step is summarised in chapter 5;
3. **Development of the structure of the risk model:** The purpose was to explore new modelling techniques, select a technique and finally develop the structure of the risk model. This step is summarised in chapter 6;
4. **Quantification of the risk model:** The purpose was to estimate the probabilities and consequences that will feed the risk model. This step is summarised in chapter 7;
5. **Estimation of the safety levels for the reference cases:** The purpose was to provide the safety level of the three reference cases. This step is summarised is chapter 8; and
6. **Analysis of results, sensitivity and other verification analyses:** The purpose was to analysis the results and perform sensitivity and verification analyses in order to provide useful findings about fire risks originating in ro-ro spaces and verify the validity of the model.

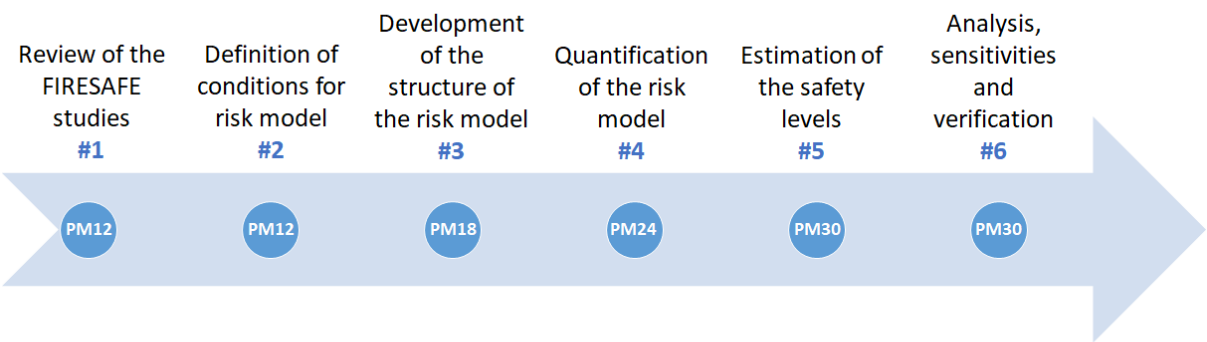


Figure 1. The main steps for the development of the risk model and risk assessment.

The methodology used to develop the risk model and perform the risk assessment is in line with the IMO FSA guidelines [1] and IACS FSA training course [10]. The risk model was not only developed by

the Work Package 04 (WP04) but also with the active support of the Development and Demonstration Work Packages (D&D WPs or WP06-WP11), of the ship operators (WP05) and seafarers. They reviewed and validated key features of the risk models (e.g. the structure) and provided valuable input data (e.g. probabilities). This is further detailed throughout the report.

The LASH FIRE deliverable D04.4 [4] provides a detailed description of the risk model and can be read in addition to the present deliverable.

In ANNEX 1: Short CVs, the short Curriculum Vitae (CVs) of the core development team of the risk model is provided.

4 Review of FIRESAFE studies

Main author of the chapter: Eric De Carvalho, BV.

Commissioned by the European Maritime Safety Agency (EMSA), the FIRESAFE studies aimed at improving the fire safety of ro-ro passenger ships in light of growing concerns about fires in ro-ro spaces. The studies were conducted by Bureau Veritas, RISE and Stena from 2016 to 2018. The studies shed light on several aspects of ro-ro space fire safety, including ignition sources, fire detection, decision-making, extinguishment, fire containment and evacuation.

To author's knowledge, the fire risk models developed during the FIRESAFE studies are the most comprehensive risk models addressing fire risk in ro-ro spaces to date. For that reason, they were used as a foundation for the LASH FIRE risk models. The following sections thus provide a brief description and review of the risk models from the FIRESAFE studies. Further details about the fire risk models developed during the FIRESAFE studies can be found in the FIRESAFE II WP1 and FIRESAFE II WP2 reports, respectively, [7], [8] and [11], as well as in the first FIRESAFE report [6]. The FIRESAFE II risk model is an enhancement of the FIRESAFE risk model.

4.1 Main structure of the risk model

The FIRESAFE II risk model divides the accident sequence into seven tiers (Figure 2), covering the whole chain of events from ignition in ro-ro space to evacuation at sea and at shore.

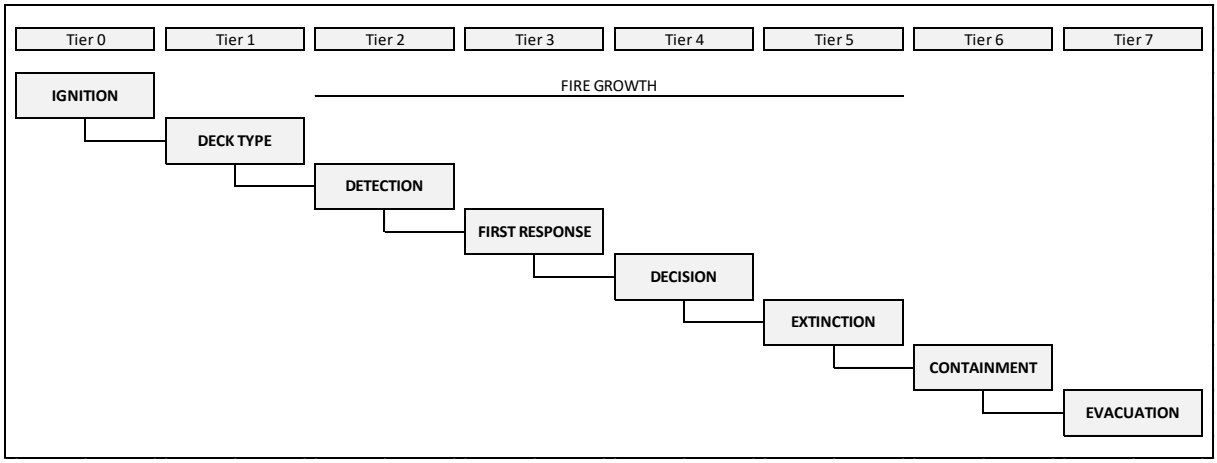


Figure 2. Chain of events for FIRESAFE II [7].

Based on the chain of events shown in Figure 2, six separate fire risk sub-models with overlapping features were developed for the three generic ships included in the study's scope:

1. Cargo Ro-ro passenger Newbuildings;
2. Cargo Ro-ro passenger Existing ships;
3. Standard Ro-ro passenger Newbuildings;
4. Standard Ro-ro passenger Existing ships;
5. Ferry Ro-ro passenger Newbuildings; and
6. Ferry Ro-ro passenger Existing ships.

This set of fire risk models covers both newbuildings and existing ships for each respective generic ship. The structure of each model is a static event tree (no time dependency) in which the failure of mitigation barriers is quantified by dedicated fault trees (or sub-models).

4.2 Nodes of the risk model and their quantification

4.2.1 Tier 0: Ignition

The initiating event 'Ignition' was investigated by analysing casualty and fleet data of FIRESAFE compliant ships over the period 2002-2015. A contribution tree was developed in order to quantify electrical failures contributing to fire in ro-ro spaces. The structure of the contribution tree is based on categories of sources of fires in ro-ro spaces that were defined in FSI 21/5 [12]. Statistics were calculated from the casualty data reported in FSI 21/5 [12] and used to quantify the contribution tree.

4.2.2 Tier 1: Deck type

Although not an event in the strict sense, the tier 'Deck type' is a refinement of the initiating event 'Ignition'. The tier considers that the sequence of events following ignition depends on the type of ro-ro space in which ignition has occurred. It is assumed that the frequency of ignition is evenly distributed in the different ro-ro spaces of the generic ships selected in the FIRESAFE Studies. This assumption is correlated to the amount of cargo and equipment transported in that space. The type of cargo that can be stowed in the different ro-ro spaces and their propensity to ignite are not addressed.

4.2.3 Tier 2: Detection

The FIRESAFE II study [7] introduced the concept of early/late detection, which is related to whether it is possible to successfully carry out first response and extinguish the fire in its initial stage. More specifically, 'Early' detection is thought to have occurred if Available Time for Safe First Response (ATSFR), i.e. the time available until conditions become untenable around the fire, disallowing first response, exceeds the Required Time for Safe First Response (RTSFR), i.e. the time to detect the fire and to set up actions for first response, at a distance equal to the effective range of portable fire extinguishers. On the other hand, if RTSFR exceeds ATSFR, detection is considered to have occurred too late, thereby making it impossible to carry out first response activities safely.

A fault tree was developed in order to model 'Early detection failure'. For late detection to occur, both 'failure of fixed fire detection system' and 'late or no manual detection' are necessary. The failure probabilities are dependent on the type of ro-ro space in which the fire occurs. In order to quantify the probabilities of bottom nodes (or basic failure events), the "expert information" approach [13] was adopted. Fire simulations were carried out to provide a basis for certain parts of the quantification of nodes. Parameters (e.g. fire location, growth) influencing smoke were studied and the RTSFR ≤ ATSFR criterion was evaluated.

Three different main fault trees were developed (excluding the versions developed per ro-ro passenger ships type and for newbuildings versus existing ships):

- Detection in closed ro-ro spaces;
- Detection in open ro-ro spaces; and
- Detection on weather decks.

4.2.4 Tier 3: First response

<u>Following early detection</u>

The probability of 'Manual firefighting failure' was calculated based on statistical analysis of a filtered set of fire casualty data. The resulting probability was then equally divided, based on expert

judgement. The calculated values were then assigned to 'First response failure' and 'Firefighting group failure', respectively.

Following late detection

By definition, the probability of first response failure following late detection was set to 100 %.

4.2.5 Tier 4: Decision-making

Similarly to detection, the FIRESAFE II study [7] introduced the concept of early/late for decision-making (hereafter referred to as "decision"). The decision tier is related to whether or not the decision to activate the fixed fire-extinguishing system has been taken early enough to have a chance to extinguish the fire. In case of 'Early' decision, the fire can be extinguished whereas, in case of 'Late' decision, the fire has developed to a stage at which only suppression is possible.

A fault tree was developed in order to model 'Late decision to respond'. For late decision to occur, either a late alarm interpretation, late confirmation or late assessment is necessary. Human factors specialists contributed to the development of the fault tree. The failure probabilities are dependent on the time of detection (early/late) and the type of ro-ro space. In order to quantify the probabilities of bottom nodes, the opinions of experts were used. These opinions were, to the extent that it was possible, supported by data from the hazard identification workshop (HazId), the review of past ro-ro space fire incidents and data from observations/interviews on board a ro-ro passenger ship. Additional data was gathered from the CORE-DATA [14] human error database and used for comparison.

Four different main fault trees were developed (excluding the versions developed per ro-ro passenger ships type and for newbuildings versus existing ships):

- Decision following early detection in both closed and open ro-ro spaces;
- Decision following late detection in both closed and open ro-ro spaces;
- Decision following early detection on weather decks; and
- Decision following late detection on weather decks.

4.2.6 Tier 5: Extinguishment

As mentioned above, fire extinguishment is only possible following an early decision. Therefore, the effectiveness of the mitigation barrier 'Extinguishment' is contingent on the timing of the decisions that are made on the bridge.

A fault tree was developed in order to model 'Extinguishment/suppression failure'. For unsuccessful extinguishment or suppression to occur, both the fixed fire-extinguishing system and manual extinguishment have to fail. The failure probabilities are dependent on the time of decision (early/late) and the type of ro-ro space in which the fire occurs. In order to quantify the probabilities of bottom nodes, available failure frequency statistics and expert judgement were used. These estimations were then synchronised with statistics drawn on a filtered set of fire casualty data.

There is no fixed fire-extinguishing system on weather decks. The probability of failure of fire extinguishment on weather decks was set to 70 % following early decision (statistical analysis of casualty data and expert judgment) and to 90 % following late decision (expert judgement).

Four different main fault trees were developed (excluding the versions developed per ro-ro passenger ships type and for newbuildings versus existing ships):

- Extinguishment or suppression following early decision in closed ro-ro spaces;

- Extinguishment or suppression following early decision in open ro-ro spaces;
- Suppression following late decision in closed ro-ro spaces; and
- Suppression following late decision in open ro-ro spaces.

4.2.7 Tier 6: Containment

In the FIRESAFE II study [8], the expression fire containment was defined as "avoidance of propagation of fire and smoke, impeding safe stay on board". The mitigation layer 'Containment' is triggered only:

- After the failure of the fire extinguishment or suppression after an early decision; or
- After the success of the fire suppression after a late decision; or
- After the failure of the fire suppression after a late decision.

Indeed, it is assumed that the fire is contained provided that it is suppressed following early decision. This is not the case following late decision, at which point the fire has had more time to develop.

A fault tree was developed in order to model 'Failure of containment'. Its structure is based on the fire containment hazards identified during the HazId. A simplified structure was developed for weather decks taking into account that weather decks are open areas with limited physical boundaries.

For unsuccessful containment to occur, either failure of fire containment or smoke containment is necessary. The failure probabilities are dependent on the success of the fire suppression and the type of ro-ro space. In order to quantify the probabilities of bottom nodes, expert judgement and first principle techniques were used. The top failure probabilities were checked against available historical data.

Six different main fault trees were developed (excluding the versions developed per ro-ro passenger ships type and for newbuildings versus existing ships):

- Containment after successful suppression of the fire in closed ro-ro spaces;
- Containment after unsuccessful suppression of the fire in closed ro-ro spaces;
- Containment after successful suppression of the fire in open ro-ro spaces;
- Containment after unsuccessful suppression of the fire in open ro-ro spaces;
- Containment after successful suppression of the fire on weather decks; and
- Containment after unsuccessful suppression of the fire on weather decks.

4.2.8 Tier 7: Evacuation

In the FIRESAFE II study [8], the failure of evacuation was defined as "an event during which at least one Life-Saving Appliance (LSA) is rendered inoperable due to smoke, flames, or other modes of failure not related to fire". The latter (also called 'intrinsic failure of the LSA') includes failure due to adverse weather conditions, technical failure, and operational failure."

The event tree developed by Vanem & Skjong [15] was used for intrinsic evacuation failure. To this number, the probability of failure of the evacuation due to the fire was added. In order to estimate the latter, a first principle technique was used. The size of the fire was estimated based on a representative unextinguished and not contained fire. Then, the probability of success of evacuation was assessed based on several parameters such as: type of ro-ro space, location of the fire in the ro-ro space, wind conditions (if relevant) and the position of the LSAs relative to the openings (aft openings, weather deck and side openings) and the fire. This quantification is mainly influenced by

the nature of the fire and the arrangement of the ro-ro spaces versus the position of the LSAs. As support to this quantification, the safety distances between openings and LSAs were determined through fire simulations and analytical calculations based on their impairment by radiant heat flux and smoke. Then, for each generic ro-ro passenger ship, the distances between openings and LSAs were checked with regards to safety distances previously determined.

4.2.9 Consequences of end events

In the FIRESAFE studies [6], the consequences to human were considered in terms of number of equivalent fatalities:

- 8 % of the total number of persons on board was considered as equivalent fatalities in the case of unsuccessful evacuation. Same assumption as in previous FSA studies SAFEDOR [16] and EMSA 3 [17];
- In order to take into account the “frequent injuries and possible indirect fatalities following such evacuation” (expert judgment), 1 equivalent fatality was considered in the case of successful evacuation; and
- None equivalent fatality in the other cases.

In the FIRESAFE II study [8], the consequences to cargo and ship were categorised under four different scenarios:

- Scenario A “Small fire”: Fire in ro-ro space successfully extinguished (by either fixed fire-extinguishing system or manual firefighting);
- Scenario D “Medium fire”: Fire in ro-ro space supressed and contained;
- Scenario B “Fire to one deck”: Fire in ro-ro space not suppressed nor extinguished but contained; and
- Scenario C “Total loss”: Fire not contained.

Those four scenarios were discussed and detailed in terms of potential fire origin, damages to cargo, damages to ship, passengers/crew, etc. The costs were estimated based on existing data from previous accidents and extrapolation of those data (expert judgement).

4.3 Summary and lessons learnt

In this section, a summary of the review of the FIRESAFE II risk model is provided. The idea is to highlight the main lessons learnt that could guide the development of the LASH FIRE risk model.

The structures of the event trees and fault trees were developed mainly based on the analysis of past accident investigation reports and the outcomes of different HazId workshops. Those two activities provided a realistic accident sequence and common failures leading to hazardous situations. The activities were very resource-consuming and as much information as possible should be reused in future projects (e.g. LASH FIRE). New methods for risk modelling techniques will be explored as part of the development of the LASH FIRE risk model (cf. section 6)

Quantifications of probabilities were mainly based on expert judgements. The expert judgments relied on many considerations such as physics of the fire, general arrangement of the ro-ro space/ship, the onboard procedures and external factors (weather, voyage, etc.). When possible, the probabilities estimated by the expert judgments were checked against historical data. The use of fire simulations or analytical calculations in order to support the expert judgements was limited. When available, reliability data were used to estimate the failure of systems. New methods or at least enhanced methods of quantification will be explored as part of the development of the LASH FIRE risk model (cf. section 7).

Even if the risk analysis techniques used in the FIRESAFE II studies can be considered as a combination of static event trees and fault trees, some time-dependency was introduced by the definition of early/late detection and early/late decision; this was a mean to address performance of fire response and firefighting as regards to the fire growth (and was therefore a function of the time).

The quantification of consequences to human, cargo and ships were based on historical data and expert judgements. The use of fire simulations can be foreseen for the development of the LASH FIRE risk model.

5 Preliminary work

Main author of the chapter: Eric De Carvalho, BV.

5.1 Definition of conditions for risk model

One of the first steps in the development of the risk model was to determine its objectives and the general conditions to be satisfied. This list of features was supported by several sources:

- LASH FIRE Grant Agreement [2];
- Feedback and lessons learnt from the FIRESAFE studies (cf. section 4.3);
- Report of the intersessional meeting of the Experts Group on FSA submitted by the Chair of the IMO FSA Experts Group [9]; and
- Other sources.

5.1.1 LASH FIRE Grant Agreement

The Grant Agreement clearly defines the risk model as a “holistic ro-ro ship fire risk model”. Rather than “ro-ro ship”, it shall be understood as “ro-ro spaces”. The risk model shall focus on fires originating from ro-ro spaces and cover all the stages of the fire development and the onboard response to fire.

The importance of the FIRESAFE studies is also highlighted as background studies and inputs for the development of the risk model.

As far as practicable, the consequence tools developed in WP04 should be used to estimate the consequences of the risk model and should provide information about the fire and smoke spread on board.

At least, three different types of ro-ro ships shall be addressed by the risk model: ro-ro passenger ships, ro-ro cargo ships and vehicle carriers.

Lastly, the final objective of the risk model is to estimate the impact of the different solutions developed by the D&D WPs. The risk model shall be able to easily assess the risk reduction induced by each Risk Control Option (RCO) in comparison to the risk level established for the reference cases.

5.1.2 Feedback and lessons learnt from the FIRESAFE studies

The main feedbacks from the FIRESAFE studies are presented in section 4.3.

5.1.3 IMO FSA Experts Group

The FSA Experts Group was instructed by MSC 101 to review the FIRESAFE studies regarding the fire safety of ro-ro spaces on passenger ships and the risk assessment criteria. The group met from 18 to 20 November 2019. The review, discussions and conclusions were summarised in a report [9].

The analysis of this document highlighted interesting comments on the FIRESAFE studies that the LASH FIRE project could benefit from.

The FIRESAFE II study was based on a categorisation per type of ro-ro passenger ship (i.e. “cargo”, “standard” and “ferry” ro-ro passenger ships). The conclusions of its cost-effectiveness assessment were drawn for those three types of ro-ro passenger ships. However, this categorisation does not exist in the SOLAS regulations, which may raise some issues in decision-making. The FSA Experts Group would have expected either quantities in order to clearly define this categorisation and/or an approach per type of ro-ro spaces (i.e. closed, open ro-ro spaces and weather deck) rather than per type of ro-ro passenger ships. The latter matches the SOLAS regulations and would have provided more harmonised recommendations. This is a point that LASH FIRE would like to try to consider when developing the risk model.

It was also expressed that external factors, such as heavy weather and/or traffic conditions, and the impact of the voyage were not addressed sufficiently in the scope of FIRESAFE studies. For the latter, it was added that “opportunities to access to shore support in case of fire would affect the results”. In the LASH FIRE project, the recourse to external intervention is out of scope [2].

5.1.4 Other sources

In the coming years, it is foreseen that number of APVs transported onboard ro-ro ships will increase. The fire hazards induced by APVs often needs a different firefighting strategy than the one used for conventional vehicles. This is a hot topic in the maritime world and will be an action addressed in the different work packages of the LASH FIRE project. Therefore, the risk model should as far as practicable address APVs (as regards as the current scientific knowledge and the current onboard situation). It shall be noted that hazards resulting from a release of flammable or toxic gas (including pool vaporisation) or a pressure build-up are out of scope.

5.1.5 List of conditions

The conditions described above were summarised in a list and used to calculate a weighted level of priority. The priority level was defined as:

- Weight = 1: Mandatory;
- Weight = 2: Condition to be satisfied if enough resources; and
- Weight = 3: “Nice-to-have”.

Separately, the partners, involved into the development of the risk model, allocated a weight to each condition. The final weight was the mean of the allocated weights.

Finally, a list of twenty-four conditions and level of priority (Table 1) was established.

This list shall not be understood as a mandatory scope of work but rather on a wish list established at the early stage of the project. In a perfect world, the perfect risk model could fulfil all those wishes. But, because of project life, at the end, it will not be the case. This list is also a means to have criteria to compare different risk modelling techniques (cf. section 5.2).

Obviously, the requirements from the Grant Agreement were allocated with a top priority level (weight = 1). This also includes to respect the budget and schedule and to ensure a continuity of the work throughout the timeframe of the project.

Table 1. List of conditions for risk model

Definition of conditions	Priority level Consolidated - Final
All stages of fire development and response addressed by risk model	1
Focus on fire in ro-ro space	1
The main tiers defined in the FIRESAFE studies will be kept and the FIRESAFE II risk model will be used as input as far as practicable	1
The consequences of the risk model will be quantified by the consequences tools developed in T04.5	1
The risk model (i.e. nodes) will be quantified by the consequence tools developed in T04.5	2
The three generic ships selected by WP05 are addressed by the risk model	1
Risk model per ro-ro space type and unit of space (e.g. lane meter)	1.5
Risk model based on the cargo fire hazard model developed by WP08	3
Improve the definition of early/late detection	1
"Extinguishment" tier from FIRESAFE study to be re-developed	1.5
"Evacuation" tier from FIRESAFE II study to be re-developed	1.5
APVs addressed by the risk model	2
Effect of heavy weather to be addressed by the risk model - at least investigated	2.5
Effect of voyage to be addressed by risk model - at least investigated	2
Introduce more physics of fire in risk model (including time-dependency of fire physics)	1
Minimising the use of expert judgements, best estimate of nodes and less conservatism	1
On demand, easy and quick sensitivity on RCOs	2
Time-dependent risk model e.g. time-dependent event/fault trees	2
User friendly risk model	2.5
Risk model and outcomes easy to present	2
The choice of the program/software of risk model ensures a continuity of work if any change in person within the timeframe of the project	1
Risk model within cost budget (direct cost such as licence cost)	1
Risk model within time budget (manhours) and schedule	1

5.2 Development of an assessment sheet

In the next steps of the risk model development, new modelling techniques were considered. In order to assess/compare the different modelling techniques, an assessment sheet was developed.

The assessment sheet contains a short description of the modelling techniques and the main references used to perform the assessment. A technique's main benefits, drawbacks and challenges are summarised in the sheet.

The last part of the assessment sheet is based on the list of conditions defined above. Depending on whether a condition is met or not by the modelling technique, the rating will be increased. Each condition adds a score proportional to it level of priority. The satisfaction of the condition can be not applicable ("N/A") to the modelling technique or unknown as regards to the resources consulted to perform the assessment. In that case, the rating of the modelling technique is not increased. The satisfaction of the condition can also be not directly reachable and some efforts of development may be necessary. In that case (tagged as Could Be Implemented or "CBI"), the score added to the rating is halved.

The template presented in Table 2 was established and used.

Table 2. Assessment sheet for modelling technique – Template

ID	MT01	
Modelling technique	**BAYESIAN NETWORK**	
Short description	Bayesian network is a probabilistic graphical model (a type of statistical model) that represents a set of random variables and their conditional dependencies via a directed acyclic graph (DAG).	
Main sources	- Surname, A., Year. *Book title*. Name of Publisher. - Company X, Year. *Title of report*. [pdf]. Available at: http://www... [Accessed YYYY-MM-DD].	
Qualitative assessment	Benefits: - XXX - XXX	
	Drawbacks: - XXX - XXX	
	Challenges / Issues foreseen / Comments: - XXX - XXX	
	Does the modelling satisfy the following conditions?	**Yes, No, CBI, Unknown or N/A**
	All stages of fire development and response addressed by risk model	
	Focus on fire in ro-ro space	
	The main tiers defined in the FIRESAFE studies will be kept and the FIRESAFE II risk model will be used as input as far as practicable	
	The consequences of the risk model will be quantified by the consequences tools developed in T04.5	
	The risk model (i.e. nodes) will be quantified by the consequence tools developed in T04.5	
	The three generic ships selected by WP05 are addressed by the risk model	
	Risk model per ro-ro space type and unit of space (e.g. lane meter)	
	Risk model based on the cargo fire hazard model developed by WP08	
	Improve the definition of early/late detection	
	"Extinguishment" tier from FIRESAFE study to be re-developed	
	"Evacuation" tier from FIRESAFE II study to be re-developed	
	APVs addressed by the risk model	
	Effect of heavy weather to be addressed by the risk model - at least investigated	
	Effect of voyage to be addressed by risk model - at least investigated	
	Introduce more physics of fire in risk model (including time-dependency of fire physics)	
	Minimising the use of expert judgements, best estimate of nodes and less conservatism	
	On demand, easy and quick sensitivity on RCOs	
	Time-dependent risk model e.g. time-dependent event/fault trees	
	User friendly risk model	
	Risk model and outcomes easy to present	
	The choice of the program/software of risk model ensures a continuity of work if any change in person within the timeframe of the project	
	Risk model within cost budget (direct cost such as licence cost)	
	Risk model within time budget (manhours) and schedule	
	TOTAL SCORE	**0**

6 Development of the structure of the risk model

Main author of the chapter: Eric De Carvalho, BV.

This section focuses on the description of the development of the structure of the risk model, i.e. the risk modelling technique that was selected and used, and the form of the risk model.

6.1 Consideration of new modelling techniques

In addition to the review of the modelling technique(s) used in the FIRESAFE studies, i.e. risk contribution tree (RCT), new modelling techniques were considered and assessed to check if they could be used to develop the new LASH FIRE risk model.

A four step-process was followed (Figure 3):

- Step 1 (cf. section 6.1.1): Literature review, approximately ten techniques were identified.
- Step 2 (cf. section 6.1.2): Five techniques from step 1 were selected and assessed through the assessment sheets and rated accordingly. The five techniques were:
    - Risk contribution tree (RCT);
    - Bayesian network (BNN);
    - Time-dependent event tree (TDET);
    - Layer of protection analysis (LOPA); and
    - Petri net (PN).
- Step 3 (cf. section 6.1.3): Based on the results of step 2, three techniques were short-listed and draft structures were developed.
- Step 4 (cf. section 6.1.4): Based on the results of step 3, one technique was selected to develop the new risk model.

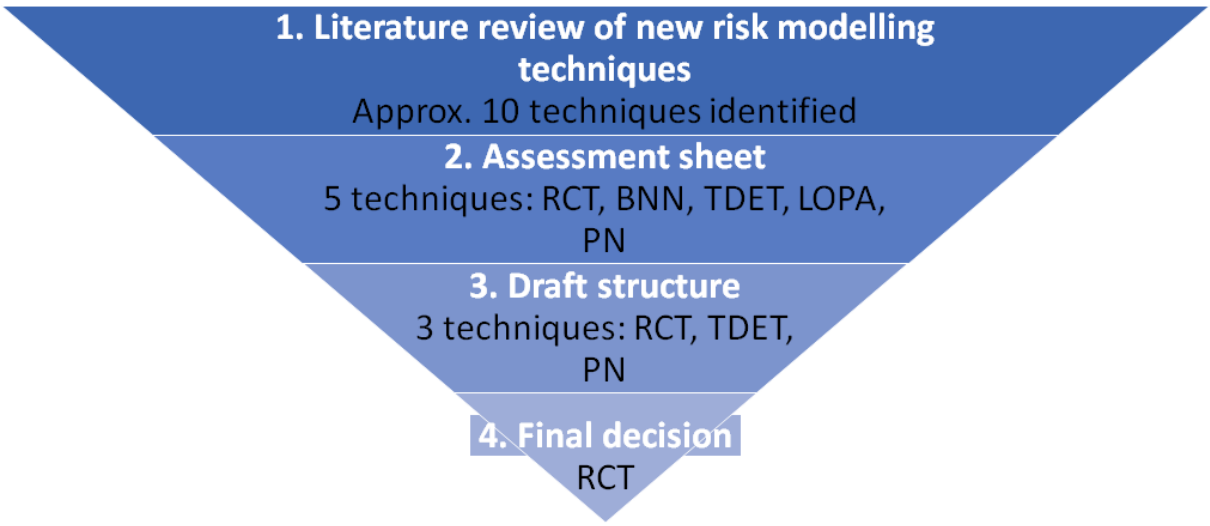


Figure 3. Process for investigation of new modelling techniques.

6.1.1 Step 1: Literature review

A literature review based of about thirty articles, books, etc. was performed. Approximately, ten risk modelling techniques were identified. Among them, only five techniques were selected for next step.

6.1.2 Step 2: Assessment of new modelling techniques

This section provides the results of the state of the art and literature review about five modelling techniques for the structure: risk contribution tree, Bayesian network, time-dependent event tree, layer of protection analysis and Petri net. The results of assessment sheets are provided at the end of the section.

6.1.2.1 Risk contribution tree

In the IMO FSA guidelines [1], a risk contribution tree is defined as "the combination of all fault trees and event trees that constitute the risk model". As example, in the FIRESAFE studies [8], the branch points from the main event trees were quantified by sub-event trees and/or fault trees.

This modelling technique is quite straightforward, well-known, well-recognised and easy to handle. Its main limitations are that it is a linear approach with respect to the sequence of events, i.e. the model does not capture time-dependency. Also, another limitation is that the model tends to grow quickly for scenarios with many potential outcomes.

6.1.2.2 Event tree

Event trees are logic diagrams used to describe and evaluate different ways an initiating event may develop.

An event tree analysis is an inductive process in which the analyst begins with an initiating event and develops the possible sequences of events that lead to different consequences (in a so-called linear process). Event trees provide a systematic way of recording the accident sequences and defining the relationship between the initiating events and subsequent events that result in accidents. The safeguard actions required to be taken after occurrence of the initiating event in order to mitigate or prevent escalation are introduced in the sequences of events.

Event trees are usually developed in a binary format (with yes/no or success/failure); they are easy to interpret and evaluate. Each path on the event tree represents a different scenario. Probabilities at branch points in the event tree define the likelihood that the event will develop in different ways up to the end event/state. Each end event in the tree represents a different outcome associated with a specific severity. Given an initiating event, all possible responses can in principle be considered in an event tree analysis.

6.1.2.3 Fault tree

Fault trees are logical representations of the many events and component failures that may cause a critical event.

A fault tree analysis is a deductive process; fault trees are powerful when it comes to describe the dependency between an effect and its cause(s). It is suitable for the analysis of complex systems with redundant components and potential for common-cause failures.

The analysis starts by defining the top event. The analysis then logically deconstructs the top event by repeatedly asking: how can this event occur? The analysis will identify combinations of lower-level events that will result in the top event. This analysis will continue until the basic failure events at a reasonable/desired detailed level are identified.

A fault tree is constructed using a set of pre-defined symbols and decision gates: OR, XOR (Exclusive OR), AND, NOT, Basic Event, Top Event, etc. Refer to Figure 4, Figure 5 and Figure 6 for symbols and the probability of gate output. Quantitative data (probabilities, failure rates, etc.) can then be assigned to the basic events if quantification of the top event is required.

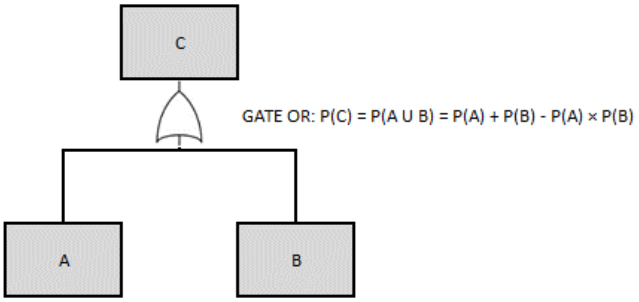


Figure 4. Gate OR.

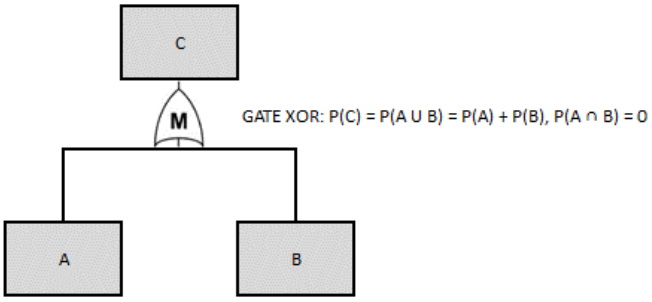


Figure 5. Gate XOR (Exclusive OR).

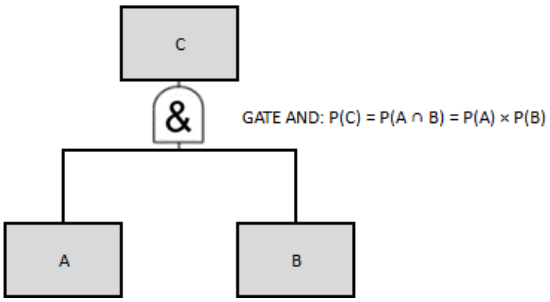


Figure 6. Gate AND.

Note: P(X) = probability of occurrence of failure X.

6.1.2.4 Bayesian network

Main author of the chapter: Kujtim Ukaj, RISE.

Bayesian networks are probabilistic graphical models (PGM) commonly used for a wide range of tasks in statistics and probability theory to express conditional dependence structures between random variables. A random variable in a Bayesian network is represented by a node, which is connected to one or several other nodes through directed links, which are sometimes called edges or arcs. Figure 7 depicts a basic structure of a 3-way Bayesian network, which is also known as the structural specification of the network.

As shown in Figure 7, nodes can be connected through directed links, which imply that there is a direct dependence between variables. The direction of the links in the given example indicates that A (the parent of B and C, respectively) influences both B and C.

Moreover, assuming A, B and C are binary variables with states {True, False}[1], and that each node has been assigned a probability distribution, the joint probability distribution of the structural specification depicted in Figure 7 can be described by Table 3.

Knowing the joint probability distribution, it is possible to compute any conditional probability of interest, for example P(B|A) or P(A|B)[2]. Furthermore, the Bayesian network illustrated in Figure 7 is merely a structured form of the joint probability distribution in Table 3. This is one of the advantages of probabilistic graphical models like Bayesian networks, in the sense that they can provide a good overview of a complex systems with causal relationships.

Bayesian networks are useful for mapping complex systems in which there are variables with mutual causal relationships. One considerable drawback of Bayesian networks, however, is that they are static, i.e. each node represents a random variable in an instant. Dynamic systems that change over time are thus not captured by Bayesian networks.

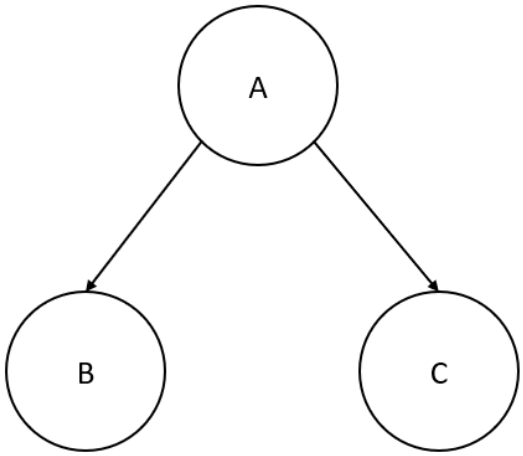


Figure 7. Structural specification of a 3-way Bayesian network.

Table 3. Joint probability distribution table of a 3-way Bayesian network

State(A)	State(B)	State(C)	P(A, B, C)
False	False	False	P(A=False, B=False, C=False)
False	False	True	P(A=False, B=False, C=True)
False	True	False	P(A=False, B=True, C=False)
True	False	False	P(A=True, B=False, C=False)
True	True	False	P(A=True, B=True, C=False)
True	True	True	P(A=True, B=True, C=True)
True	False	True	P(A=True, B=False, C=True)
False	True	True	P(A=False, B=True, C=True)

[1] One may for example imagine that A is a disease, and B and C are symptoms.
[2] One can for example infer the probability of having the disease A, given the presence of symptoms B and C.

6.1.2.5 Time-dependent event tree

Unlike “conventional” or “static” event trees (presented in section 6.1.2.2), time-dependent event trees take explicitly into account the temporal development of an accident.

In a time-dependent event tree approach, the accident is divided into several time intervals. The sequence of events within a time interval is represented by an event tree. The end events of the event trees are called states of the “system”. Over the different time intervals, the event trees keep the same structure but the probabilities of their branch points and the states of the “system” change with time. The full time-line of the accident is obtained by combining the successive event trees through a transition process, linking the states at different time intervals.

This modelling technique is a logical enhancement of “static” event trees since it takes time-dependency of the sequence of events into account. Depending on the number of time intervals to be considered, the transitions tend to be complex to handle. Moreover, the use of fault trees to quantify branch points is less straightforward when a time-dependent approach is used.

6.1.2.6 Layer of protection analysis

Main author of the chapter: Sixten Dahlbom, RISE.

LOPA is a method commonly used in the petrochemical industry to primarily evaluate the efficacy of different safeguards for a given (often high consequence) scenario. Figure 8 presents illustratively the idea of protection layers; however, the result from a LOPA is more often summarised in text/table form (e.g. in excel or in specific software). The risks evaluated in a LOPA are often identified in a qualitative risk assessment, e.g. a HazId. The method is referred to as simple and time effective [18] and provides an ‘order of magnitude’ accuracy.

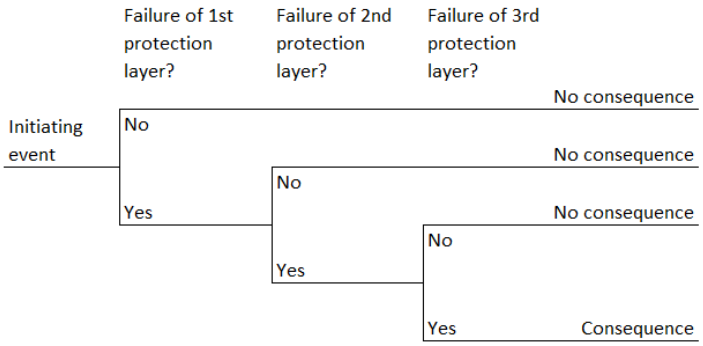


Figure 8. Concept of protection layers.

The method requires all safeguards to be independent, which is not always the case; many safeguards have a (partial) dependency (e.g. a common gauge or control system). Also, the method looks at single cause-consequence pairs [19] and cannot deal with failures that are compound events i.e. double jeopardy is normally not handled when using LOPA.

6.1.2.7 Petri net

Main author of the chapter: Sixten Dahlbom, RISE.

Petri nets were originally developed to study chemical processes but has since then been developed and is nowadays more generic, being a graphical notation for stepwise processes including choice, iteration, and concurrent execution. Petri nets are comprised of places, transitions, tokens and arcs (cf. example in Figure 9). Places represent conditions or local system states, this could correspond to e.g. “Early detection” or “Unsuccessful 1st response” in the FIRESAFE studies [6] and [7]. Transitions describe events and could be associated with e.g. probability distribution functions or time delays. When an event occurs, the transition fires and token(s) move between places (the tokens indicate that a local state holds). It is also possible to assign information such as ro-ro space type to a token, i.e. a “coloured token”. Firing of a system is associated with certain rules, one of the firing rules describes how tokens move in the Petri net (as illustrated in Figure 9), another describes when a transition is enabled (all places connected to it as inputs contain at least one token).

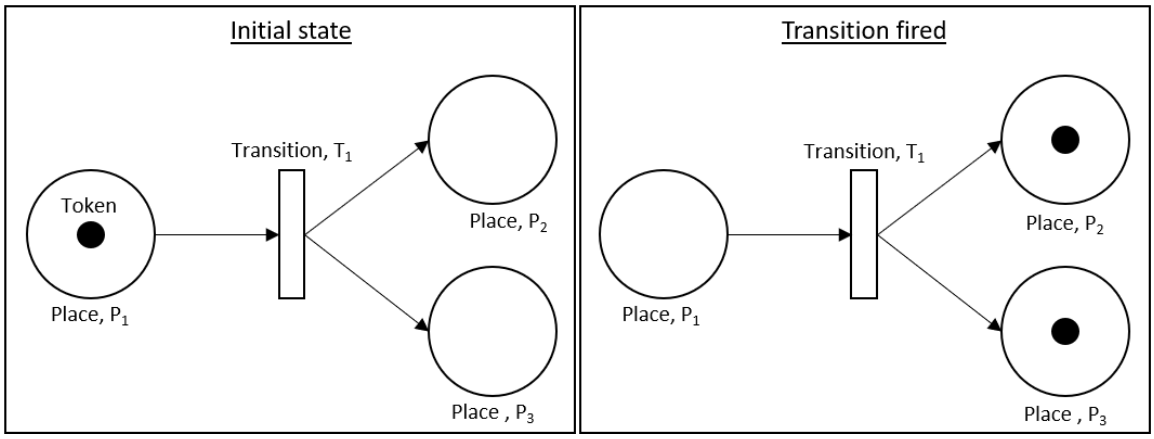


Figure 9. General Petri nets with tokens, places, arcs and transitions. To left: the Petri net at its initial state, to right: the Petri net after firing.

Petri nets are very flexible, something exemplified by the possibility to introduce loops, handle dependencies between places and handle time-dependency. Through some small modifications of the formal Petri net, it would also have been possible to assign the size of the fire (Heat Release Rate or HRR) to transitions.

Conversion of an event tree or a fault tree to a Petri net has been elaborated and described by different researchers e.g. [20] and [21]. This means that a lot of the work made in the FIRESAFE studies could be reused.

One of the concerns with Petri nets is the need of special software, or programming e.g. in MATLAB. Some software was reviewed (cf. section 6.1.3.3), but no one meeting the needs of LASH FIRE was identified. Another concern with Petri nets is the risk that it becomes (too) convoluted and complex, something that would make the quantification difficult (thereby reducing the overall quality of the work).

6.1.2.8 Rating of modelling techniques

The result from the assessment sheets is provided in Table 4. The three modelling techniques with the highest scores (risk contribution tree, time-dependent event tree and Petri net) were further assessed in step 3.

Table 4. Rating of modelling techniques

Modelling techniques	Rating
Risk contribution tree	78
Bayesian network	53
Time-dependent event tree	78
Layer of protection analysis	53
Petri net	54

6.1.3 Step 3: Analysis of new modelling techniques

In the following sections, the work performed on the three selected modelling techniques for the structure is described. This will include tests and draft structures of risk model.

6.1.3.1 Risk contribution tree

This modelling technique was no further investigated because it was the technique used in the FIRESAFE studies.

6.1.3.2 Time-dependent event tree

In order to explore possibilities of the modelling technique, an event tree from the FIRESAFE studies was converted into a time-dependent event tree. The technique used to build the time-dependent event tree is based on the work from VTT [22].

Three time steps were defined based on the definitions from FIRESAFE:

- T1 = early detection and early decision. The first is in its early stage. The first response and fire extinguishment is still possible in this time interval;
- T2 = late detection and early decision. The fire is growing. Now, the first response is not possible anymore but the fire extinguishment is still possible. All fires have been detected. If the fire is successfully extinguished or supressed, then its containment to the ro-ro space is guaranteed; and
- T3 = early or late detection and late decision. The fire is still growing. Now, the fire extinguishment is not possible anymore. If the fire is successfully supressed, then its containment to the ro-ro space is no more guaranteed.

Those three time steps can be easily related to the fire growth. This is a benefit from a time-dependent event tree.

The branch “Closed ro-ro spaces” of FIRESAFE model [8] was slighted adjusted to match a time-dependent process (Figure 10). The probability of each branch point has been highlighted in grey. The end states have been highlighted in green or red depending on their status over time. The states in green represent the final states, i.e. states from where you cannot change over time (e.g. the fire has been extinguished). The states in red represent the transitional states. The transitional process between the different states over time is depicted in Figure 11.

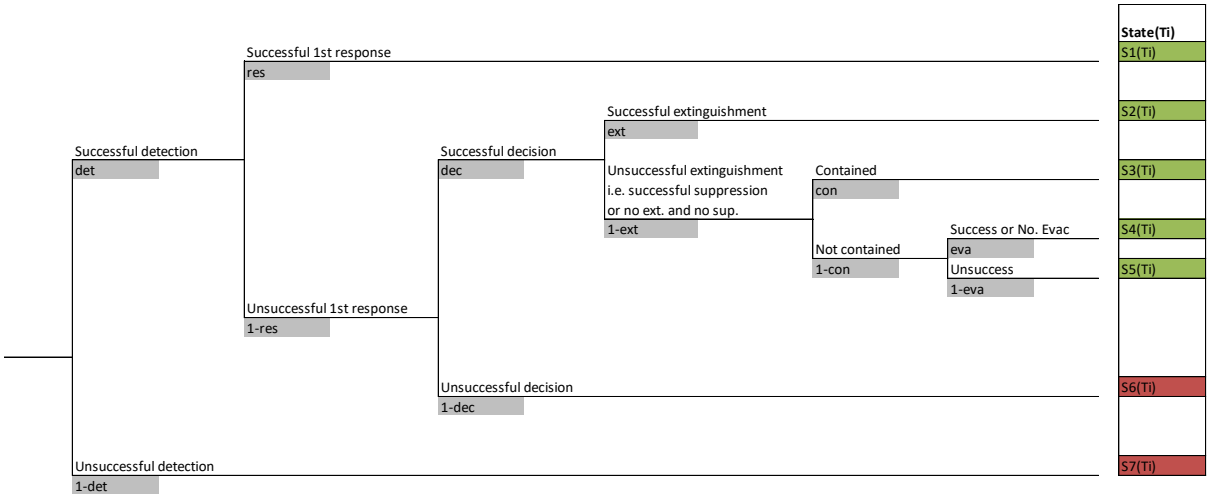


Figure 10. Time dependent event tree – Event tree structure.

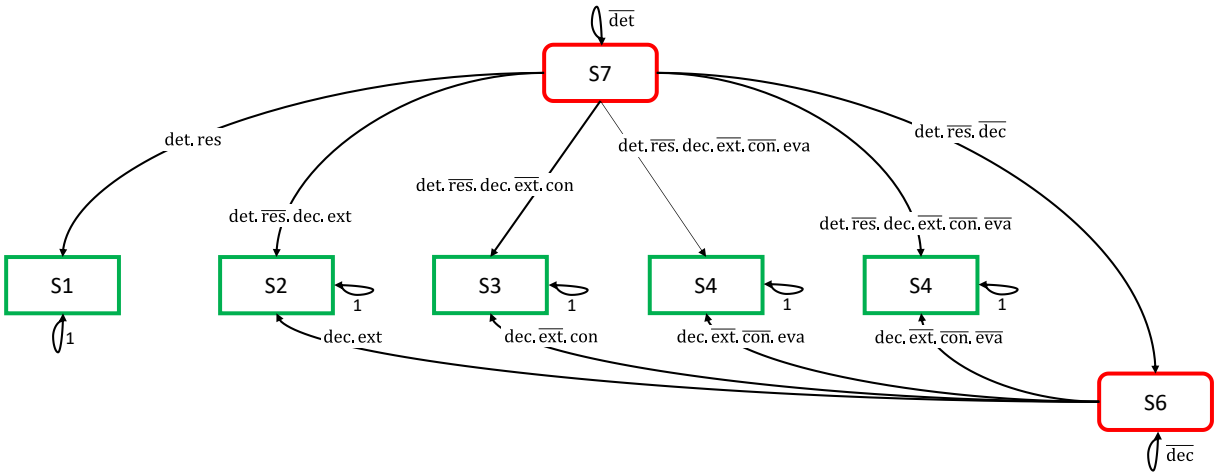


Figure 11. Time-dependent event tree – Transitional process.

The event trees at different step steps were filled up with the same probabilities as in the original event tree. The quantification of the event trees is depicted in Table 5.

Table 5. Time-dependent event tree – Probability of states and branch points at each time step

	T0	T1	T2	T3
Probability S1	0	0.228	0.228	0.228
Probability S2	0	0.318	0.433	0.433
Probability S3	0	0.024	0.032	0.155
Probability S4	0	0.030	0.041	0.141
Probability S5	0	0.009	0.012	0.042
Probability S6	0	0.153	0.253	0
Probability S7	1	0.238	0	0
det	-	0.762	1	1
res	-	0.300	0	0
dec	-	0.714	0.580	1
ext	-	0.834	0.834	0
con	-	0.375	0.375	0.487
eva	-	0.770	0.770	0.770

Table 5 provides the probability of branch points and states at each time step, from T0, i.e. the fire starts, to T3, i.e. the fire is too severe to be extinguished. This kind of information about the probabilities and representation are very valuable and emphasise the time-dependency process. But this technique seems more complex to apply when combined with a fault tree technique (i.e. more quantification to be foreseen). The probabilities provided by Table 5 were no further analysed because it was not the purpose of the exercise.

6.1.3.3 Petri net

Main author of the chapter: Sixten Dahlbom, RISE.

In order to explore possibilities of the modelling technique, part of the event tree from the FIRESAFE studies was converted into a Petri net. The resulting Petri net is presented in Figure 12 (to be compared with the branch "Closed ro-ro spaces" of FIRESAFE model [8]). This Petri net was implemented in the MATLAB Petri Net toolbox, which was kindly supplied by the PNTool Team at Gheorghe Asachi Technical University of Iasi. The Petri net was validated through assignment of static probabilities to the transitions, same probabilities of the end places as in the original event tree were calculated.

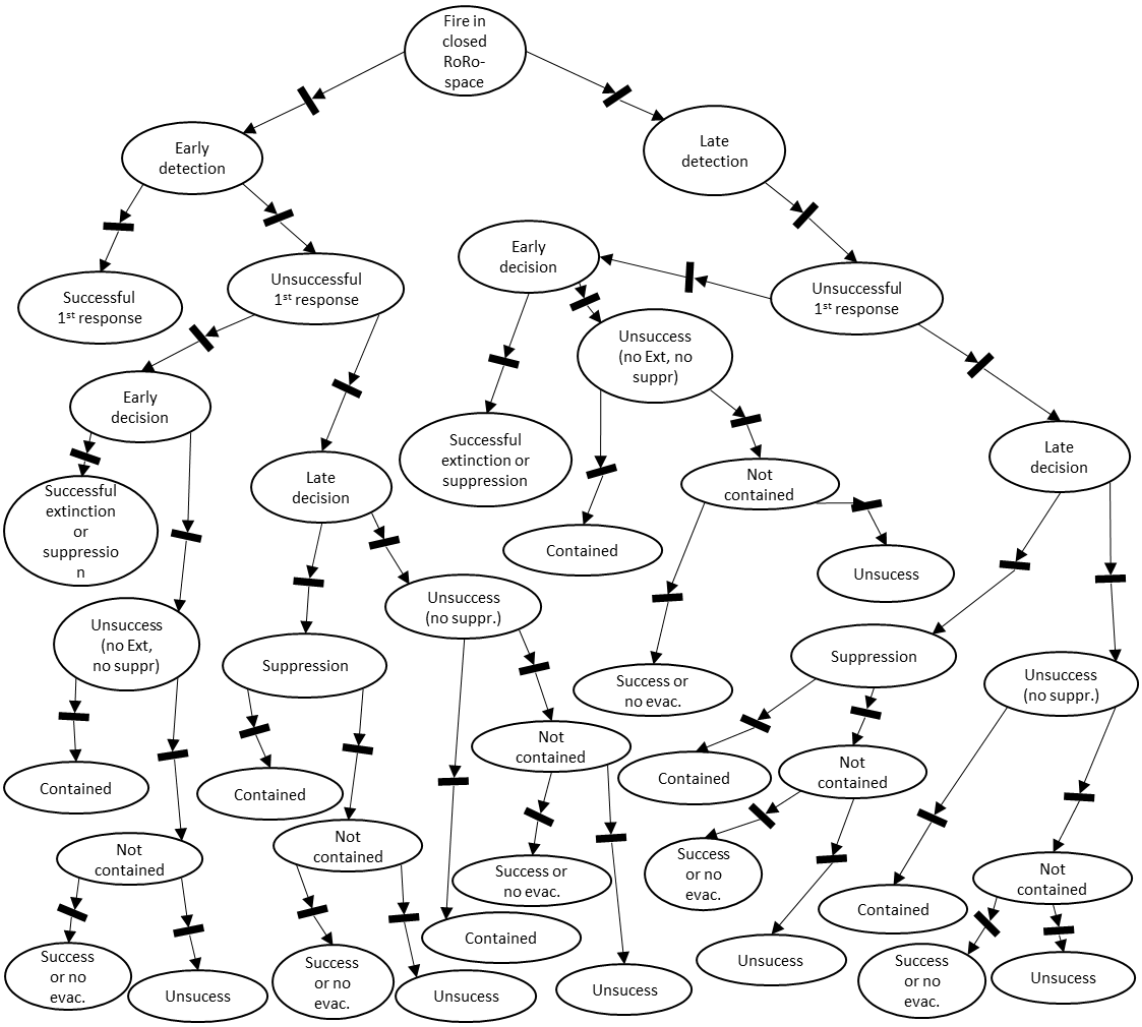


Figure 12. Conversion of the branch "Closed ro-ro spaces" of FIRESAFE model to a Petri net.

The Petri Net toolbox in MATLAB and the CPN Tools software were reviewed. They were both easy to use, but did not provide all desired features. Also, when the size of the Petri net was increased, the usability was decreased (due to space/zoom limitations). From this work, it was concluded that further exploration would have been needed, either by the use of other commercial software or by development of an in-house script. This fact would have reduced the ability to share and spread the risk model, something that was considered to be a drawback.

During the further investigation of Petri net, its strengths as modelling technique was realised and it must be recognised that the method provides many upsides, e.g. the possibility to combine time-dependent and static functions (e.g. transition-timed delay, position-timed delay, constant probabilities, probabilities as a function of time). Petri Nets also offer the possibility to define dependencies between different places (which can be very difficult in an event tree).

6.1.4 Step 4: Final decision

The results from step 3 were presented and discussed with a panel of risk modelling experts the 10 September 2020. The final decision was to use the risk contribution tree technique to develop the new risk model. This choice is the best option in terms of resource and schedule. Several risk contribution trees for ro-ro passenger ships were already developed in the FIRESAFE studies. For continuity and consistency with the FIRESAFE studies, the new risk model shall be based as much as practicable on FIRESAFE model.

6.2 Final structure – Application to LASH FIRE

This section summarises the development of the final structure of LASH FIRE risk model and provides the description of final structure.

6.2.1 Development

The new risk model structure is based on the risk model that was developed during the FIRESAFE studies [6], [7] and [8]: several tiers represented by an event tree dividing the accident sequence over different subsequent events (Figure 13), themselves further detailed by sub-event tree(s) and/or fault tree(s).

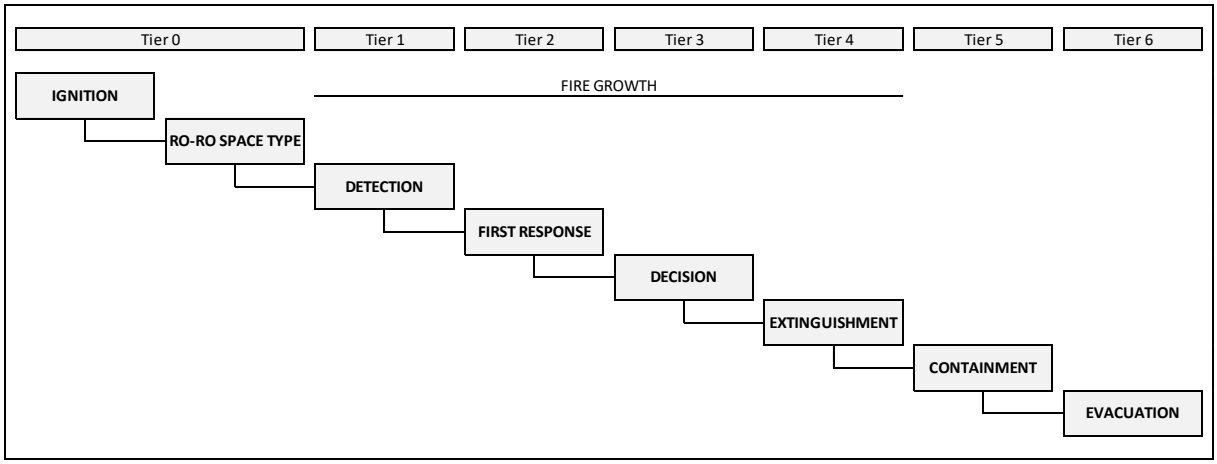


Figure 13. Chain of events for LASH FIRE.

The primary purpose of the structure is to pave the way for the quantification of risks and enable an evaluation of effectiveness of Risk Control Measures (RCMs). With that in mind, the development of the structure of LASH FIRE risk model was conducted in several stages.

<u>Stage 1</u>

From September to November 2020, the first stage was to refine parts of the FIRESAFE II risk model. Parts of the structure (e.g. ignition, first response and evacuation tiers) were modified to better model the risk, although most of the structure is unchanged. Also, the FIRESAFE studies addressed only ro-ro passenger ships, not taking ro-ro cargo ships and vehicle carriers into consideration. The structure developed for ro-ro passenger ships was adapted/converted to ro-ro cargo ships and vehicle carriers.

<u>Stage 2</u>

In December 2020, the draft risk model structures were presented and detailed to the WP leaders and ship operators. The participants were provided with the draft risk model structure and explanatory text two weeks prior to the one day-workshop. During the workshop, the participants gave verbal feedback on the draft structure. Comments and reviews of the structures were also provided in written form from the reviewers from December 2020 to January 2021. During the same period (December 2020), a first description of the solutions (or RCMs) to be developed was given by D&D WPs.

Stage 3

The final stage was to implement the comments from the WP leaders and thereby finalise the structures. In this work, it was also ensured that the structure addresses all solutions described by D&D WPs. Milestone 08 related to structure of risk model was reached on time (end February 2021).

The following sections describe new developments of the risk model structure (since the FIRESAFE studies). This deliverable addresses and describes the new developments only, for all other parts of the structure refer to the description provided in the FIRESAFE studies reports [6]**,** [7] **and** [8]**.**

The complete structure of the risk model is provided in ANNEX 2: Structure of LASH FIRE risk model.

6.2.2 Main risk model structure

Six different main risk models were developed:

1. Ro-ro passenger newbuildings;
2. Ro-ro passenger existing ships;
3. Ro-ro cargo newbuildings;
4. Ro-ro cargo existing ships;
5. Vehicle carrier newbuildings; and
6. Vehicle carrier existing ships.

The main event trees developed in the FIRESAFE studies for ro-ro passenger ships was kept unchanged and used for both ro-ro passenger and ro-ro cargo ships (cf. Figure 14). In the case of vehicle carrier, the event tree was changed (cf. Figure 15); only the branches for closed ro-ro spaces were deemed relevant (only closed ro-ro spaces for vehicle carriers), i.e. the branches for open ro-ro spaces and weather decks were removed.

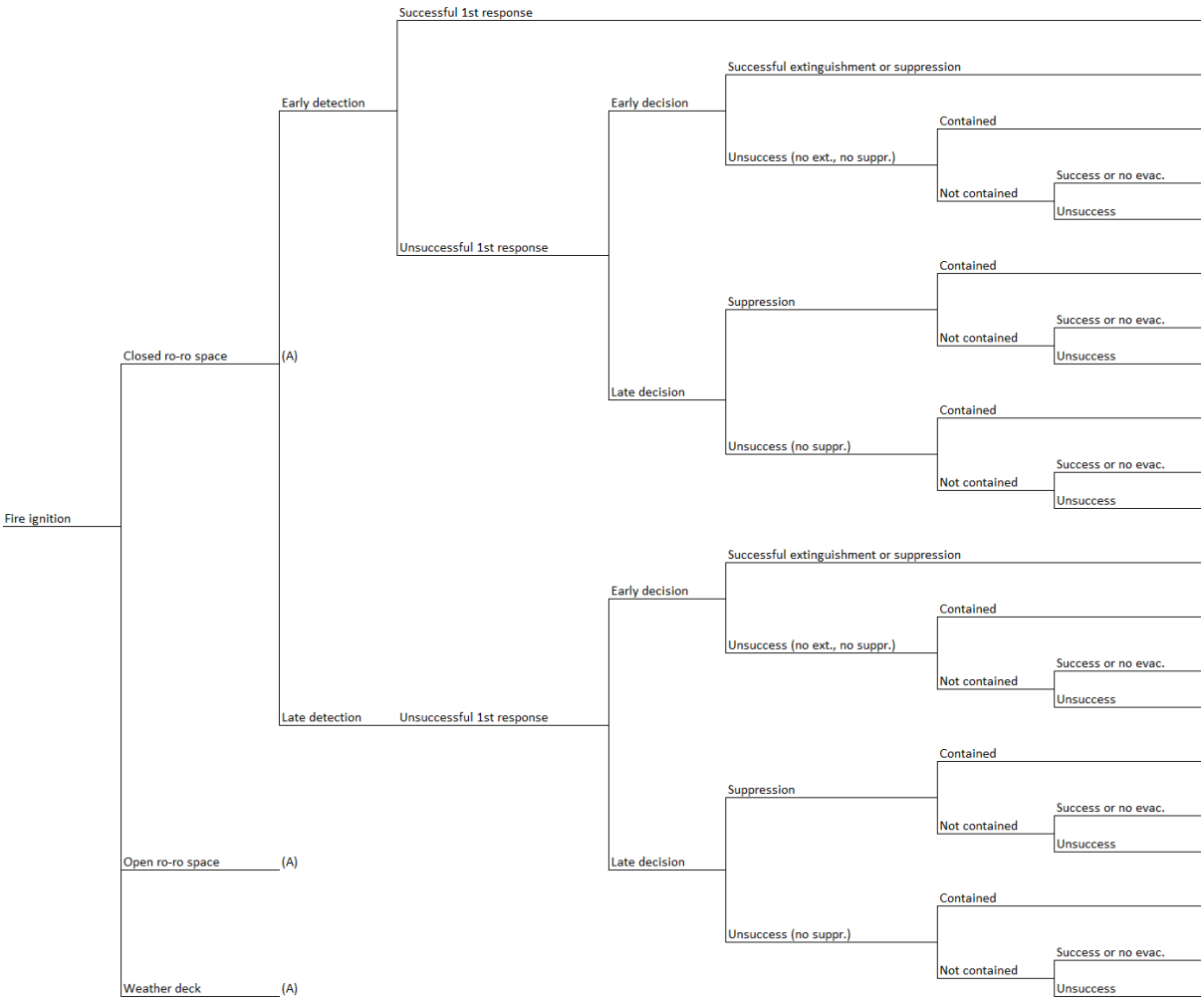


Figure 14. Main event tree – Ro-ro passenger and ro-ro cargo ships.

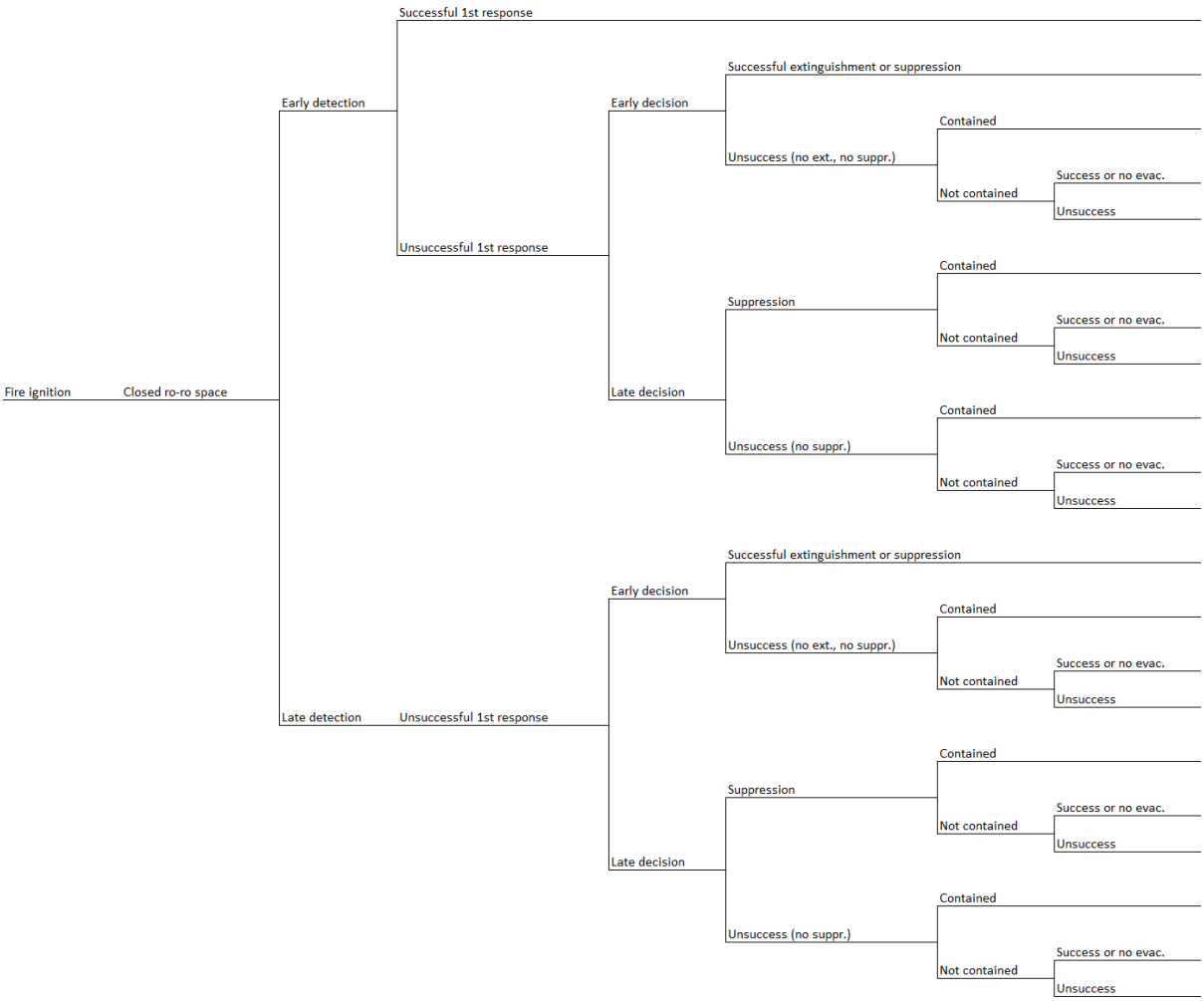


Figure 15. Main event tree – Vehicle carriers.

6.2.3 Ignition

The ignition contribution tree is based on the work done in the FIRESAFE studies [6]. The fire ignition in ro-ro spaces is firstly divided into three different ignition sources: *Ship equipment*, *Ship cargo* and *Other origin*.

The category *Ship equipment* includes both fixed and portable (potentially plugged in to the ship's electrical system) equipment. Fires due to faulty cables connected to reefers, electrical vehicles, etc. do not belong to this category, but to the category *Ship cargo*. The category *Ship cargo* includes all types of cargo transported by a ro-ro ship and stowed in a ro-ro space. The category *Other origin* includes, for example, fires due to cargo shift and arson.

The category *Ship cargo* is further divided into *Conventional vehicle*, *Alternatively Powered Vehicle (APV)* and *Cargo unit*, in order to distinguish fires originating from the vehicles themselves and their transported goods. In order to reflect the increase in transports of APVs, the category *APV* has been added since FIRESAFE.

The category *APV* is divided into *Electric Vehicle* and *Other APV* in order to distinguish the associated hazards. The sub-category *Electric Vehicle* includes battery electric, plug-in hybrid electric, plug-in electric, hybrid electric and fuel cell electric vehicle, whereas the sub-category *Other APV* includes vehicles powered by compressed gas or liquid/liquefied fuels. The category *Cargo unit* is then divided into *Temperature-controlled (cargo unit)* and *Other cargo unit*, in order to separate refrigerated or heated units from other cargo.

All categories are finally divided into two different fire causes: *Electrical* and *Other*, referring to whether the fires were caused by an electrical fault or not.

For *Electrical* fires originating from *Electric vehicle* and *Temperature-controlled (cargo unit)*, it is distinguished between fires related to the C*onnection* to ship power supply or to *Other (electrical cause)*, i.e. not directly related to the electrical power connection.

6.2.3.1 Ignition – Closed and open ro-ro spaces

The ignition contribution trees for closed and open ro-ro spaces is presented in Figure 16. Nodes highlighted in orange are new or modified nodes since the FIRESAFE studies.

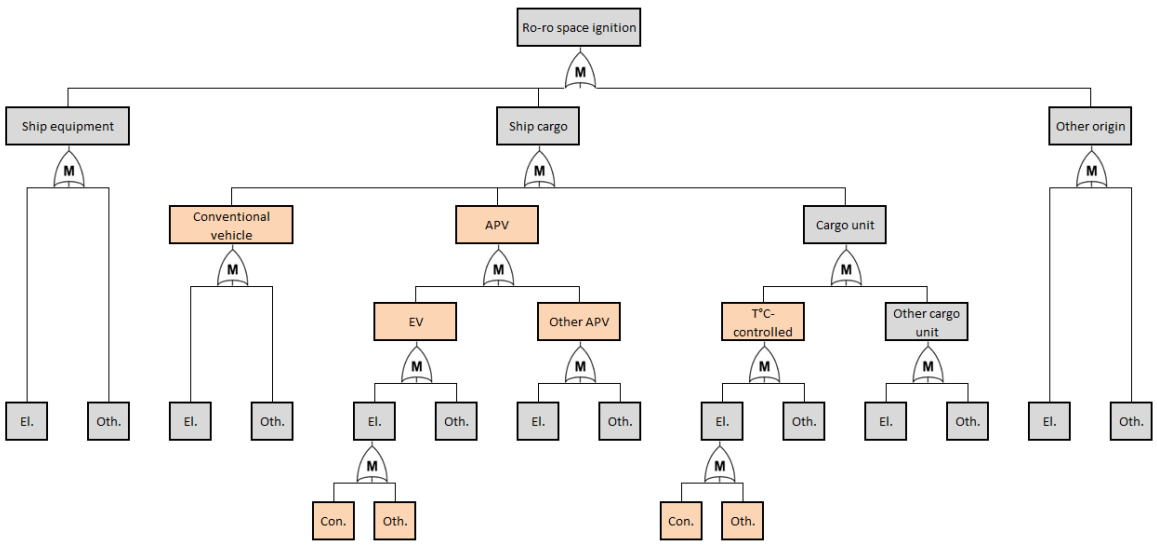


Figure 16. Contribution tree for ignition – Closed and open ro-ro spaces.

On ro-ro cargo ships, the charging service of electrical vehicle is deemed not allowed. This is the only difference between ro-ro passenger and ro-ro cargo ships that was considered.

On vehicles carriers, there is no temperature-controlled cargo unit nor electrical connection allowed.

6.2.3.2 Ignition – Weather decks

The ignition contribution trees for closed and open ro-ro spaces is presented in Figure 17.

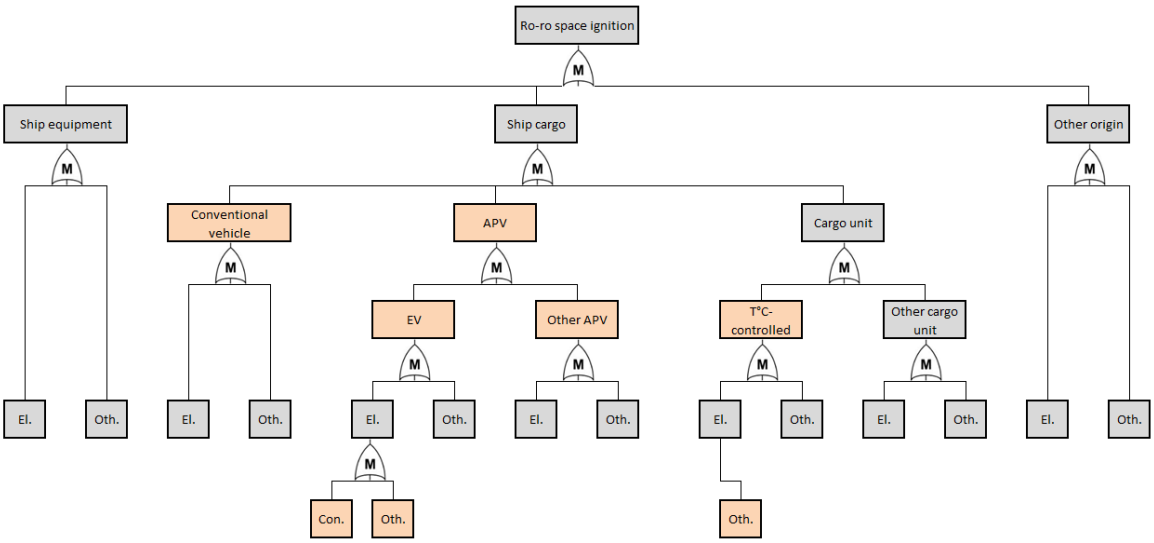


Figure 17. Contribution tree for ignition – Weather decks.

On weather decks, it is deemed that connection of temperature-control cargo unit to ship power supply is not a standard operational practice. They will rather run on diesel. This is the only difference between closed/open ro-ro spaces and weather decks that was considered.

The other consideration as regards as charging service in ro-ro cargo ships presented in the section above is still relevant for weather decks.

6.2.4 Detection

Very few nodes were added or changed since the FIRESAFE studies. They are highlighted in orange in Figure 18-Figure 21.

6.2.4.1 Detection – Closed and open ro-ro spaces

The *Manual deactivation* node was renamed as *Manual deactivation for operational purpose* (Figure 18).

Detection from passengers is mostly relevant for ro-ro passenger ships and not for ro-ro cargo ships nor vehicle carriers. Therefore, the *Crew/passenger detection failure* node was adapted for ro-ro cargo ships and vehicle carriers (*Crew detection failure* node in Figure 19).

Unlike ro-ro passenger and cargo ships, very limited direct view of deck from bridge is assumed for vehicle carriers (*Bridge detection failure* node in Figure 19).

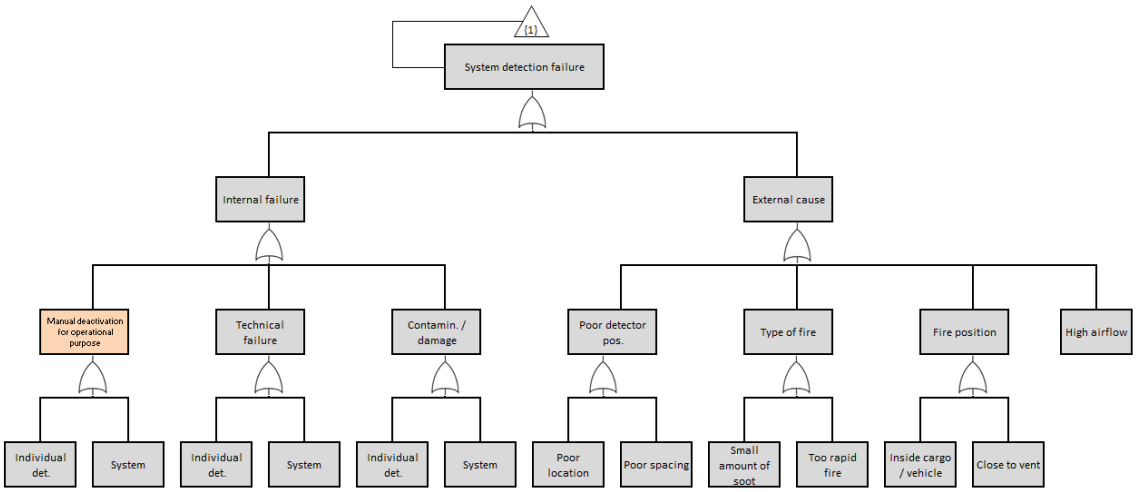


Figure 18. Sub-tree for "System detection failure" –Closed and open ro-ro spaces.

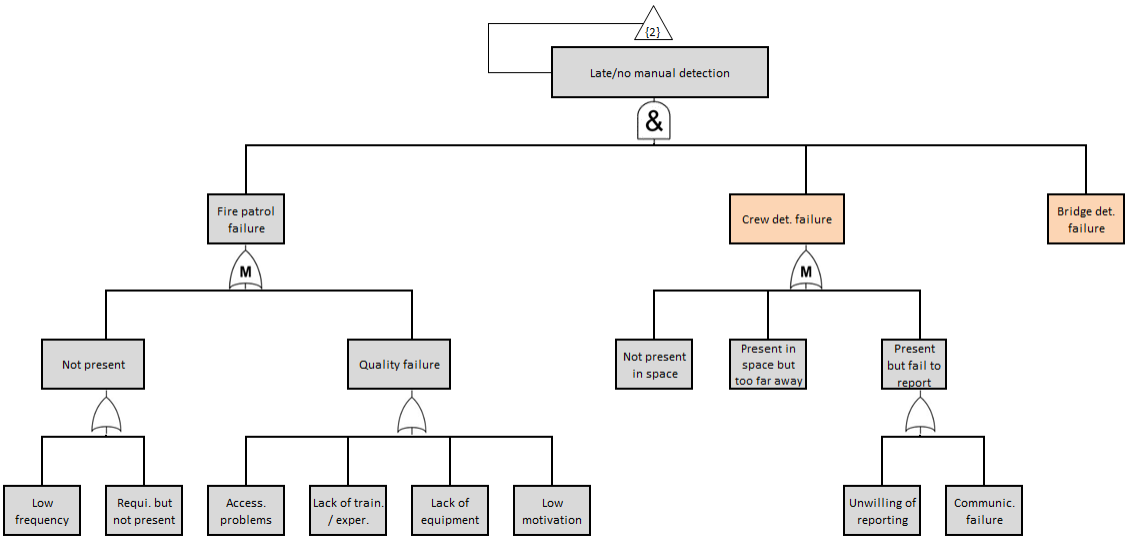


Figure 19. Sub-tree for "Late/no manual detection" – Closed and open ro-ro spaces.

6.2.4.2 Detection – Weather decks

No automatic detection system is required on weather decks. But as part the LASH FIRE project, automatic detection systems on weather decks will be investigated as RCM. In order to quantify their effectiveness, the *System detection failure* branch (Figure 20 and Figure 21) was added.

The detection systems on weather decks will consist of flame, infrared heat or linear thermal detection technologies. Their specific failure modes (in orange in Figure 21) are:

- *Smouldering fire (no flame)*: fires with no flame will be hard to be detected with those technologies of detectors.
- *Cargo between fire and detector*: the cargo may hide the fire seat from detectors and prevent an early detection.
- *Flame deflection*: the wind may deflect the flame from the area of coverage of detectors.
- *Cool down of fire seat*: the wind and rain may cool down the weather deck and slowdown the triggering of detection threshold.

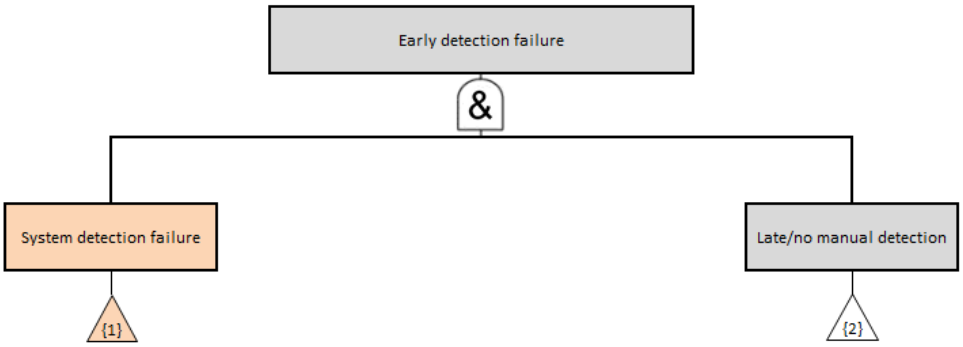


Figure 20. Detection fault tree –Weather decks.

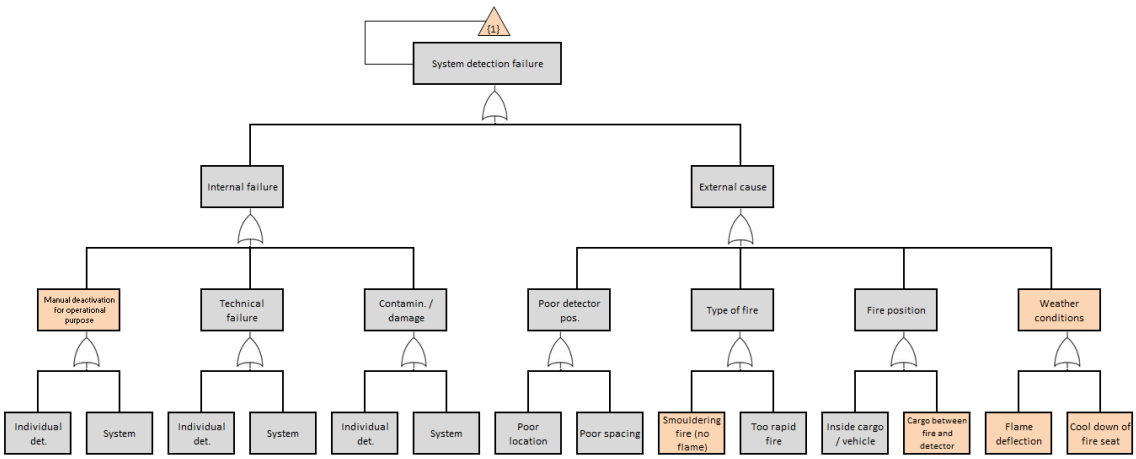


Figure 21. Sub-tree for "System detection failure" – Weather decks.

The other considerations presented in the section above are still relevant for weather decks.

6.2.5 First response

A simple fault tree (Figure 22) was developed to address the different failure modes related to the first response. First response shall be understood as the attempt from any crew member wearing standard seafarer clothes (not firefighter's outfits) to extinguish early fires with portable fire extinguisher or other means not specific to firefighter.

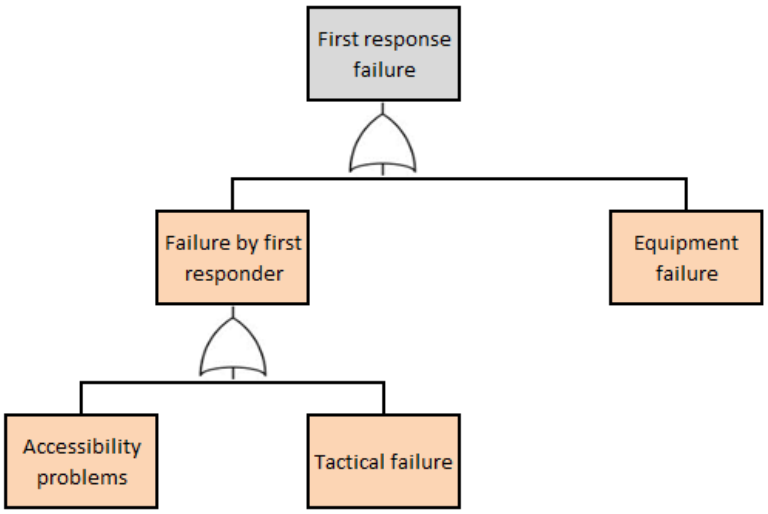


Figure 22. First response fault tree – Closed, open ro-ro spaces and weather decks.

The *Failure of first response* is first split between *Failure of the first responder* and *Failure of equipment.*

Failure of equipment: equipment used for first response and required in the regulations (mostly portable fire extinguisher) may be non-functioning, not at the right location or inadequate to tackle the fires at its early stage (e.g. APV fires).

The *Failure of first responder* is further split between *Accessibility problems* and *Tactical failure*.

Accessibility problems: one of the reasons to not carry out effectively the first response may be no access to the fire seat due to not enough space between cargo or fire seat located at the top, inside or below the cargo on fire.

Tactical failure: every seafarer must receive basic training or instruction in fire prevention and firefighting technics. But even with this basic training, crew member may not know exactly how to carry out the first response or prefer delaying the first response in case of "unusual" fire situations (e.g. APV fires). This failure mode also includes the fact that no crew member may be available to carry out the first response or notified early enough.

6.2.6 Decision

Main author of the chapter: Kujtim Ukaj, RISE.

The nodes, added or changed since the FIRESAFE studies, are highlighted in orange in Figure 23-Figure 27.

6.2.6.1 Decision – Closed and open ro-ro spaces

The *Late assessment* sub-tree for closed and open ro-ro spaces is presented in Figure 23.

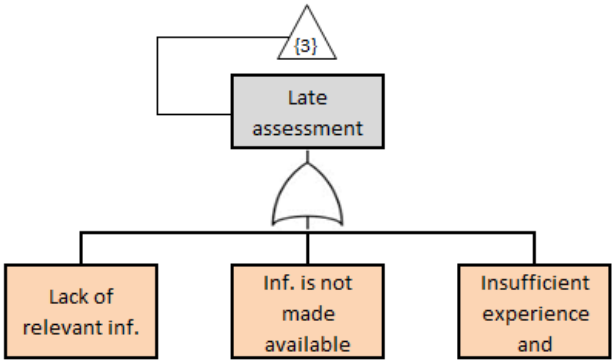


Figure 23. Sub-tree for "Late assessment" – Closed and open ro-ro spaces.

Based on initial information from the fire scene, the decision-maker on the bridge has to assess the situation and choose a response strategy, typically to activate a fixed extinguishing system, to order a manual firefighting operation or both. Data describes three sets of circumstances that might delay assessment.

Lack of relevant information:

According to experts, cargo information is not essential in order to make the decision about first response, but the presence of APV is one piece of information (seldom available) that may be relevant for this phase of decision-making. Another example of relevant information is the temperature at all detector locations.

Furthermore, in the management of a situation that extends over some time, it is of major importance that the crew can keep track of the development of the situation (for example in case of tactical activation). One aspect of this has to do with the way the alarm history is managed and made available. In many of currently available solutions, there is a risk that crucial temporal information gets lost.

Information is not made available readily:

Sometimes information is available, but delays may occur if the information is presented in an unintuitive way (user-hostile interfaces are not uncommon) and not made available readily. An assessment can be delayed if time has to be spent searching for information about vehicles and cargo around the fire scene, or if other crucial information is too demanding (due to for example a bad user interface) to look up in the heat of the moment.

Insufficient experience and competence:

In order to make a proper assessment, the necessary competence and experience has to be present. This may be less likely under certain circumstances, such as night-time operations when persons in command positions (working on daytime schedules) have gone to bed. The operational state may also affect the availability of key personnel for situation assessment, for example if the ship is in a position demanding the direct attention of the crew (e.g. narrow passages, large amounts of surrounding traffic, manoeuvring in harbours, other technical issues e.g. in the engine). In some cases, delays may also be caused by the distance to the bridge for relevant personnel.

All Officers and Masters have formal training in fire management, but according to informants, the way in which recurring exercises and drills are arranged and implemented varies greatly between shipping companies, and sometimes even between ships belonging to the same company. For example, the degree of realism in terms of situation complexity, interactions, communication, and context may affect the actual ability of the crew to make decisions under real-world conditions.

Late implementation was added under the top event (Figure 24) to take into account decision delays caused by for example hesitation to execute a response strategy (e.g. carrying out the actual activation of the drencher).

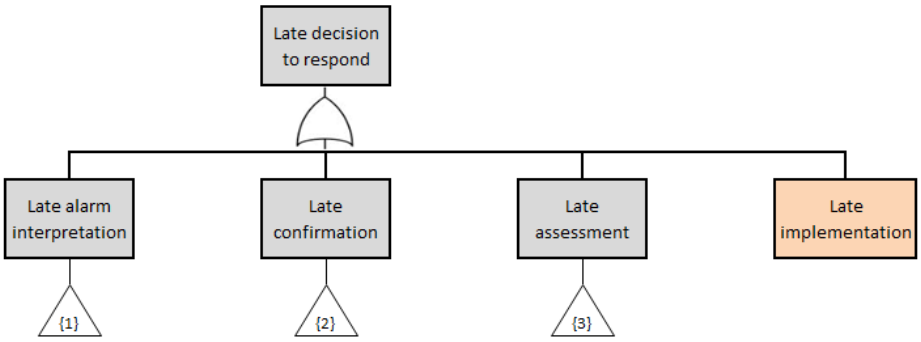


Figure 24. Decision fault tree – Closed and open ro-ro spaces.

6.2.6.2 Decision – Weather decks

No automatic detection system is required on weather decks. But as part the LASH FIRE project, automatic detection systems on weather decks will be investigated as RCM. In order to quantify their effectiveness, the *Late alarm detection* branch, the *Late technical confirmation* node and the *Late arrival at detector point* branch were added (Figure 25, Figure 26 and Figure 27).

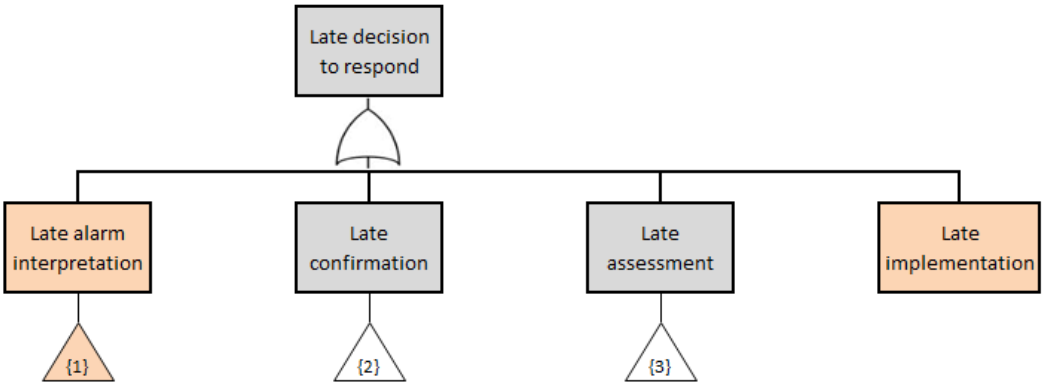


Figure 25. Decision fault tree – Weather decks.

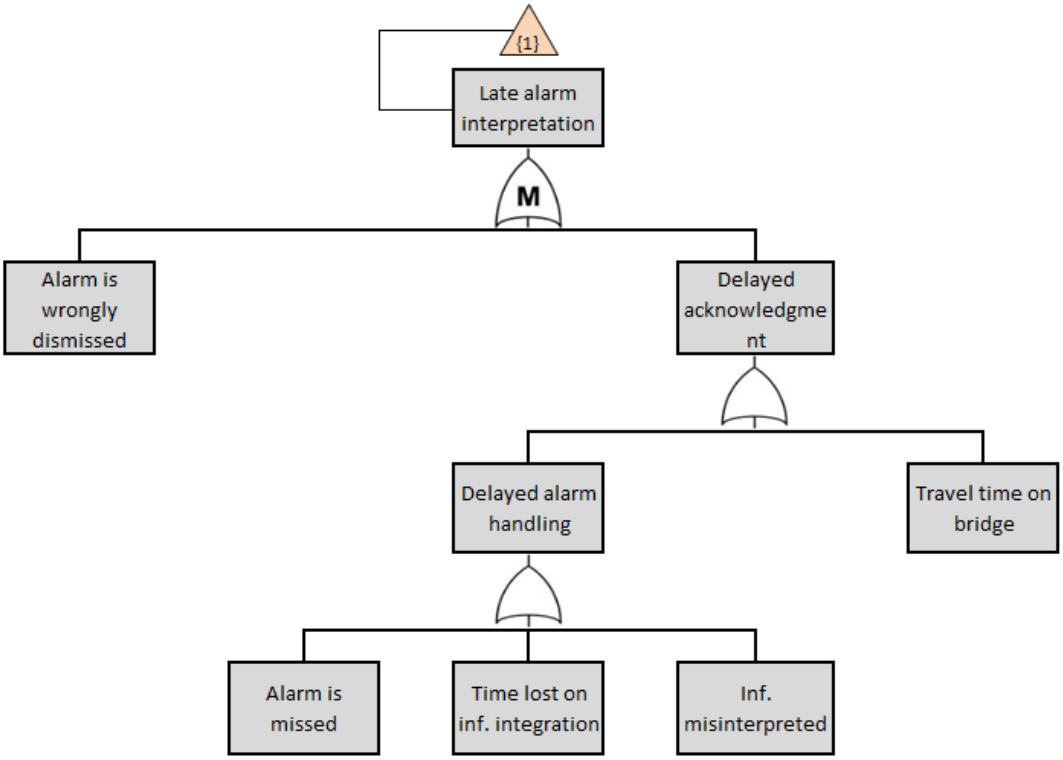


Figure 26. Sub-tree for "Late alarm interpretation" – Weather decks.

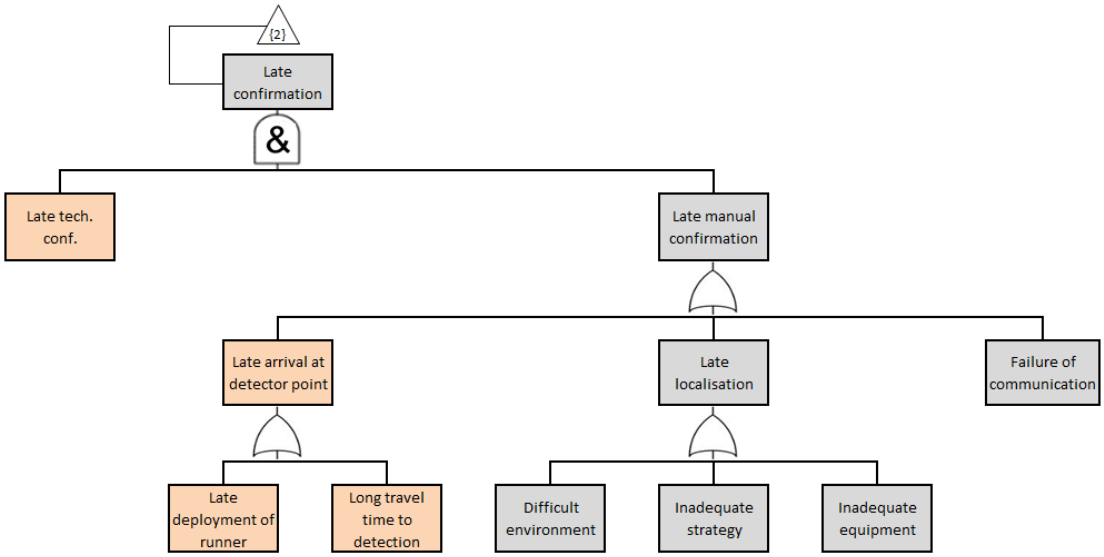


Figure 27. Sub-tree for "Late confirmation" – Weather decks.

The other considerations presented in the section above are still relevant for weather decks.

6.2.7 Extinguishment

Main author of the chapter: Kujtim Ukaj, RISE.

The nodes, added or changed since the FIRESAFE studies, are highlighted in orange in Figure 28 and Figure 29.

6.2.7.1 Extinguishment – Closed and open ro-ro spaces

In the FIRESAFE studies, a drencher system was used as starting point for the model since it was requested by EMSA to focus on this type of extinguishing system given their prevalence on ro-ro passenger ships. Within the LASH FIRE project, the scope was extended beyond ro-ro passenger ships, and the model has therefore been slightly modified (and generalised) to take into account other fixed systems. Therefore, the *Supply fail* branch was simplified (Figure 28).

Apart from fixed system failure, *Manual extinguishment failure* may also lead to extinguishment/suppression failure. The sub-tree for *Manual extinguishment failure* is almost the same as first response failure which is described in section 6.2.5. An additional node relating to *Lack of personnel* was however included under *Manual extinguishment failure* (Figure 28). This new node takes into account that firefighters take turns to fight the fire (air cylinders have a limited amount of oxygen), which requires some firefighters from the group to be on standby mode fully equipped while other group members are actively fighting the fire.

Another key difference is that *Manual extinguishment failure* relates to failure by the firefighting group (while fully equipped with the appropriate protective clothing and equipment) to extinguish a fire, whereas first response failure relates to failure by one or several crew members to put out the fire safely while wearing standard seafarer clothes. As the name implies, first response is carried out in the initial stages of the fire, in contrast to firefighting carried out by the firefighting group which normally occurs at a later stage when the fire has grown in size (provided that first response has not been successful). The main takeaway is that, apart from *Lack of personnel*, the reasons for failure are assumed to be the same in principle: *Accessibility problems*, *Tactical failure* and *Equipment failure* (keeping in mind that a first responder does for example not have access to the same equipment as a smoke diver) (Figure 28).

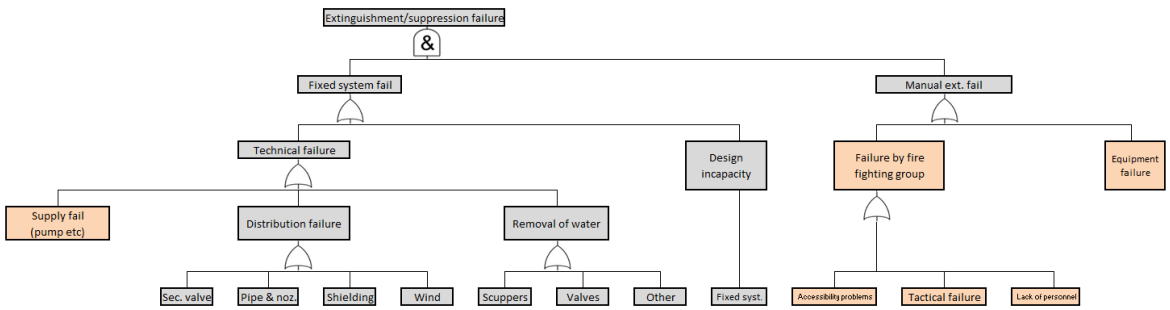


Figure 28. Extinguishment fault tree – Closed and open ro-ro spaces.

6.2.7.2 Extinguishment – Weather decks

No fixed fire-extinguishing system is required on weather decks. But as part the LASH FIRE project, fixed fire-extinguishing systems on weather decks will be investigated as RCM. In order to quantify their effectiveness, the *Fixed system fail* branch (Figure 29) was added.

The fixed fire-extinguishing systems on weather decks will consist of autonomous, semi-autonomous or manual fire monitor technologies. An additional failure mode under *Distribution failure* called *Transmission & logic* was added (Figure 29). This node takes into account fixed extinguishment systems that can fail due to signal deviations in for example closed feedback systems. Examples include remotely controlled fire monitors as well as autonomous fire monitors.

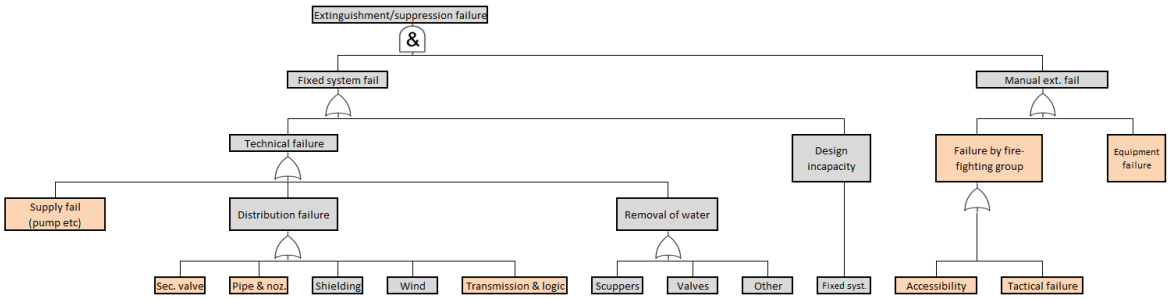


Figure 29. Extinguishment fault tree – Weather decks.

The other considerations presented in the section above are still relevant for weather decks.

6.2.8 Containment

Very few nodes were added or changed since the FIRESAFE studies. They are highlighted in orange in Figure 30 and Figure 31.

6.2.8.1 Containment – Closed and open ro-ro spaces

On vehicle carriers, end and side openings were deemed non-existing. Therefore, both flame and (external) smoke spread through openings were deemed not applicable.

Failure of active compartmentalisation was added under both *Heat spread* and *Internal smoke spread* (Figure 30 and Figure 31) in order to consider vertical segregation of closed and open ro-ro spaces as RCM and quantify its effectiveness. The systems investigated in the LASH FIRE project consisting of compartmentalisation internal to ro-ro spaces aim at preventing heat and smoke spread.

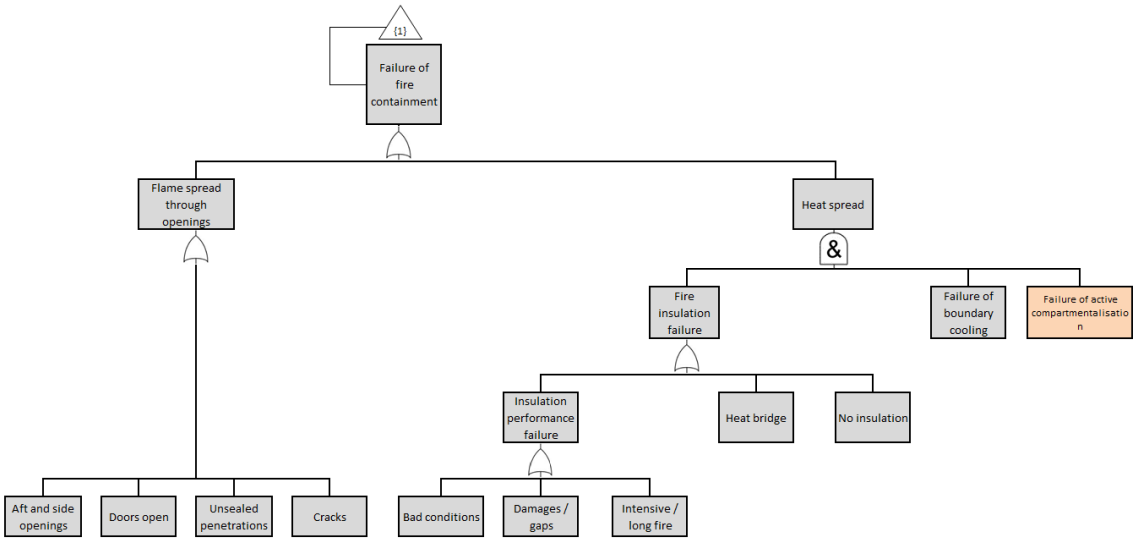


Figure 30. Sub-tree for "Failure of fire containment" – Closed and open ro-ro spaces.

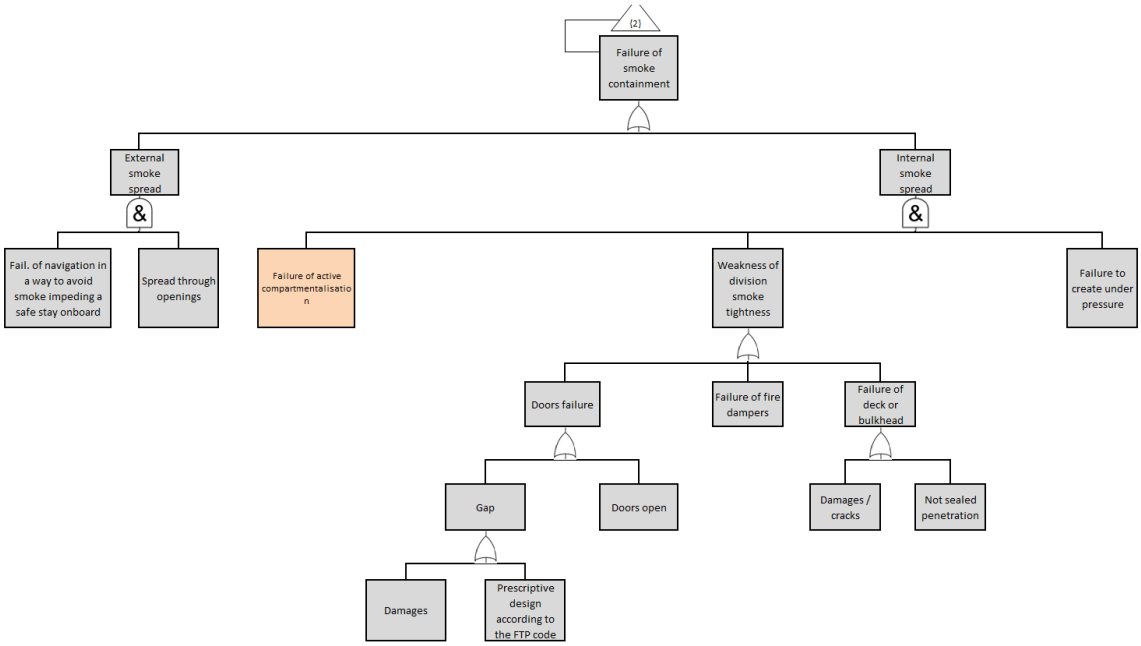


Figure 31. Sub-tree for "Failure of smoke containment" – Closed and open ro-ro spaces.

6.2.8.2 Containment – Weather decks

The containment fault tree for weather decks was not changed since the FIRESAFE studies.

6.2.9 Evacuation

Main author of the chapter: Sixten Dahlbom, RISE.

Evacuation is defined as unsuccessful when at least one of the LSAs, for any reason, is inaccessible/inoperable. The same definition as in FIRESAFE II is used. The LSAs considered are rigid life-rafts, lifeboats, and fire-protected lifeboats. The reason not to include LSAs as lifebuoys, lifejackets, immersion suits, etc. is that a failure of one of these is not expected to cause a large evacuation failure (with multiple loss of lives).

In the context of fire, an LSA is rendered inoperable when the radiative heat flux from flames causes it to deteriorate, e.g. melt or burn, or when conditions near the LSA are such that embarkation is associated with a high degree of danger, regardless of whether it is due to flames radiation or smoke.

NB! Heat transfer (through deck or bulkhead) due to fire is not considered as a potential reason for causing loss of an LSA, i.e. the structural fire integrity under evacuation routes and embarkation stations should be sufficiently thermally insulated, in line with SOLAS II-2/9.

6.2.9.1 Extension of the main event tree

In order to better describe evacuation, the tier "Not contained" (tier 5 in Figure 13) in the main event tree (cf. Figure 14 or Figure 15) was extended according to the left-hand side of Figure 32. The extended event tree corresponds to a structure reported by Vanem and Skjong [15]. Even though the focus of Vanem and Skjong was on ro-ro passenger ships (especially for the quantification part), it is assumed that the structure, as such, is valid for any type of ro-ro ship. The extended event tree covers evacuation both at sea and at shore.

In order to reduce size and complexity of the main event tree, the information from the extended even tree is reduced to only two tiers, i.e. "Success or No evac.[3]" and "Unsuccess" (right hand side of Figure 32). The quantification will be made for the extended even tree, the result will then be summarised, according to the colour coding in Figure 32, to the two tiers presented in the main event tree.

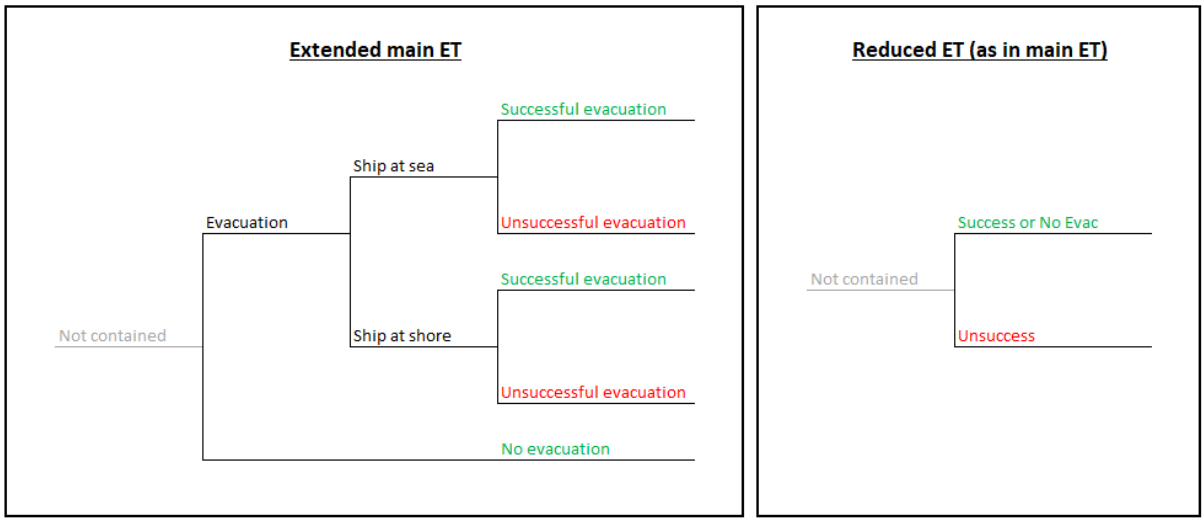


Figure 32. Left: Extension of the main even tree (according to a structure reported by Vanem and Skjong [15]); Right: Reduced number of tiers to facilitate interpretation of the main event tree. The three tiers in green to the left (extended) corresponds to the single tier in green to the right (reduced). The two tiers in red to the left (extended) corresponds to the single tier in red (reduced) to the right.

6.2.9.2 Development of fault trees

Fault trees were developed to cover:

- The ship types: ro-ro passenger ship, ro-ro cargo ship and vehicle carrier;
- The fire origins: open ro-ro space, closed ro-ro space and weather deck;
- The states: "at sea" and "at shore"; and
- The cases: "Suppression" and "No suppression" (corresponding to tier 4 in Figure 13).

This gives rise to several different fault trees; however, several of them are identical and differ only with respected to the quantification. Therefore, the number of structures can be reduced to three; namely, one for each type of ro-ro space (closed space, open space and weather deck).

The three structures are further described under respective heading below. The structures of the fault trees are independent on ship type and depends only on the type of ro-ro space.

6.2.9.2.1 Evacuation fault trees with ships at sea

The definition of "at sea" is all occasions not covered by "at shore" (cf. section 6.2.9.2.2).

Closed ro-ro spaces:

The fault tree that models unsuccessful evacuation at sea with a fire origin in a closed ro-ro space is presented in Figure 33-Figure 35 (in order to maintain readability, the fault tree was divided into

[3] No evac. stands for "no evacuation is needed", and as such, belongs to the success branch of the evacuation event.

three sub fault trees). The root causes for an unsuccessful evacuation can be divided into the four subgroups: *Routine failure*; *Technical failure of LSA*; *LSA inaccessible* and *LSA inoperable due to fire*.

A *Routine failure* could, as described in the fault tree (Figure 34), either be caused by *Failure of communication* or the *Human factor*. Examples of reasons for *Communication failures* are language barriers and failure of technical communication apparatus (e.g. wireless technology, as was the case during a fire on Mecklenburg-Vorpommern). Examples of reasons for *Human failure* could be stress or insufficient competence caused by inappropriate or (even total) lack of training.

A *Technical failure of an LSA* (Figure 33), e.g. intrinsic failure of an LSA is defined as any reason for an LSA to not work properly. This could be caused both by failure of hardware (rust, a loose contact, water leakage, leakage of hydraulic oil, etc.) or, if applicable, software (if e.g. any logic is needed to operate an LSA). In addition, rough weather could also contribute to *Technical failure of an LSA*.

The LSA may be inaccessible (Figure 34) if a fire (smoke, heat, soot, etc.) impacts the evacuation path; if the evacuation path is blocked (e.g. by debris as could be the case in heavy weather); or if the capacity of the evacuation path turns out to be insufficient (which could happen if any other evacuation path is unusable).

Fire impact (Figure 35) can either be impact on an LSA from flames or from smoke. Ways for an LSA to deteriorate could e.g. be if it melts or burns, or when conditions in the LSA's direct proximity are such that embarkation is associated with a high degree of danger (or being impossible), regardless of whether it is due to flames, heat radiation or smoke.

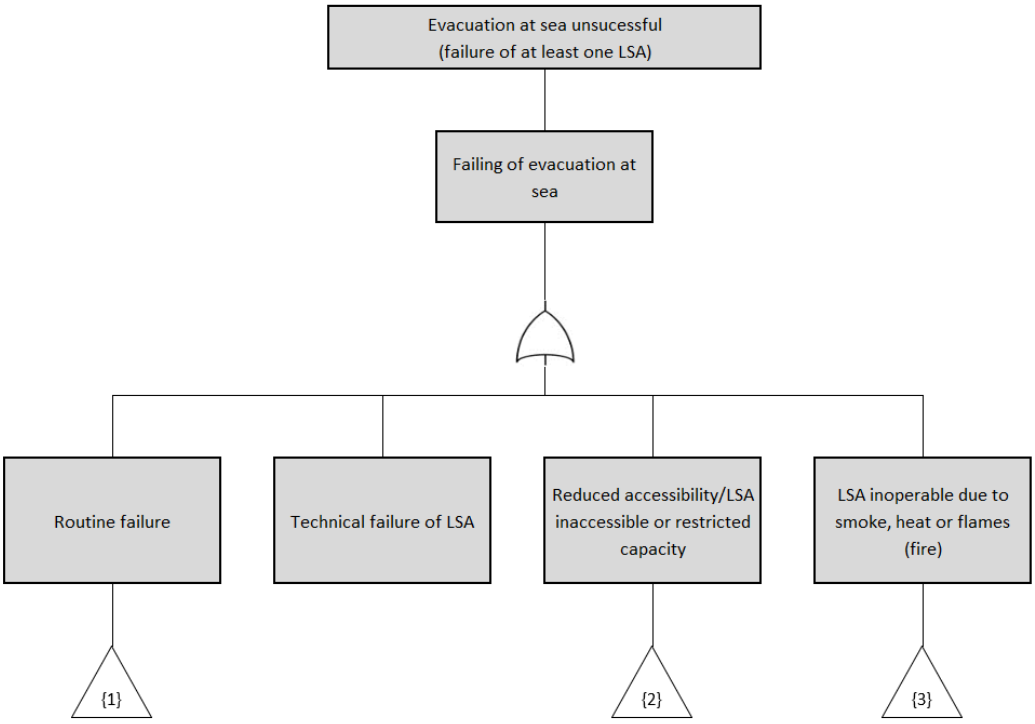


Figure 33. Evacuation at sea fault tree – Closed, open ro-ro spaces and weather decks.

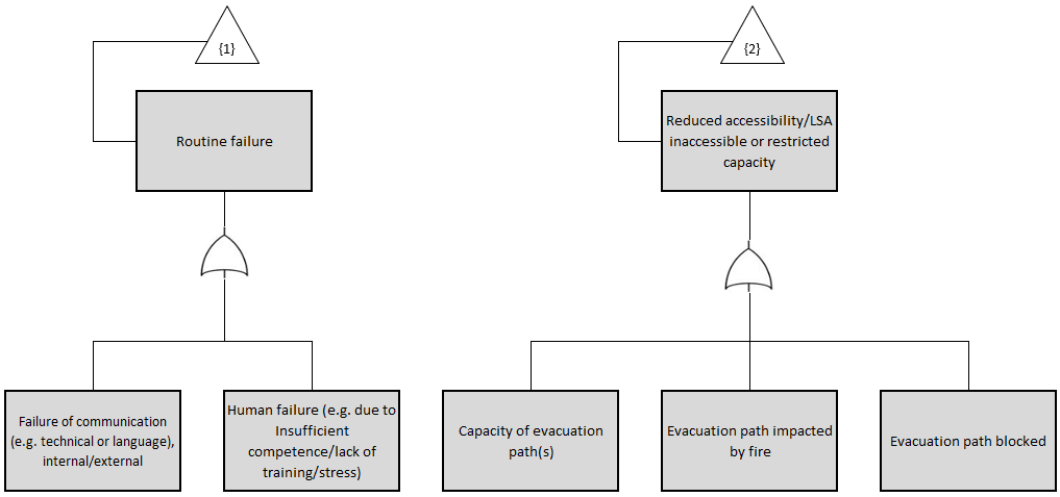


Figure 34. Sub-tree for "Routine failure" and "LSA inaccessible" – Closed, open ro-ro spaces and weather decks.

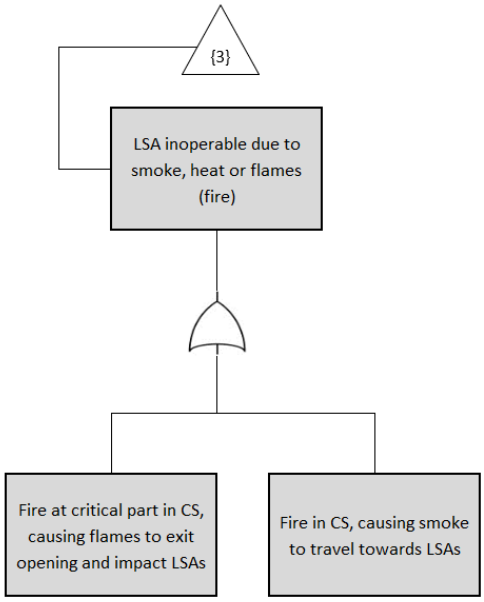


Figure 35. Sub-tree for "LSA inoperable due to fire" – Closed ro-ro spaces.

Open ro-ro spaces:

Open ro-ro spaces are notoriously vulnerable during fire due to the very nature of such spaces, i.e. the total opening area is relatively large and as a consequence the amount of oxygen available for a fire is practically unlimited. In addition to this, fires in open ro-ro spaces are particularly difficult to contain, causing uncontrolled flame and smoke spread, such as on the Norman Atlantic, Lisco Gloria, and Sorrento.

With regards to the subgroups *Routine failure*; *Technical failure of LSA* and *LSA inaccessible*, the open ro-ro space fault tree is identical to the closed ro-ro space fault tree – Refer to the previous section "Closed ro-ro spaces" and to Figure 33 and Figure 34 for a detailed description of these sub groups.

The subgroup *LSA inoperable due to fire* (cf. Figure 36) mentions three different zones, namely: zone A (partially critical zone), zone B (critical zone) and zone C (partial critical zone). A fire in zone B will

always render in an inoperable LSA. A fire in zone A or zone C may, depending on the wind direction have an impact on at least one of the LSAs. The zoning (A, B, C) is made as in the FIRESAFE II study [8]. To illustrate the zoning, the resulting zones (in FIRESAFE II) are presented in Figure 37.

If the fire is within a critical zone, it was assumed that evacuation failure will always occur due to flame spread through openings (It should be noted here that no consideration was given to conduction of heat through the structure, since the structural fire integrity under evacuation routes and embarkation stations should be sufficiently thermally insulated in line with SOLAS II-2/9). If a fire on the other hand occurs in a partially critical zone, the probability for evacuation failure was assumed to be contingent on the wind direction. If the wind direction is towards LSAs, evacuation failure will occur.

Successful suppression was not considered to affect the probability of evacuation failure for open ro-ro spaces, based on that:

- Fire in the critical zone will lead to flame spread to LSAs, and tactical activation of the drencher system in other areas will not impact whether LSAs are affected in the critical zone.
- Fire in partially critical zones will lead to evacuation failure in case of a wind direction towards LSAs, and tactical activation of the drencher system in the critical zone will not affect whether smoke impacts evacuation.

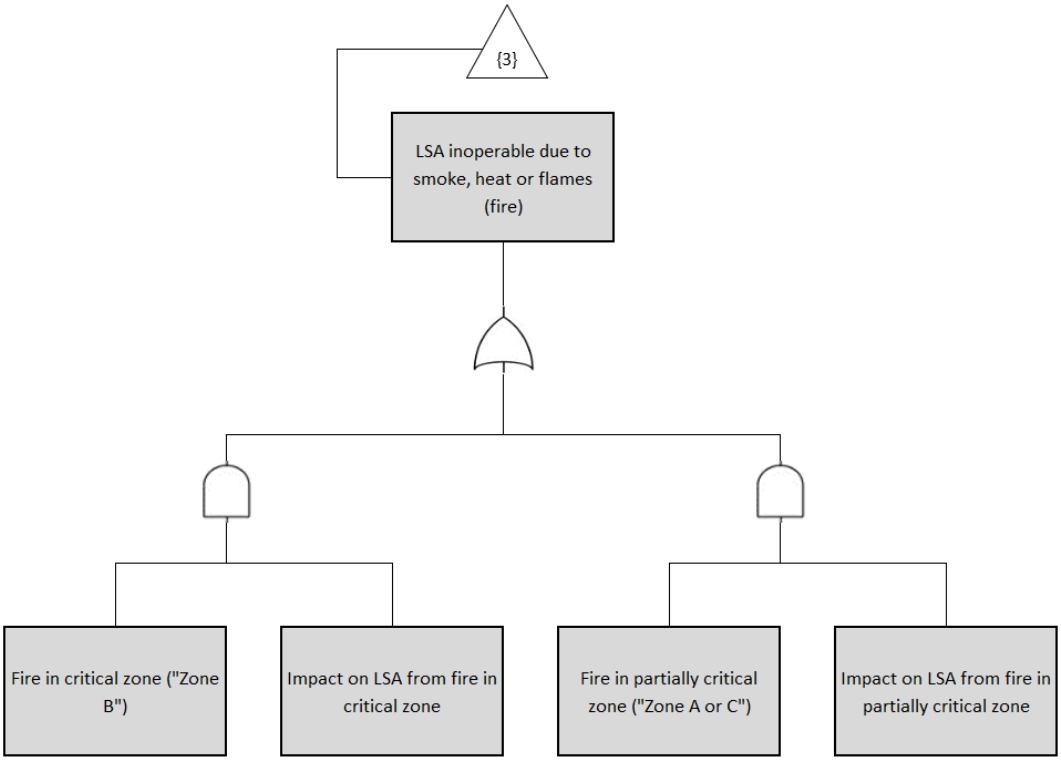


Figure 36. Sub-tree for "LSA inoperable due to fire – Open ro-ro spaces.

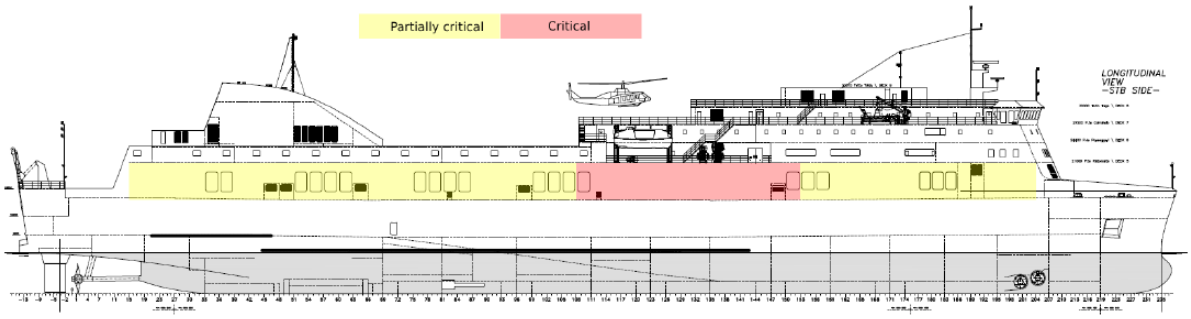


Figure 37. Partially critical and critical zones as in FIRESAFE II [8] (for illustrative purpose only).

Weather decks:

This fault tree is almost identical to the closed ro-ro space fault tree (Figure 33 to Figure 35), only the phrasing in some of the bottom nodes (cf. Figure 38) and, of course, quantification differ. Refer to the previous section "Closed ro-ro spaces" for a detailed explanation of the weather deck fault tree.

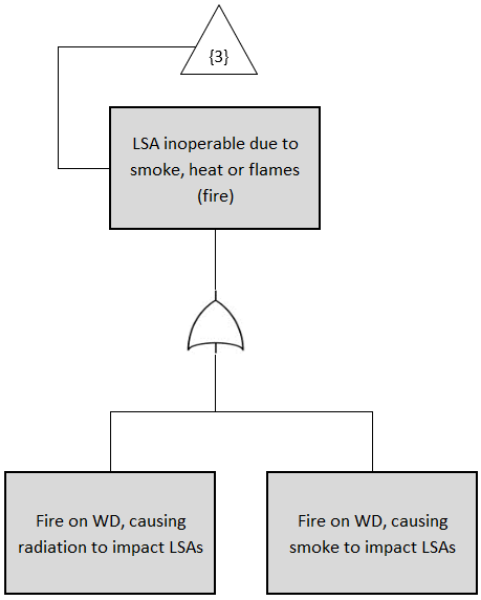


Figure 38. Sub-tree for "LSA inoperable due to fire – Weather decks.

6.2.9.2.2 Evacuation fault tree with ships at shore

At shore is defined as the ship being in a port or on a river, very close to land.

Since the focus of LASH FIRE is on onboard firefighting and onboard mitigation actions, and in order to ease the quantification, it was agreed to, on a detailed level, only quantify the fault tree with ships at sea. The probability of failure of evacuation with ships at shore will be quantified relative to the probability of failure of evacuation with ships at sea.

7 Quantification of the risk model

Main author of the chapter: Léon Lewandowski, BV.

This section focuses on the quantification of the risk model, i.e. the quantification of the frequency of the initial event, the subsequent probabilities leading to the fire scenarios and the consequences of the fire scenarios.

7.1 Quantification of the ignition frequency

The calculation of the ignition frequency is extensively elaborated in the LASH FIRE deliverable D04.2 [3]. Based on the outcome of D04.2 and the cargo capacities of the three generic ships, the frequencies of fire ignition in ro-ro spaces were estimated as provided in Table 6.

Table 6. Frequency of fires per type of ro-ro space for the three generic ships

Ship type	Space type	Fire frequency per ro-ro space (shipyear^{-1})	Total fire frequency (shipyear^{-1})
Ro-ro passenger ship (Stena Flavia)	Closed	3.54E-03	5.35E-03
	Open	1.59E-03	
	Weather	2.18E-04	
Ro-ro cargo ship (Magnolia Seaways)	Closed	1.52E-03	2.61E-03
	Open	4.94E-04	
	Weather	5.95E-04	
Vehicle carrier (Torrens)	Closed	2.13E-03	2.13E-03

Noted that a corrigendum of D04.2 is provided in ANNEX 3: Corrigendum D04.2 and that the details about the estimation of fire frequencies per type of ro-ro spaces for ro-ro cargo ships are provided in ANNEX 4: Frequency of fires in ro-ro spaces per ro-ro space type – Ro-ro cargo ships (not provided in D04.2, work carried out after D04.2).

7.2 Methodology for quantification of probabilities

In the following section, the different methodologies developed and used for the quantification of probabilities are summarised.

7.2.1 Statistical data

The first step during the quantification of the risk model was to extract historical data from the WP04 Casualty database (for more information about the WP04 Casualty database, please refer to the LASH FIRE deliverable D04.2 [3]), and additional details from other sources of information (e.g. accident investigation reports). The list of accident investigation reports is provided in ANNEX 5: List of accident investigation reports. In total, 59 incidents were investigated. From these cases, several pieces of information were gathered such as the course of the incident, if the decisions had been taken early enough, the problems that occurred, etc. The objective was not to use these results as is, but rather to compare them to future results (expert judgement for instance) to double-check their validity.

The main issue with historical data was the questionable relevance of some results when too few cases were available. An arbitrary criterion was decided to solve this problem: if the number of corresponding cases was above or equal to 9, the result was considered pertinent and could potentially be used. If the number of cases was less than 9, but equal to or above 5, the percentage found has been kept for informational purposes, with much more caution. If the number of cases was below 5, the percentage found was disregarded.

The historical probabilities are provided in ANNEX 10: Compilation of event trees probabilities.

7.2.2 Expert judgement

Main author of the chapter: Stina Andersson, RISE.

As explained before, to this date, the fire risk models developed in the FIRESAFE studies are the most comprehensive risk models addressing fire risk(s) in ro-ro spaces. Therefore, it was decided to use results from the FIRESAFE studies as far as practicable to quantify the risk model in LASH FIRE. When this was deemed irrelevant, and neither historical data nor simulations were available, expert judgement was used to quantify the bottom nodes of the risk model. The process of using expert judgement to quantify the risk model consisted of several steps. The steps are presented in Figure 39 and further elaborated below.

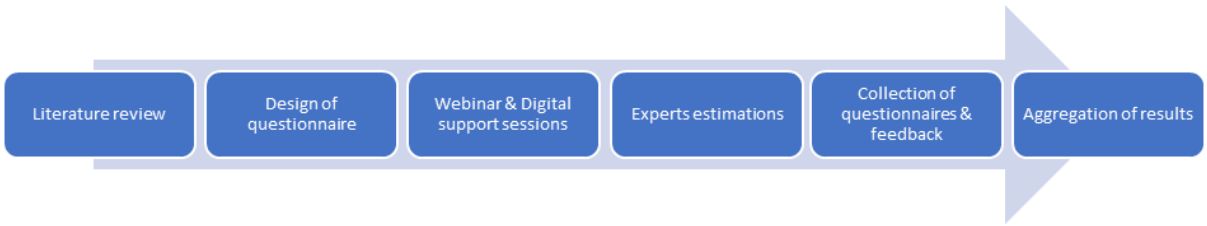


Figure 39. Overview of expert judgement process.

At the start of the process, a review of different methods for using expert judgement was made. Individual based approaches, group-based approaches and combinations of individual and group-based approaches were considered. A literature review of common heuristics and biases when using expert judgement was also made. A summary of the findings is presented in ANNEX 6: Literature review of heuristics and biases during expert judgement. Based on the review of different methods and the literature review of biases, it was decided to use an individual based approach by designing a questionnaire that each participating expert was asked to answer individually. Initially, the aim was

to use the so-called Delphi-method, an iterative method where the experts can update their estimate in several rounds [23]. However, due to limitations in time and feasibility, only one round of expert judgement process was carried out.

Effort was put into ensuring diversity amongst the participating experts. This was to minimise the effects of biases in the expert judgement process [24]. Invitation to participate in the expert judgement process was sent out through the LASH FIRE consortium to gather a group of experts for each type of ship, according to their domain of expertise. The composition of the experts is given in Figure 40.

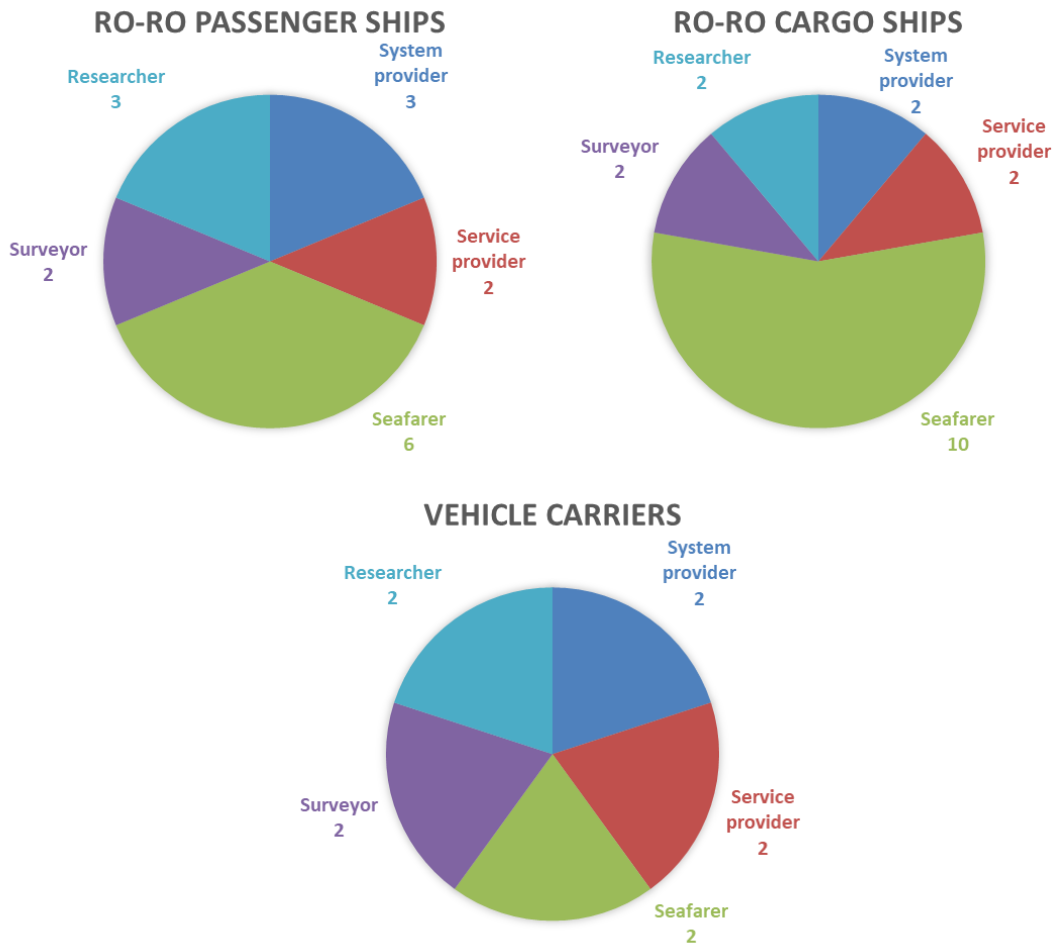


Figure 40. Expert categories repartition for the three ship types.

The questionnaire was designed using Microsoft Excel. Excel was chosen since it does not require an internet connection, which was brought up as an important aspect for seafarers, and to facilitate the handling of the returned data for WP04. To make the experts' task easier, and ensure good results, the questionnaire was developed to be as concrete as possible. For example, it has been shown that the estimates of conditional probabilities become more accurate when problems are described using "natural frequencies" (1 out of 100 observations) rather than "probabilities" (0.01 or 1%) [25]. Based on this, the questionnaire was designed to only include questions relating to observations of fires. That means that the questions asked were not "*what is the probability that the firefighting group cannot access the fire in an open ro-ro space?*", but rather "*there have been 100 fires in open ro-ro spaces. In how many of those incidents would you estimate that the firefighting group were unable*

to access the fire?". The questionnaire was complemented by an instruction document, explaining the background to the risk model and how to use the questionnaire. The questionnaire was sent out on a feedback round and amended before it was sent out to the experts. Part of the questionnaire template is presented in ANNEX 7: Questionnaire Template.

To further facilitate the experts' task of providing estimates for the quantification trough the questionnaire, a webinar was held on the 8th of June 2021 where all participating experts were invited. During the webinar the risk model and the questionnaire was explained by members of WP04, and the experts were free to ask question to clarify any point. The webinar was also recorded and made available to the experts. Several "digital support session" were held by WP04 during the weeks following the webinar, to help experts while they were filling out the questionnaire. The questionnaire was anonymous, and all experts were informed of the purpose of the questionnaire and how their estimates were to be used in the quantification. The ethics and personal data requirements set up by the LASH FIRE project were satisfied; among other, the informed consent of the participants was asked, the personnel data were limited to the strict necessity and were deleted after the post-processing of the questionnaires.

When the experts had filled in the questionnaires, the questionnaires were gathered by the facilitators (RISE & BV). The individual estimates were then aggregated by the facilitators by compiling all individual estimates and calculating the average value for each bottom node. Aggregating individual estimates draws upon the "wisdom of the crowd"-theory; by aggregating many estimates, you typically get more accurate results compared to most of the individual estimates [26] [27]. The average value from the expert estimations was then used as the probability in the risk model for the nodes where expert judgement was used.

7.3 Quantification of the probabilities – Application to LASH FIRE

In the following section, the application to LASH FIRE of above methodologies is summarised.

ANNEX 8: Tables showing quantification method for all fault trees is providing in details for each bottom nodes the methodology used for quantification.

The final values of the probabilities of the bottom nodes are provided in ANNEX 9: Probabilities of LASH FIRE risk model.

7.3.1 Ignition

Even though the structure of the ignition contribution tree was taken from FIRESAFE II with slight adjustments, all bottom nodes were re-evaluated in the light of the WP04 Casualty database.

The goal for the ignition contribution tree was to use as much historical data as possible. When there were not enough relevant historical events to draw a conclusion and compute a probability, assumptions had to be made (summarised in Table 7), all of which were approved by experts from WP05.

Most of the fires described in the accident reports occurred in closed ro-ro spaces and on ro-ro passenger ships. Hence, when historical data was not sufficient to evaluate the probability of a node, the assumptions made in most of the cases were based on closed ro-ro space(s) and/or to ro-ro passenger ships. For instance, some nodes of the “ro-ro cargo ships – open ro-ro space” were quantified by comparing them to their equivalent for “ro-ro cargo ships – closed ro-ro space” and other to “ro-ro passenger ships – open ro-ro space”.

Table 7. Assumptions taken for the quantification of the ignition fault tree

Assumption	Percentage	Source
Percent of EV amongst all boarded vehicles	2.0%	FSA: "Electric Mobility on RoRo/RoPax vessels" [28]
Percent of GPV amongst all vehicles on closed/open deck	2.6%	Inputs from ship operator
Percent of GPV amongst all vehicles on weather deck	2.6%	Inputs from ship operator
Percent of connected reefers in open deck	70%	Inputs from ship operator
Percent of connected reefers in weather deck amongst all reefers	0%	No connected reefers on WD (they will run on diesel)
Percent of connected EV on ro-ro cargo ships amongst all EV	0%	No connected EV on ro-ro cargo ships (no charging service)
Percent of ignition due to connection for EV	75%	FSA: "Electric Mobility on RoRo/RoPax vessels" [28]
Percent of electrical ignition for other APV	same as CV	No data
Percent of electrical ignition for EV	90%	Historical data
Percent of electrical ignitions due to connection for reefers (Closed)	90%	Historical data
Percent of electrical ignition for CV on ro-ro cargo ships	same as ro-ro passenger ships	No data
Percent of electrical ignition for reefers on ro-ro cargo ships	same as ro-ro passenger ships	No data
Percent of electrical ignition for other cargo units on ro-ro cargo ships	same as ro-ro passenger ships	No data
Percent of electrical ignition for CV on vehicle carriers	90%	Historical data
Percent of electrical ignition for cargo unit on vehicle carriers	same as ro-ro passenger ships	No data

APV = Alternatively Powered Vehicle, CV = Conventional Vehicle, EV = Electric Vehicle, GPV = Gas-Powered Vehicle.

7.3.2 Detection

Since there are no changes in the detection fault tree since the FIRESAFE studies for closed and open ro-ro spaces, the detection fault tree for ro-ro passenger ships was quantified with values for the *standard ro-ro passenger ship* from FIRESAFE II. The quantification of the detection fault tree for ro-ro passenger ships are explained in the FIRESAFE II reporting [7] and will not be elaborated further here. The only node that was re-quantified during LASH FIRE was “Fire patrol failure/…/Low frequency”. The quantification of this node is described below.

The node “Fire patrol failure/…/Low frequency” was quantified to 70% in FIRESAFE II (for ro-ro passenger ships), based on probability calculations. These calculations were performed again in LASH FIRE, based on the following assumptions:

- If the fire patrol passes during the incipient phase of a fire, the fire will be detected by the fire patrol;
- Safe manual first response is possible during the incipient phase of a fire;
- The incipient phase of a vehicle fire lasts between 0 and 60 minutes, uniformly distributed; and

- The frequency of fire patrol was set to once every hour for ro-ro passenger ships, one every two hours for ro-ro cargo ships, and one every five hours for vehicle carriers.

The above stated assumption allows calculation of the probability of early detection failure for the three types of ro-ro ships. The probabilities of early detection failure by fire patrol are summarised in Table 8.

Table 8. Probability of early detection failure by fire patrol (due to low frequency) for the different types of ro-ro ships

Type of ship	Fire patrol frequency	P(Early detection failure by fire patrol)
Ro-ro passenger ship	1h	50%
Ro-Ro cargo ship	2h	75%
Vehicle Carrier	5h	90%

For ro-ro cargo ships, all nodes below “manual detection failure”, except “bridge detection failure”, were quantified by expert judgement. Due to the lower number of personnel on board ro-ro cargo ships and the different regulatory requirements compared to ro-ro passenger ships, the nodes below “manual detection failure” could not be based on values from FIRESAFE II and were therefore quantified using expert judgement. Indeed, the expert judgement yielded higher probabilities for “manual detection failure” for ro-ro cargo ships (61.4% for closed ro-ro spaces and 60.7% for open ro-ro spaces) compared to ro-ro passenger ships (37.7%, both for closed and open ro-ro spaces). For the “system detection failure” part of the fault tree, the only nodes where the difference between ro-ro cargo ships and ro-ro passenger ships were deemed too great to use values from FIRESAFE II were for the following two nodes:

- System detection failure \ Internal failure \ Manual deactivation for operational purpose \ Individual detector; and
- System detection failure \ Internal failure \ Manual deactivation for operational purpose \ System.

These two nodes were therefore quantified by expert judgement. The rest of the nodes under “system detection failure” were quantified using the values from FIRESAFE II.

For vehicle carriers, apart from a few exceptions, all nodes were quantified by expert judgement. The exceptions are:

- System detection failure \ External cause \ Type of fire \ Small amount of soot;
- System detection failure \ External cause \ Type of fire \ Too rapid fire; and
- System detection failure \ External cause \ Fire position \ Close to vent.

These three probabilities were quantified using the FIRESAFE II values, because it was assumed that the difference between ro-ro passenger ships and vehicle carrier had a negligible impact on them.

7.3.3 First response

Since the “First response failure” fault tree was developed in LASH FIRE, there were no values to be used from the FIRESAFE studies. All nodes in the “First response failure” fault trees for all three types of ro-ro ships were quantified using expert judgement.

Following an early detection:

The frequency of failed first response greatly differs between FIRESAFE II, expert judgement and historical data. This is because of two reasons:

- Strictly speaking, FIRESAFE II did not quantify first response failure. It quantified the "manual firefighting failure" (with a probability of 49%) then equally split this result into "Firefighting group failure" (70%) and "First response failure" (also 70%); and
- Historical data frequencies from databases are not reliable when it comes to first response, because of an under-reporting of successful first response (if the first response is successful, then the consequences of the fire are less serious, hence, the fire is less likely to be reported).

Operators incident data from the LASH FIRE's Maritime Operators Advisory Group (MOAG) were gathered and analysed. The result from this is very close to the results based on expert judgement (displayed in Table 9). It was thus decided to keep expert judgement to quantify the risk model.

Table 9. Comparison between MOAG dataset and LASH FIRE expert judgement for the "successful first response" frequency

	MOAG dataset	**LASH FIRE expert judgement**
P(Successful first response)	64%	From 59% to 67%

Following a late detection:

By definition of "late detection", a safe manual first response is not possible. Therefore, in case of late detection, the probability of failure for first response was set to 100% for all three types of ro-ro ships.

7.3.4 Decision

The top node "late decision" is split into four sub-nodes: "Late alarm interpretation"; "Late confirmation"; "Late assessment" and "Late implementation". This last sub-node was not present in the FIRESAFE II risk model. Hence, it was quantified by expert judgement.

For ro-ro passenger ships and ro-ro cargo ships:

- "Late alarm interpretation" and "Late confirmation" were quantified using FIRESAFE II values (*standard ro-ro passenger ship* for ro-ro passenger ships and *cargo ro-ro passenger ship* for ro-ro cargo ships); and
- The nodes in the "late assessment" category, however, were redefined in LASH FIRE. They were quantified via expert judgement.

For vehicle carriers, all nodes were quantified by expert judgement.

7.3.5 Extinguishment

The "extinguishment failure" node was subdivided into "Fixed system failure" and "Manual failure". All of "Fixed system failure" sub nodes were quantified with FIRESAFE II values, except for vehicle carriers, where they all were quantified by expert judgement.

For "Manual failure", it was necessary to consider two cases:

Following an early decision:

In FIRESAFE II, the probability for “Manual failure” was arbitrarily set to 70%, as explained in the paragraph 7.3.3. In the LASH FIRE risk model, this node now has four sub-nodes, all were quantified by expert judgement.

Following a late decision:

In FIRESAFE II, the probability for “Manual failure” was set to 100% for closed ro-ro spaces and open ro-ro spaces, and 90% for weather decks (because weather decks do not have any fixed extinguishing system, the 90% instead of 100% was to avoid having an inevitable extinguishment failure). The value quantified by experts was smaller, around 60%-80%. This was considered too small with regard to the definition of late decision (cf. section 4.2.5) and to the estimation from FIRESAFE, and in order to raise it, it was decided to scale all bottom nodes under “Manual failure” for each type of ship and each type of space to get a manual failure at 90%.

7.3.6 Containment

As for the previous tiers, as much as possible of the FIRESAFE II values were used for the quantification of the containment tier for all three types of ro-ro ships.

For the ro-ro passenger ships, all nodes of the containment fault trees were quantified using the FIRESAFE II values.

For ro-ro cargo ships and vehicle carriers, the nodes were quantified with values from FIRESAFE II where there was deemed to be no or negligible difference compared to ro-ro passenger ships. However, there were several nodes were the values from FIRESAFE II were deemed irrelevant. For example, a few nodes under the “Failure of containment” fault tree were quantified by using ship specific parameters in FIRESAFE II in such a way that the values could not be used for other types of ships than ro-ro passenger ships. These nodes were quantified using expert judgement for ro-ro cargo ships and vehicle carries.

For ro-ro cargo ships, approximately half of the bottom nodes were quantified using FIRESAFE II values. For vehicle carriers, only a few nodes were quantified using FIRESAFE II values. Otherwise, expert judgement was used.

7.3.7 Evacuation

Main author of the chapter: Sixten Dahlbom, RISE.

Failure of evacuation was split into two fault trees, one for evacuation failure at sea and one for evacuation failure at shore. Failure at shore was quantified by asking experts to estimate the ratio of failure at shore to failure at sea. Hence, rather than quantifying the bottom nodes of the fault tree for evacuation at shore, the top event was quantified directly by using expert judgement.

Quantification of failure at sea was made by using both expert judgement (routine failure, technical failure and reduced accessibility) and calculations (LSA inoperable due to smoke, heat or flames). The calculations were made in a way similar to the FIRESAFE II study [8], but with ship specific parameters updated to match the three generic ships). The main assumption made during the quantification phase was that fires in closed ro-ro spaces have no impact on LSAs, i.e. due to arrangements of the generic ships and it was also assumed that smoke exiting through ventilation ducts would not impact any of the LSAs.

Finally, the probabilities of ship at sea vs. ship at shore, given an evacuation, were estimated through statistics about location (at sea or close to shore/at shore) of ro-ro ships when the fire starts. The assumption that was made is that if the ship is at shore or close to shore then the evacuation will be at shore, otherwise at sea.

7.3.8 Level of agreement between experts

For each tier presented above (from detection to evacuation), an "agreement score" between experts was calculated, to get an idea of how much controversial each tier amongst them is. A method to compute this score is given by the IMO in its FSA guidelines [1]. Unfortunately, this method is only useful when experts are asked to make rankings, not when they have to assign a value to parameters.

Hence, another method had to be used, and Krippendorff's Alpha was chosen. The point of this method is to use the observed percentage of matches, to compute the percentage obtained if the experts had answered randomly, and then to deduce the percentage of matches based on a true agreement and not by chance [29]. It can be summarised this way (with O the event "*a match is observed*", and C the event "*a match is obtained by chance*"):

$$\alpha = \frac{P(O) - P(C)}{1 - P(C)}$$

This coefficient gives a reliability of the percentage calculated, explained in Table 10.

Table 10. Agreement amongst experts for different values of α

$\boldsymbol{\alpha = 1}$	Total agreement amongst experts
$\boldsymbol{\alpha = 0}$	No agreement amongst experts apart from what could be expected by chance
$\boldsymbol{\alpha < 0}$	Strong disagreement: even a random distribution would have given a better score

One has to be careful though, as α does not tell anything about the validity of a result, but only about its reliability. This idea is summarised in the Figure 41 [29].

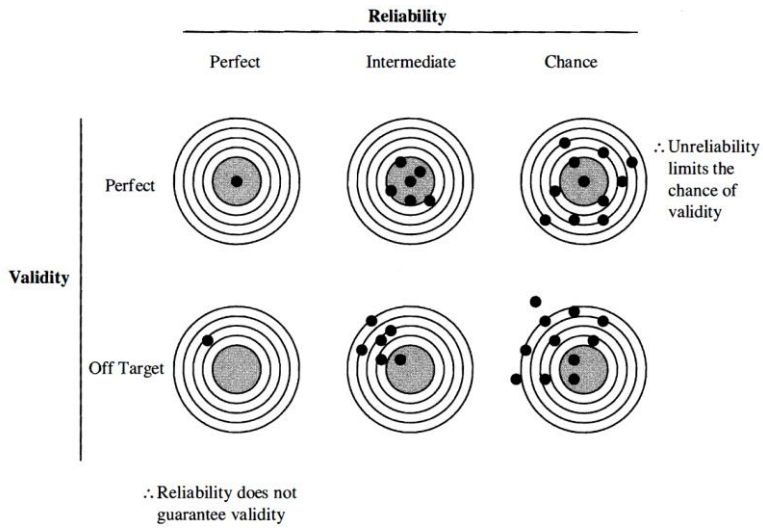


Figure 41. Relationship between validity and reliability [29].

The agreement scores obtained for the different types of ro-ro ships are presented in Table 11, Table 12 and Table 13.

Table 11. Agreement scores amongst experts for the different tiers, for ro-ro passenger ships

Node	Score
Detection CO	0.751
1st Response CO	0.535
1st Response W	0.578
Decision CO-Early detection	0.398
Decision CO-Late detection	0.121
Decision W-Early detection	0.420
Decision W-Late detection	0.185
Extinguishment CO-Early decision	0.293
Extinguishment CO-Late decision	0.220
Extinguishment W-Early decision	0.344
Extinguishment W-Late decision	0.305
Containment C-Successful suppression	0.600
Containment C-Unsuccessful suppression	-0.133
Containment O-Successful suppression	0.658
Containment O-Unsuccessful suppression	-0.203
C: Closed ro-ro space; O: Open ro-ro space; W: Weather deck	

Table 12. Agreement scores amongst experts for the different tiers, for ro-ro cargo ships

Node	Score
Detection C	0.628
Detection O	0.667
Detection W	0.693
1st Response CO	0.535
1st Response W	0.578
Decision CO-Early detection	0.135
Decision CO-Late detection	0.094
Decision W-Early detection	0.159
Decision W-Late detection	0.117
Extinguishment CO-Early decision	-0.028
Extinguishment CO-Late decision	-0.032
Extinguishment W-Early decision	0.024
Extinguishment W-Late decision	-0.005
Containment C-Successful suppression	0.746
Containment C-Unsuccessful suppression	0.348
Containment O-Successful suppression	0.329
Containment O-Unsuccessful suppression	0.279
Containment W-Successful suppression	0.362
Containment W-Unsuccessful suppression	0.500
C: Closed ro-ro space; O: Open ro-ro space; W: Weather deck	

Table 13. Agreement scores amongst experts for the different tiers, for vehicle carriers

Node	Score
Detection C	0.837
1st Response CO	0.352
Decision C-Early detection	0.821
Decision C-Late detection	0.754
Extinguishment C-Early decision	0.600
Extinguishment C-Late decision	0.184
Containment C-Successful suppression	0.882
Containment C-Unsuccessful suppression	0.626
C: Closed ro-ro space; O: Open ro-ro space; W: Weather deck	

7.3.9 Verification of quantification

The complete quantification of the event trees is available in ANNEX 10: Compilation of event trees probabilities. In this annex the final probabilities computed at event trees level for the LASH FIRE model, the probabilities estimated through historical data and the probabilities from the FIRESAFE II model are summarised for verification. The most important differences between LASH FIRE quantification and FIRESAFE II quantification have been explained in the previous sections. The major disparities between the different types of ro-ro spaces and different types of ro-ro ships have been spotted and the authors have verified that these differences are legitimate.

7.4 Quantification of the consequences

Main author of the chapter: Eric De Carvalho, BV.

This section focuses on the quantification of the consequences (impact on human, cargo and ship) as outcomes of the risk model.

7.4.1 Development of fire scenarios

For the risk model, "fire scenarios" shall be understood as the end branches of the main event trees (Figure 14 and Figure 15). As it is recognised that it is generally not possible to estimate all the potential outcomes of a risk model, it was decided to categorise the different end branches in a limited number of generic fire scenarios, starting from the work performed in the FIRESAFE studies [6]. The different end branches were grouped, based on their expected consequences. Therefore, six different generic fire scenarios were defined (Table 14 and Figure 42).

Table 14. Definition of the six generic fire scenarios

ID	Scenario	General Narrative	Fatality Narrative	Cargo Damage Narrative	Ship Damage Narrative
A1	Small fire	Fires extinguished by portable extinguisher	No fatalities, no injuries	Damage to 1 vehicle 50% (no damage to goods)	No damage to vessel but sanitation needed No off-hire
A2	Small fire	Fires extinguished by firefighting	No fatalities, no injuries	Damage to 1 vehicle 100% (damage to goods)	Minor damage: Damage to ceiling No off-hire
B	Medium fire	Fires suppressed and contained	No fatalities, no injuries	If drencher system: Damage to 1 vehicle 100% + 4 vehicles 50% If CO_2 system: Damage to 13 vehicles 100% + 12 vehicles 50%	Non-severe damage: Damage to ceiling, structure and equipment Off-hire several days
C	Fire to one deck	Fires not suppressed but contained	No fatalities, no injuries	Damage to cargo of 1 entire deck + 50% above deck	Severe damage: Damage to 1 entire deck Off-hire several weeks
D1	Total loss	Fires not contained and evacuation success	Single fatality or multiple severe injuries	100% loss of cargo	Total loss: 100% loss of ship value
D2	Total loss	Fires not contained and evacuation unsuccessful	Multiple fatalities	100% loss of cargo	Total loss: 100% loss of ship value

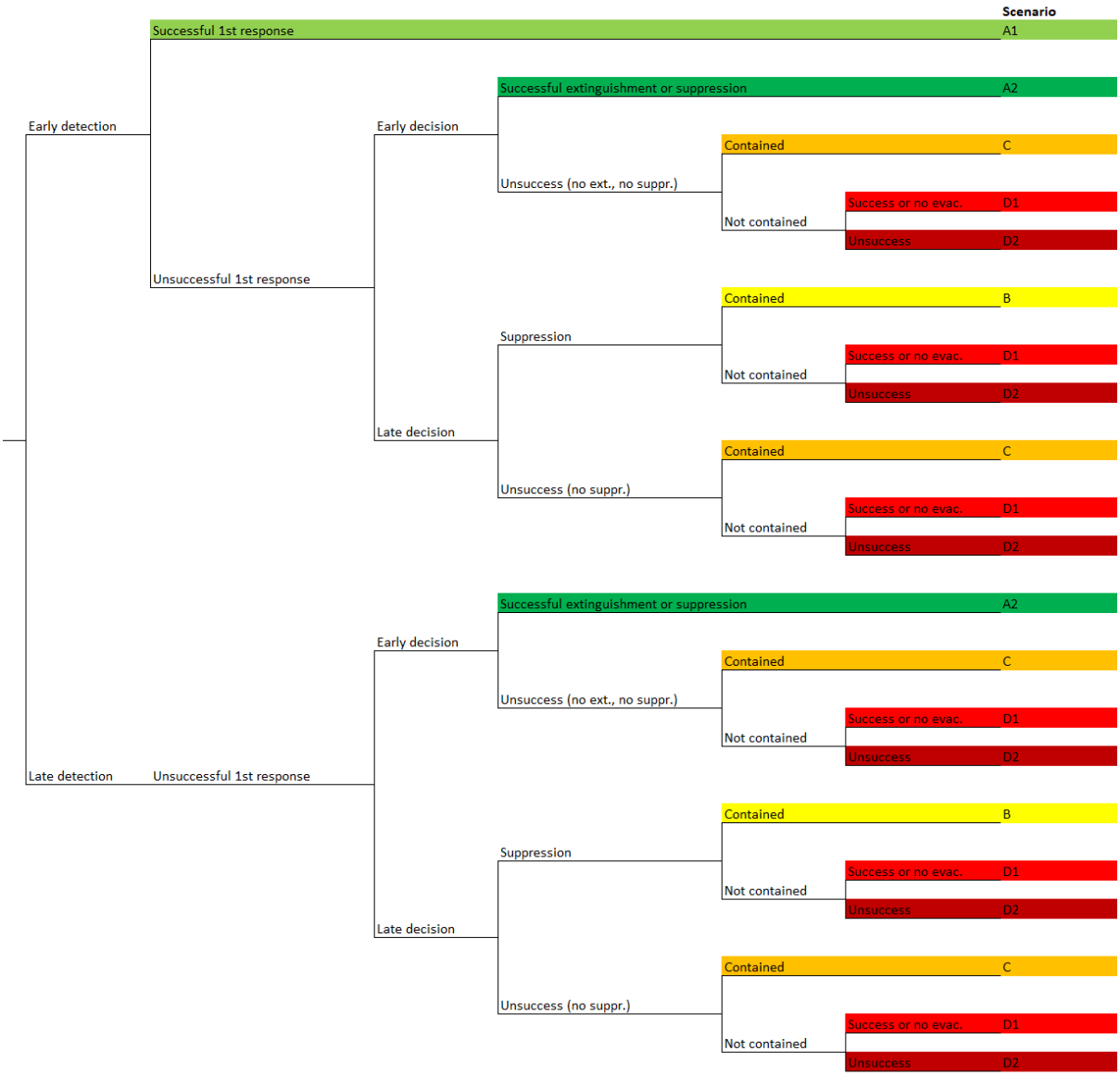


Figure 42. Fire scenarios assigned in the main event tree.

As in the FIRESAFE studies, fatalities are only considered when the fire and smoke spread out of the ro-ro space and impede safe stay on board.

Unlike FIRESAFE, the small fires were split regarding the means of extinguishment (scenario A1 and A2). It was deemed that the fire size and so the level of cargo and ship damage will not be the same in case the fire is successfully extinguished by portable extinguisher(s) or by the fixed fire-extinguishing system.

The damage to cargo caused by the medium fires (scenario B) were deemed dependent on the type of fixed fire-extinguishing system used in ro-ro spaces. Different activation times can be expected for drencher systems and CO_2 systems. Therefore, the extend of the fire will not be the same at activation time. The extent of the damage in terms of number of vehicles was based on the results of the fire and smoke spread simulations run for the WP04. The details about the simulations and the summary of the results can be found in LASH FIRE deliverable D04.3 [30]. ANNEX 11: Swift detection also provides an analysis of the fire and smoke spread simulations.

7.4.2 Consequences

The below average values and orders of magnitude for consequences and costs were deemed sufficient to feed the risk model.

7.4.2.1 Fatality

When the evacuation is successful (scenario D1), a 1 equivalent fatality fixed value was assigned for ro-ro passenger ships to take into account the frequent injuries and possible indirect fatalities following such evacuation (as in the FIRESAFE studies).

When the evacuation is unsuccessful (scenario D2), 5% of Persons on Board (POB) was considered relevant as fatality rate for ro-ro passenger ships. Previous FSA studies (SAFEDOR [16], EMSA 3 [17] and FIRESAFE [6]) used a fatality rate of 8% but it was not clear why. In the FIRESAFE study, two accidents (amongst the FIRESAFE fleet) led to fatalities with fatality of 3.9% and 7.0%. In LASH FIRE, only one accident (amongst the LASH FIRE fleet) led to fatalities with a fatality rate of 5.5%.

For ro-ro cargo ships with a much lower POB than ro-ro passenger ships and with almost only trained crew, the number of fatalities were deemed much lower. Therefore, a 0.01 equivalent fatality fixed value was set for scenario D1 (two orders of magnitude lower than ro-ro passenger ships, based on POB and severity index of Appendix 4 of IMO FSA guidelines [1]) and a 0.35 equivalent fatality fixed value was set for scenario D3 (based on statistics from the WP04 Casualty database).

For vehicle carriers, a 0.05 equivalent fatality fixed value was set for scenario when there will likely be the activation of CO_2 systems (scenario A2, B, C and D1). CO_2 systems were considered to potentially cause a treat to crew's life, e.g. if crew member is trapped into the ro-ro space when the CO_2 is released (cf. accident investigation report of Pyxis in ANNEX 5: List of accident investigation reports). This number (0.05) is based on statistics from the WP04 Casualty database. In the WP04 Casualty database, no injuries or fatalities were reported in case of evacuation (but some were reported in case of firefighting activities). Therefore, with no historical data, the same equivalent fatality fixed value as for ro-ro cargo ships was set for vehicle carriers when the evacuation is unsuccessful (i.e. 0.35 for scenario D2).

For the generic ro-ro passenger ship (Stena Flavia), a capacity of 852 passengers and 28 crew members was considered. The same average passenger occupancy rate as EMSA 3 [16] and FIRESAFE [6] was used, i.e. 62.5%. Therefore, a total POB of 561 persons was considered for the risk model.

For the generic ro-ro cargo ship (Magnolia Seaways), a capacity of 12 passengers and 14 crew members was considered (total POB of 26 persons for the risk model).

For the generic vehicle carrier (Torrens), a capacity of 24 crew members was considered (total POB of 24 persons for the risk model).

Table 15 summarises the fatality rates and number of equivalent fatalities used to feed the risk model.

Table 15. Fatality rate and equivalent fatality assigned to each fire scenario

ID	Scenario	General Narrative	Fatality Narrative	Fatality Rate (%) or Equivalent Fatality		
				Ro-pax	Ro-ro cargo	Vehicle carrier
A1	Small fire	Fires extinguished by portable extinguisher	No fatalities, no injuries	0	0	0
A2	Small fire	Fires extinguished by firefighting	No fatalities, no injuries	0	0	0.05
B	Medium fire	Fires suppressed and contained	No fatalities, no injuries	0	0	0.05
C	Fire to one deck	Fires not suppressed but contained	No fatalities, no injuries	0	0	0.05
D1	Total loss	Fires not contained and evacuation success	Single fatality or multiple severe injuries	1	0.01	0.05
D2	Total loss	Fires not contained and evacuation unsuccessful	Multiple fatalities	5% of POB	0.35	0.35

7.4.2.2 Cost of cargo damage

For ro-ro passenger ships, the costs were based on the following cargo:

- Scenario A1 and A2: average of personal cars and trucks, trailers and transported goods; and
- Scenario B, C and D: trucks, trailers and transported goods.

For fires to one deck (scenario C), the deck capacity was averaged, based on all decks cargo distribution for Stena Flavia. The deck was considered to be filled by 70% (same assumption as in the FIRESAFE studies [6]).

For total loss (scenario D1 and D2), the total capacity of Stena Flavia was first considered, i.e. 208 personal cars and 146 trucks, trailers and transported goods. Then, the decks were considered to be filled by 70% (same assumption as in the FIRESAFE studies [4]).

For ro-ro cargo ships, the costs were based on trucks, trailers and transported goods as cargo.

For fires to one deck (scenario C), the deck capacity was averaged, based on all decks cargo distribution for Magnolia Seaways. The deck was considered to be filled by 70%.

For total loss (scenario D1 and D2), the total capacity of Magnolia Seaways was first considered, i.e. 237 trucks, trailers and transported goods. Then, the decks were considered to be filled by 70%.

For vehicle carriers, the costs were based on the following cargo:

- Scenario A1, A2 and B: real data from accident investigation report of Courage; and
- Scenario C and D: new cars.

For fires to one deck (scenario C), the deck capacity was averaged, based on all decks cargo distribution for Torrens. The deck was considered to be filled by 70%.

For total loss (scenario D1 and D2), the total capacity of Torrens was first considered, i.e. 6 564 new cars. Then, the decks were considered to be filled by 70%.

For each cargo, the following prices were considered:

- Personal car = 20 000 € [16];
- Truck = 110 000 € [6];
- Trailer = 18 000 € [16];
- Transported good = 40 000 € [16]; and
- New car = 40 000 €.

The price for a new car was assumed twice the price for a personal car. This assumption was verified against several references.

Table 16 summarises the costs of cargo damage used to feed the risk model. Those numbers were presented to ship operators of WP05.

Table 16. Cost of cargo damage assigned to each fire scenario

ID	Scenario	General Narrative	Cargo Damage Narrative	Cargo Damage Cost		
				Ro-pax	Ro-ro cargo	Vehicle carrier
A1	Small fire	Fires extinguished by portable extinguisher	Damage to 1 vehicle 50% (no damage to goods)	32 500 €	55 000 €	65 648 €
A2	Small fire	Fires extinguished by firefighting	Damage to 1 vehicle 100% (damage to goods)	94 000 €	168 000 €	131 295 €
B	Medium fire	Fires suppressed and contained	If drencher system: Damage to 1 vehicle 100% + 4 vehicles 50% If CO_2 system: Damage to 13 vehicles 100% + 12 vehicles 50%	504 000 €	504 000 €	2 494 605 €
C	Fire to one deck	Fires not suppressed but contained	Damage to cargo of 1 entire deck + 50% above deck, 70% of cargo capacity	6 024 480 €	10 451 700 €	22 974 000 €
D1	Total loss	Fires not contained and evacuation success	100% loss of cargo, 70% of cargo capacity	20 081 600 €	27 871 200 €	183 792 000 €
D2	Total loss	Fires not contained and evacuation unsuccessful	100% loss of cargo, 70% of cargo capacity	20 081 600 €	27 871 200 €	183 792 000 €

7.4.2.3 Cost of ship damage

The cost of total loss (scenario D1 and D2) was based on the price of ro-ro newbuildings and existing ro-ro ships of about 20-years old (provided by confidential sources). Those prices did not address ro-ro ships using alternative fuels or power (e.g. LNG or batteries). In that case, the price should be much higher. Those costs do not include the salvage costs. No data about salvage costs were found.

Based on the same approach than FP 54/INF.2 [31], ratios of ship values were considered for the different levels of reparation (scenario A2, B and C). Reparation costs were considered independent of either the ship is a newbuilding or existing ship and therefore were calculated on the basis of newbuilding values. If the reparation costs exceeded the ship value (which was the case for scenario C - existing ships), they would be capped to the ship values. By that means, the willingness for reparation will be more likely for newbuildings than for existing ships, which sounds logical. The following ratios were used:

- Scenario A2: 0.5% of ship values [31];
- Scenario B: 1% of ship values;
- Scenario C: 80% of ship values [6]; and
- Scenario D1 and D2: 100% of ship values.

The resulting costs of reparation were compared to real accident costs provided by confidential sources. There was a good matching.

The costs for sanitation were considered to be 1 000 € for all ro-ro ships (same assumption as in the FIRESAFE studies [6]).

Table 17 and Table 18 summarise the costs of ship damage used to feed the risk model. Those numbers were presented to ship operators of WP05.

Table 17. Cost of ship damage assigned to each fire scenario – Newbuildings

ID	Scenario	General Narrative	Ship Damage Narrative	Ship damage Cost – Newbuildings		
				Ro-pax	Ro-ro cargo	Vehicle carrier
A1	Small fire	Fires extinguished by portable extinguisher	No damage to vessel but sanitation needed No off-hire	1 000 €	1 000 €	1 000 €
A2	Small fire	Fires extinguished by firefighting	Minor damage: Damage to ceiling No off-hire	625 000 €	275 000 €	325 000 €
B	Medium fire	Fires suppressed and contained	Non-severe damage: Damage to ceiling, structure and equipment Off-hire several days	1 250 000 €	550 000 €	650 000 €
C	Fire to one deck	Fires not suppressed but contained	Severe damage: Damage to 1 entire deck Off-hire several weeks	100 000 000 €	44 000 000 €	52 000 000 €
D1	Total loss	Fires not contained and evacuation success	Total loss: 100% loss of ship value	125 000 000 €	55 000 000 €	65 000 000 €
D2	Total loss	Fires not contained and evacuation unsuccessful	Total loss: 100% loss of ship value	125 000 000 €	55 000 000 €	65 000 000 €

Table 18. Cost of ship damage assigned to each fire scenario – Existing ships

ID	Scenario	General Narrative	Ship Damage Narrative	Ship damage Cost – Existing ships		
				Ro-pax	Ro-ro cargo	Vehicle carrier
A1	Small fire	Fires extinguished by portable extinguisher	No damage to vessel but sanitation needed No off-hire	1 000 €	1 000 €	1 000 €
A2	Small fire	Fires extinguished by firefighting	Minor damage: Damage to ceiling No off-hire	625 000 €	275 000 €	325 000 €
B	Medium fire	Fires suppressed and contained	Non-severe damage: Damage to ceiling, structure and equipment Off-hire several days	1 250 000 €	550 000 €	650 000 €
C	Fire to one deck	Fires not suppressed but contained	Severe damage: Damage to 1 entire deck Off-hire several weeks	65 000 000 €	10 000 000 €	13 000 000 €
D1	Total loss	Fires not contained and evacuation success	Total loss: 100% loss of ship value	65 000 000 €	10 000 000 €	13 000 000 €
D2	Total loss	Fires not contained and evacuation unsuccessful	Total loss: 100% loss of ship value	65 000 000 €	10 000 000 €	13 000 000 €

8 Estimation of the safety levels for the reference cases

Main author of the chapter: Léon Lewandowski, BV.

This section focuses on safety levels (i.e. Potential Loss of Life, of Cargo and of Ship), computed from the risk model for each type of ro-ro ship.

8.1 Safety level of human

The Potential Loss of Life (PLL) for the three generic ships was determined based on the probabilities, frequencies computed in the risk model and on the consequences associated with each scenario (cf. Section 7.4). It has to be noted that the PLL is in "equivalent" fatalities, because it was considered that several injuries (this number depends on the severity of the injury) were equivalent to one fatality, as stated in the IMO FSA guidelines [1].

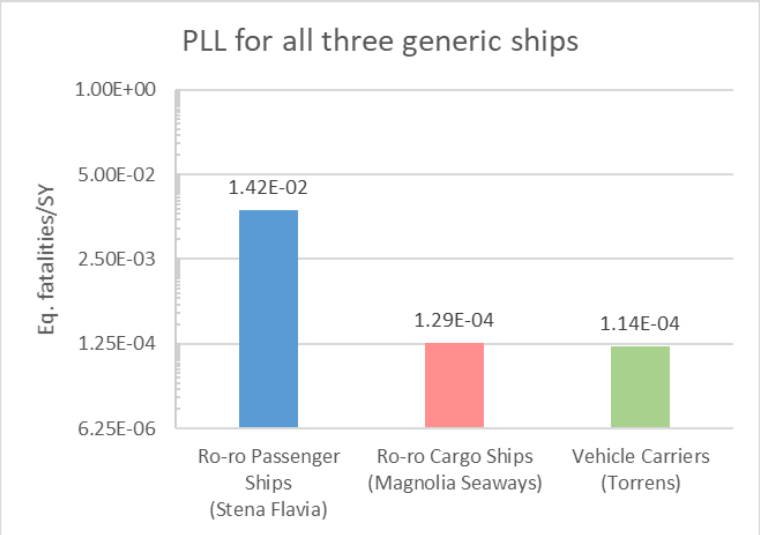


Figure 43. Potential Loss of Life for the three generic ships.

Figure 43 displays the modelled PLL for each generic ship. With no surprise, the ro-ro ship type with the highest modelled PLL (1.42E-2 equivalent fatalities per shipyear) is the ro-ro passenger ship, due to the high number of persons on board.

Ro-ro cargo ships and vehicle carriers have a modelled PLL very close to each other (1.29E-4 and 1.14E-4 eq. fat. per shipyear, respectively).

8.2 Safety level of cargo

The main consequences to cargo are loss of cargo, cargo not re-usable, no more saleable, cleaning, and repair of cargo. The Potential Loss of Cargo (PLC) was determined the same way as the PLL, the outcomes of the scenarios are presented in the previous part.

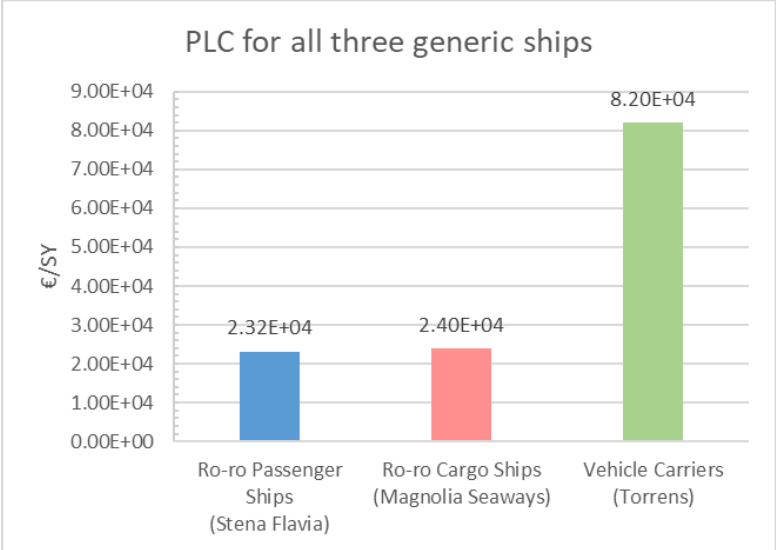


Figure 44. Potential Loss of Cargo for the three generic ships.

Figure 44 displays the modelled PLC for the three generic ships, expressed in euros per shipyear. The vehicle carriers have by far the highest modelled PLC (8.20E4 €/SY against 2.32E4 €/SY for ro-ro passenger ships and 2.40E4 €/SY for ro-ro cargo ships), by having a modelled potential loss approximately four times larger than for the other two types of ro-ro ships. This can easily be explained by the quantity of the cargo carried by vehicle carriers, far more consequent than in ro-ro cargo ships and ro-ro passenger ships.

8.3 Safety level of ship

The main consequence to ship is a loss of operability induced by cleaning, repair, inspection, investigation, etc. after the fire and a loss of property. The damages to ship are mainly caused by the heat and the smoke (soot deposits). The Potential Loss of Ship (PLS) was calculated the same way as the PLC and the PLL.

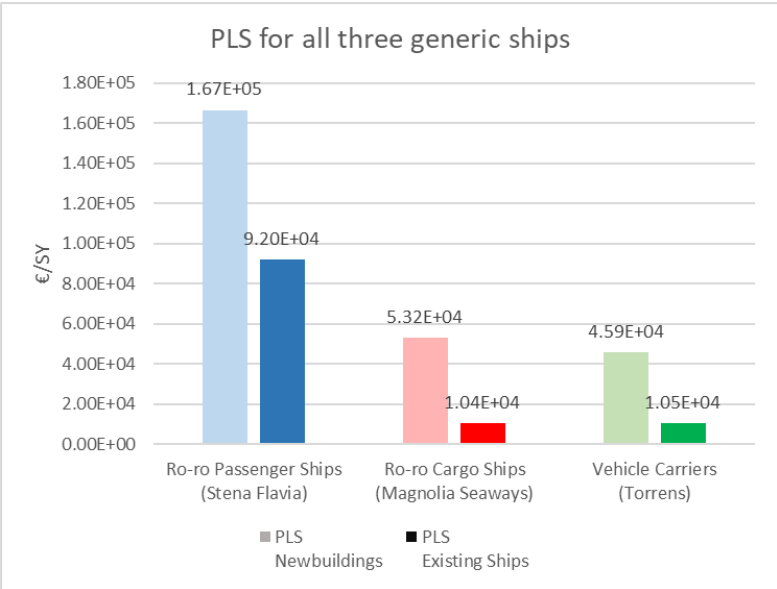


Figure 45. Potential Loss of Ship for the three generic ships.

Figure 45 displays the modelled PLS for the three generic ships, expressed in euros per shipyear. The ro-ro passenger ships have by far the highest modelled PLS, while the PLS for ro-ro cargo ships and vehicle carriers are sensibly the same.

8.4 Summary of safety levels

Table 19 summarises the modelled Potential Losses of Life, Cargo and Ship which have been detailed above.

Table 19. Potential Losses summary

	Potential Loss of Life (eq. fat./SY)	**Potential Loss of Cargo (€/SY)**	**Potential Loss of Ship (€/SY)**	
			Newbuildings	**Existing ships**
Ro-ro passenger ships	1.42E-2	2.32E4	1.67E5	9.20E4
Ro-ro cargo ships	1.29E-4	2.40E4	5.32E4	1.04E4
Vehicle carriers	1.14E-4	8.20E4	4.59E4	1.05E4

9 Risk and sensitivity analyses

Main author of the chapter: Léon Lewandowski, BV.

This section focuses on the analyses performed in order to compare results obtained in the LASH FIRE study to previous studies, as well as to identify high-risk areas. It also contains a sensitivity analysis on the bottom nodes of the risk model, to determine the top risk contributing nodes, and an analysis of expert estimates.

9.1 Comparison between LASH FIRE results, historical data and previous studies

Table 20 summarises the different PLLs computed for previous studies, as well as the PLL obtained using the WP04 Casualty Database.

The LASH FIRE risk model PLL is one order of magnitude higher than the historical LASH FIRE PLL, the SAFEDOR study PLL and EMSA III study PLL. It is of the same order of magnitude as the FIRESAFE risk model PLL.

Table 20. PLL for ro-ro passenger ships from different studies

Study	PLL (eq. fatalities/SY)
LASH FIRE (model)	1.42E-02
LASH FIRE (historical)	3.46E-03
FIRESAFE (model)	2.30E-02
FIRESAFE (historical)	8.14E-03
SAFEDOR (ro-ro spaces only)	4.89E-03
EMSA III (ro-ro spaces only)	1.23E-03

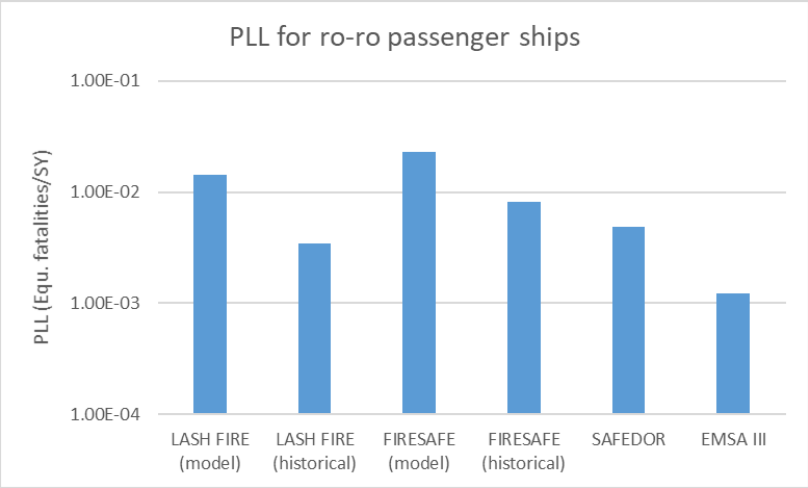


Figure 46. PLL for ro-ro passenger ships from different studies.

9.2 Safety level per ro-ro space type

In order to determine which ro-ro space poses the highest threat to human life in term of fire origin, the PLL calculated in the previous part was broken down to the contributions from each ro-ro space, both for the generic ships, and in a more general way for the whole fleet.

9.2.1 PLL per ro-ro space type for the three generic ships

Figure 47 displays the distribution of the PLL amongst the three types of spaces applied to the Stena Flavia, that means the PLLs per ro-ro space are scaled by the exact number of lane meters per ro-ro space reported for the Stena Flavia. It can be noted that the distribution of the PLL is quite the same as the fire frequency one, displayed in the LASH FIRE deliverable D04.2 [3]. On board the Stena Flavia, according to the risk model, the top risk contributor ro-ro spaces in term of loss of life seem to be the open ro-ro spaces.

Note: Here, the designated space is the space where the fire starts, not the space where someone stands when the potential fatality occurs.

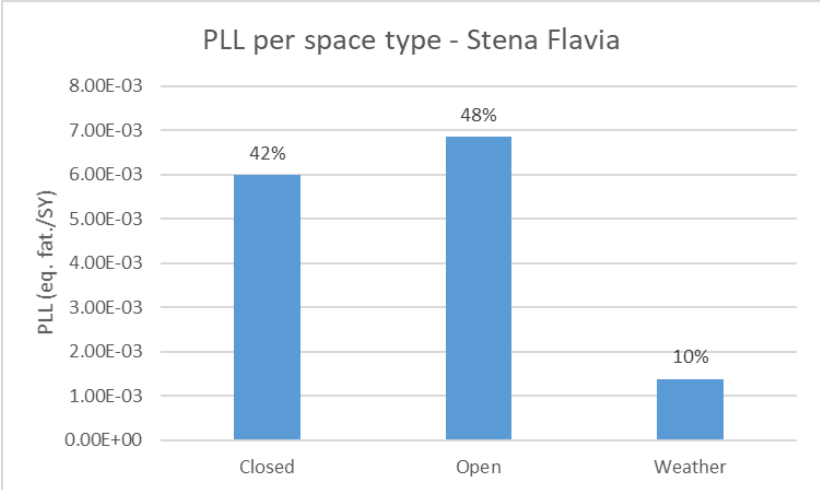


Figure 47. PLL for the different space types applied to Stena Flavia.

Figure 48 also shows the distribution of the PLL amongst the three types of spaces, but this time applied to the Magnolia Seaways, that means the PLL per ro-ro space are scaled by the exact number of lane meters per ro-ro space reported for the Magnolia Seaways. One remarkable point is that the PLL distribution is the exact opposite as the one for the Stena Flavia: according to the risk model, the top risk contributor ro-ro spaces seem to be the weather decks, and the open ro-ro spaces would be the low risk contributor ro-ro spaces.

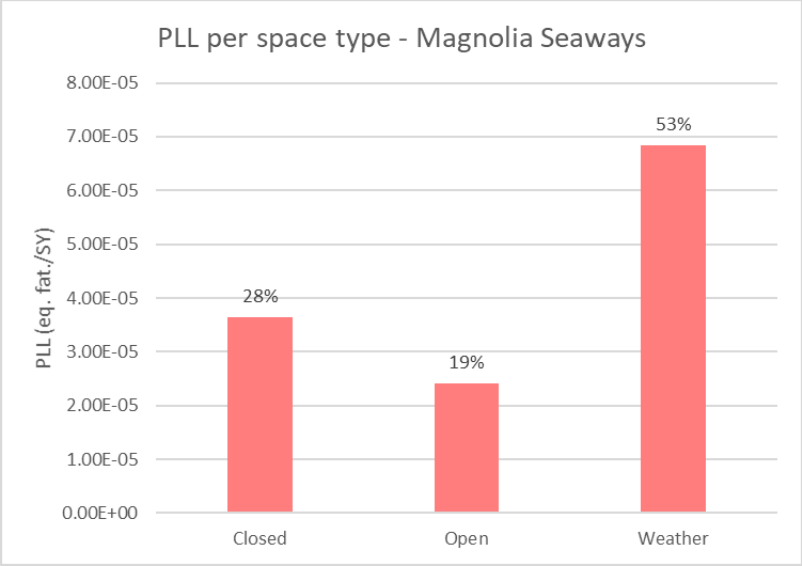


Figure 48. PLL for the different space types applied to Magnolia Seaways.

Due to the small number of reported fires on board ro-ro cargo ships, and since the fire that was considered as an open ro-ro space fire in fact happened in an unknown space[4], a sensitivity analysis has been performed to test the robustness of these PLLs:

- One fire was added or subtracted for each ro-ro space in the calculation of the ignition frequency;
- The PLL was then computed again, with this new frequency.

These new PLLs were plotted in Figure 49 to Figure 51. The global PLL calculated did not change from the base case more than 20%, so under the hypothesis that the database used is representative of the world fleet, we can hardly question the fact that the top risk contributor ro-ro spaces are the weather decks.

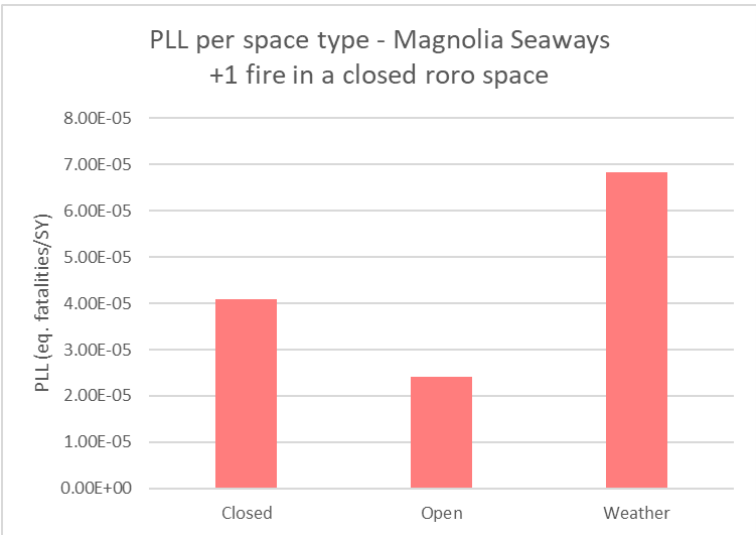


Figure 49. PLL for the different space types reported to Magnolia Seaways, assuming one more fire in a closed ro-ro space.

[4] More details available in ANNEX 4: Frequency of fires in ro-ro spaces per ro-ro space type – Ro-ro cargo ships.

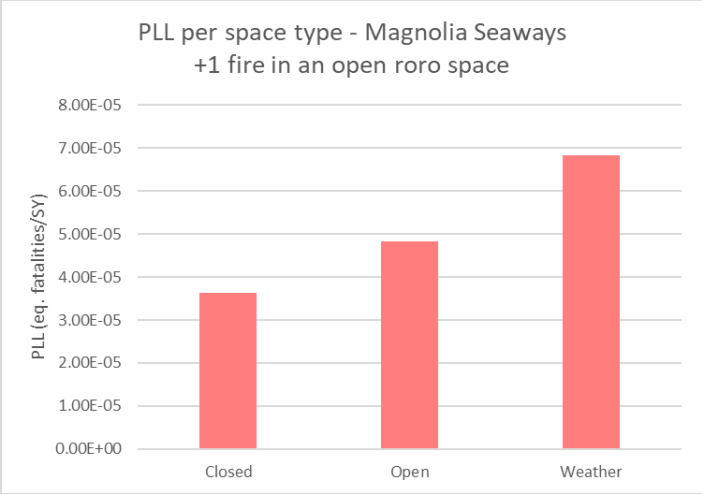


Figure 50. PLL for the different space types reported to Magnolia Seaways, assuming one more fire in an open ro-ro space.

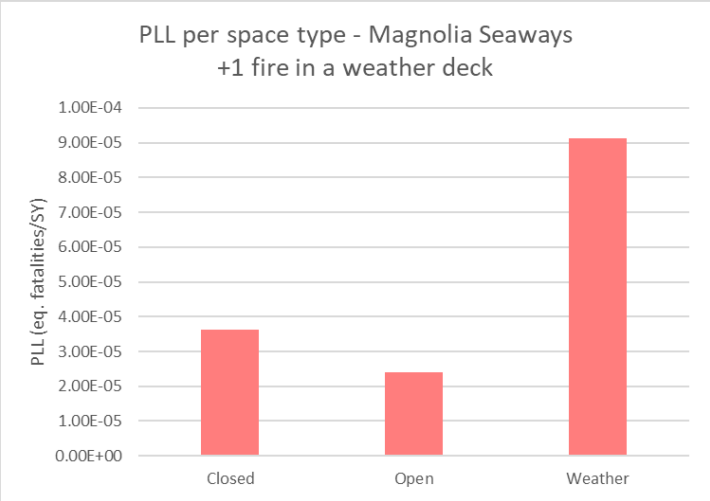


Figure 51. PLL for the different space types reported to Magnolia Seaways, assuming one more fire in a weather deck.

9.2.2 Normalised PLL per ro-ro space type

The previous results (modelled PLL for the different types of ro-ro spaces for the three generic ships) were expressed in eq. fatalities per shipyear. In order to give more generic results, these values have been normalised regarding the cargo capacity of the generic ships, as well as the number of persons on board. The purpose of this normalisation was to provide generic results independent from the scaling effect of cargo capacity and number of persons on board (as far as possible). These results are presented below.

Figure 52 displays the PLL for the three types of ro-ro spaces for ro-ro passenger ships. This PLL is expressed in eq. fatalities per shipyear per lane meter per person on board. Hence, this normalised PLL[5] is unaffected by the capacity of the ship or by its personnel on board.

[5] As presented before, some scenarios have for consequence a fixed number of fatalities (a “fixed contribution”), and some other have a variable number of fatalities (a “variable contribution”), based on the passenger capacity. The fixed contribution quickly becomes negligible, so only the variable contribution is presented here.

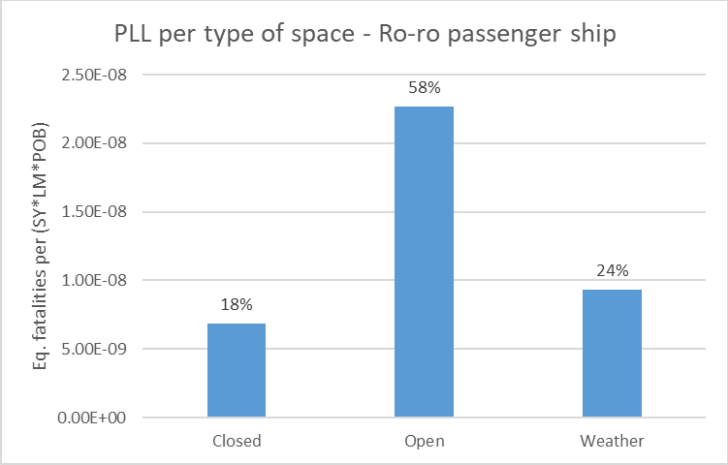


Figure 52. Normalised PLL for ro-ro passenger ships.

As it was the case for the Stena Flavia (Figure 47), the open ro-ro spaces remain the top risk contributor ro-ro spaces. But without any scaling effect, the weather decks per unit of space have now a higher risk level than the closed ro-ro spaces.

Figure 53 displays the normalised PLL (expressed in eq. fatalities per ship year per lane meter) for the three types of ro-ro spaces for ro-ro cargo ships.

It would seem that the weather decks are the top risk contributor ro-ro spaces (same trend as Figure 48 for Magnolia Seaways). Without any scaling effect, the closed and open ro-ro spaces per unit of space have a closer risk level.

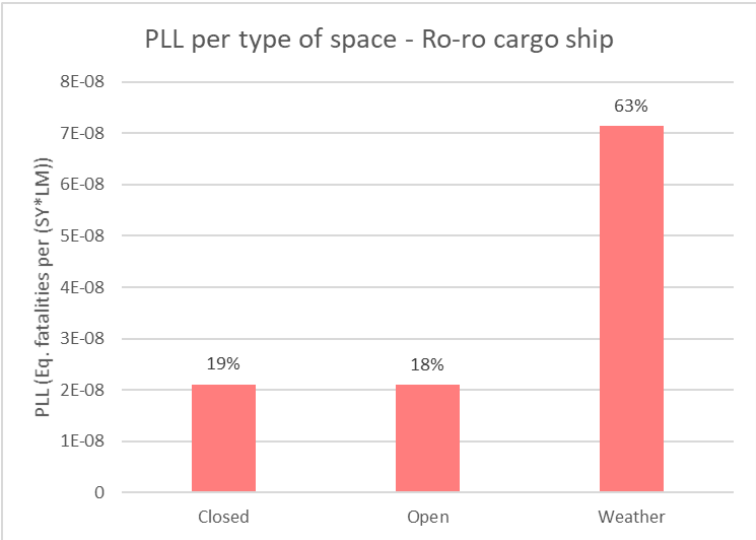


Figure 53. Normalised PLL for ro-ro cargo ships.

9.3 Sensitivity analysis of ignition frequency and fatality model: estimation of PLL distributions for the whole LASH FIRE fleet

On one hand, the WP04 Fleet General Database provides the POB and the cargo capacity (LM or CEU) for each ship, which are the main parameters to estimate the ignition frequency and the number of equivalent fatalities (provided by the fatality model). On the other hand, the FIRESAFE studies deemed two of the most sensitive parameters regarding the risk evaluation were the ignition frequency and the fatality model [6]. Therefore, it was decided, for each ro-ro ship in the database, to use its actual cargo capacity to estimate its ignition frequency and to use its actual POB to estimate the number of equivalent fatalities, and finally to estimate its PLL (varying only the ignition frequency and the number of eq. fatalities).

9.3.1 Ro-ro passenger ships

Figure 54 and Figure 55 display the distribution of the estimated PLL for the whole ro-ro passenger ship fleet, varying only the ignition frequency and the number of eq. fatalities per ship. The bright red value indicates the position of the generic ship in the distribution, in this case the Stena Flavia. The generic ship has a PLL located above the third quartile (75% of the values).

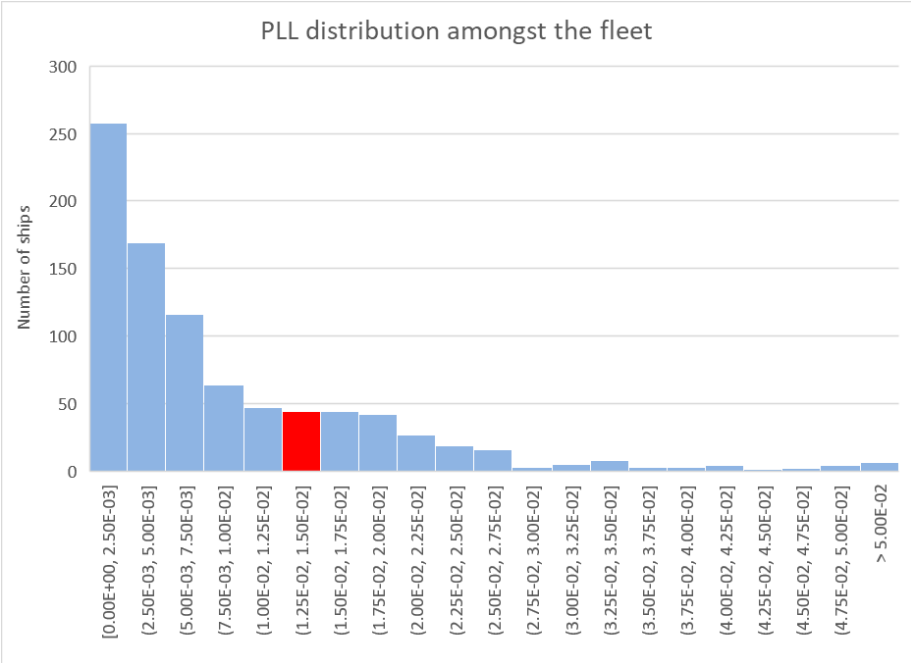


Figure 54. PLL distribution amongst the ro-ro passenger ships fleet (bar chart).

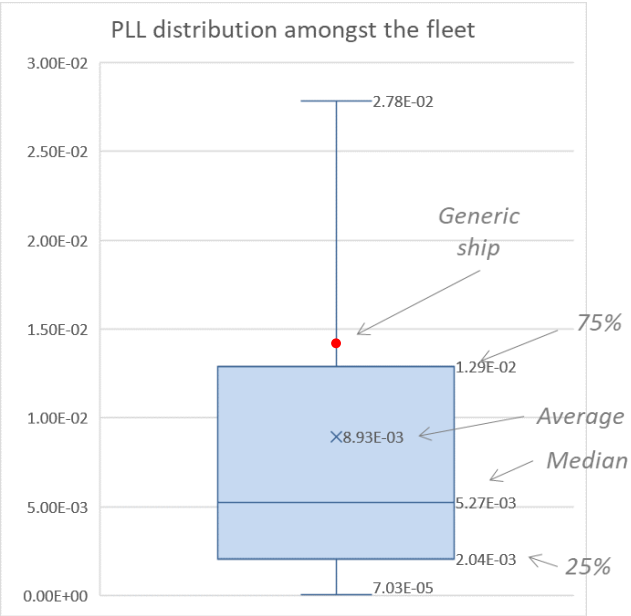


Figure 55. PLL distribution amongst the ro-ro passenger ships fleet (boxplot).

9.3.2 Ro-ro cargo ships

Figure 56 and Figure 57 display the distribution of the estimated PLLs for the whole ro-ro cargo ship fleet, varying only the ignition frequency per ship. The bright red value indicates the position of the generic ship in the distribution, in this case the Magnolia Seaways. In the same way as for the ro-ro passenger ships, the generic ship has a PLL located above the third quartile (75% of the values).

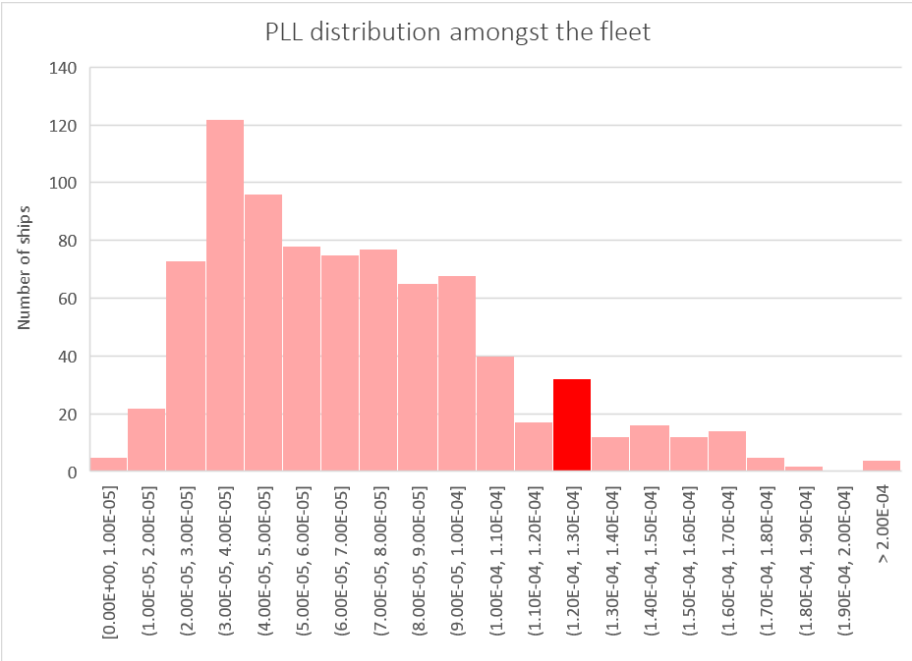


Figure 56. PLL distribution amongst the ro-ro cargo ship fleet (bar chart).

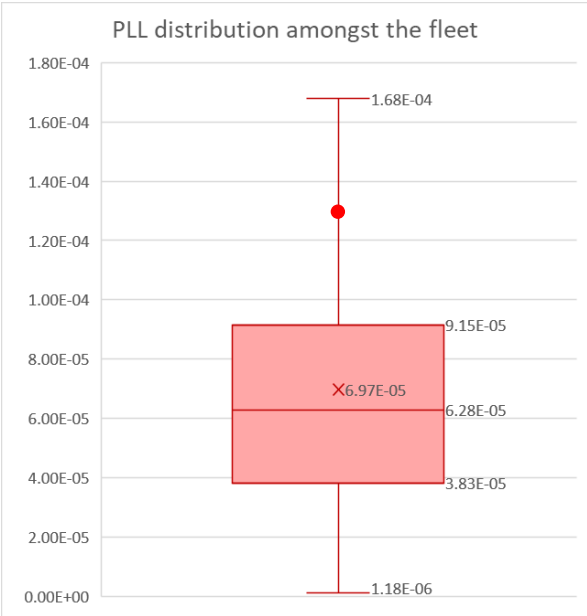


Figure 57. PLL distribution amongst the ro-ro cargo ship fleet (boxplot).

9.3.3 Vehicle carriers

Figure 58 and Figure 59 display the distribution of the estimated PLL for the whole vehicle carrier fleet, varying only the ignition frequency per ship. The bright red value indicates the position of the generic ship in the distribution, in this case the Torrens. For the generic ship, the PLL is located on the third quartile (75%).

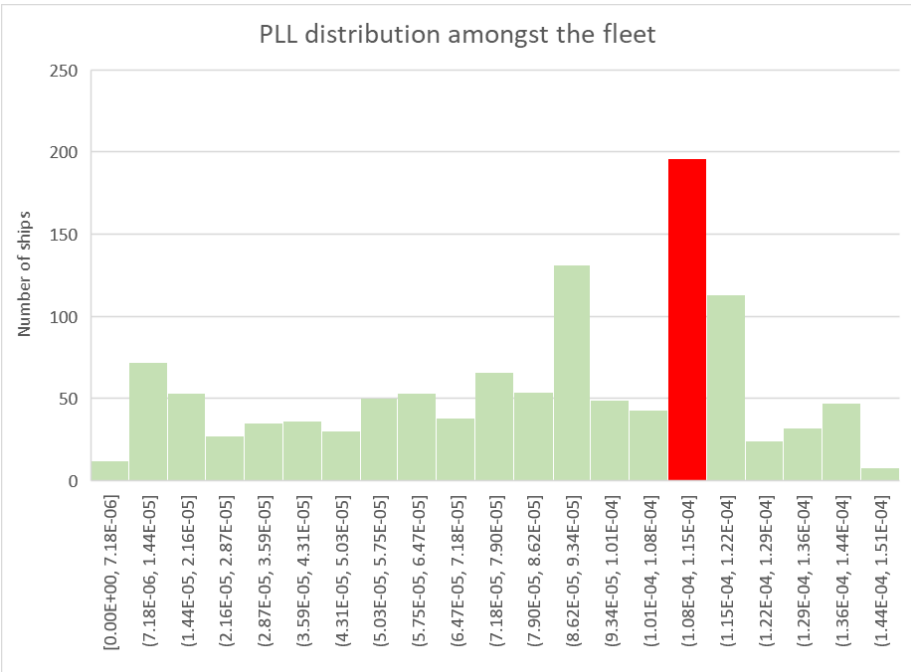


Figure 58. PLL distribution amongst the vehicle carrier fleet (bar chart).

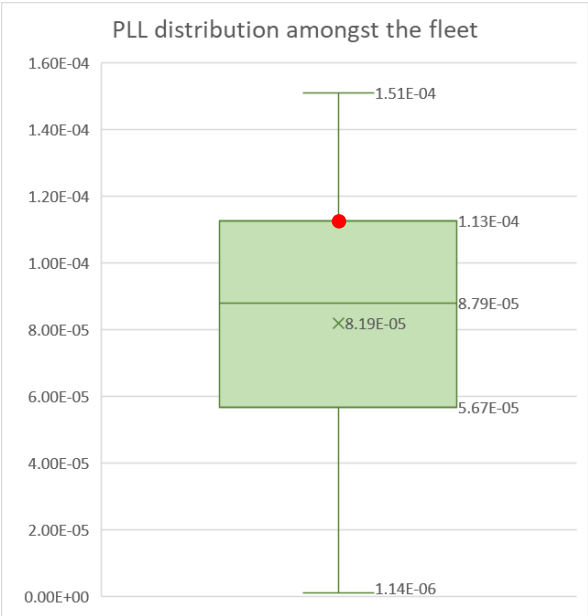


Figure 59. PLL distribution amongst the vehicle carrier fleet (boxplot).

9.4 Sensitivity analysis of bottom nodes

Main author of the chapter: Stina Andersson, RISE.

A simple sensitivity analysis of the bottom nodes was made for the reference cases to see which bottom nodes have the biggest impact on the PLL value. The sensitivity analysis was made by decreasing the bottom nodes with 10% (multiplying with 0.9) and analysing how the PLL value was affected. Only one type of bottom node was changed at a time. However, bottom nodes that are present in several places in the risk model were changed simultaneously. Hence, the bottom node:

- "Extinguishment/suppression failure \ Manual extinguishment fail \ Failure by fire-fighting group \ Tactical failure"

was changed in six places in the risk model for ro-ro passenger ships (following early or late decision on open ro-ro space, closed ro-ro space or weather deck), whilst the same bottom node was only changed in two places in the risk model for vehicle carriers (following early or late decision, only closed ro-ro space).

The bottom nodes with the biggest impact on the PLL (>1% change of PLL) are presented in the tables below (Table 21, Table 22 and Table 23).

This sensitivity analysis is important to identify which bottom nodes are the key risk drivers. It will support the next step of the FSA process by identifying which nodes shall be affected to reduce the risk and therefore what shall be the key properties of the developed RCOs.

9.4.1 Ro-ro Passenger ships

Table 21. Key risk bottom nodes – Ro-ro passenger ships risk model

Fault Tree	Bottom nodes with >1% effect on total PLL
Ignition	• Ship cargo \ Conventional vehicle \ Electrical • Ship cargo \ Conventional vehicle \ Other than electrical • Ship cargo \ Cargo unit \ T°C-controlled cargo unit \ Electrical \ Connection • Ship cargo \ Cargo unit \ T°C-controlled cargo unit \ Other than electrical
Detection	• Late/no manual detection \ Fire patrol failure \ Not present \ Low frequency • Late/no manual detection \ Crew(/passenger) detection failure \ Not present in space • Late/no manual detection \ Bridge detection Failure
First Response	• Failure by first responder \ Accessibility problems • Failure by first responder \ Tactical failure
Decision	• Late assessment \ Lack of relevant information
Extinguishment	• Fixed system fail \ Design incapacity \ Fixed system • Manual extinguishment failure \ Failure by fire-fighting group \ Accessibility problems • Manual extinguishment failure \ Failure by fire-fighting group \ Tactical failure
Containment	• Failure of fire containment \ Flame spread through openings \ Aft and side openings • Failure of fire containment \ Heat spread \ Failure of boundary cooling • Failure of smoke containment \ Internal smoke spread \ Failure to create under pressure
Evacuation	• Failing of evacuation at sea \ Routine failure \ Human failure (e.g. due to Insufficient competence/lack of training/stress) • Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in critical zone ("Zone B") • Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in critical zone

9.4.2 Ro-ro cargo ships

Table 22. Key risk bottom nodes – Ro-ro cargo ships risk model

Fault Tree	Bottom nodes with >1% effect on total PLL
Ignition	• Ship cargo \ Conventional vehicle \ Electrical • Ship cargo \ Conventional vehicle \ Other than electrical • Ship cargo \ Cargo unit \ Other cargo unit \ Electrical • Ship cargo \ Cargo unit \ Other cargo unit \ Other than electrical
Detection	• Late/no manual detection \ Fire patrol failure \ Not present \ Low frequency • Late/no manual detection \ Crew(/passenger) detection failure \ Not present in space • Late/no manual detection \ Bridge detection Failure
First Response	• Failure by first responder \ Accessibility problems • Failure by first responder \ Tactical failure
Decision	None
Extinguishment	• Manual extinguishment failure \ Failure by fire-fighting group \ Accessibility problems
Containment	• Failure of fire containment \ Heat spread \ Failure of boundary cooling • Failure of smoke containment
Evacuation	None

9.4.3 Vehicle carriers

Table 23. Key risk bottom nodes – Vehicle carriers risk model

Fault Tree	Bottom nodes with >1% effect on total PLL
Ignition	• Ship cargo \ Conventional vehicle \ Electrical
Detection	• Late/no manual detection \ Fire patrol failure \ Not present \ Low frequency • Late/no manual detection \ Crew(/passenger) detection failure \ Not present in space • Late/no manual detection \ Bridge detection Failure
First Response	• Failure by first responder \ Accessibility problems • Failure by first responder \ Tactical failure
Decision	None
Extinguishment	None
Containment	• Failure of smoke containment \ Internal smoke spread \ Failure to create under pressure
Evacuation	None

9.5 Analysis of expert estimates

Main author of the chapter: Stina Andersson, RISE.

As explained in section 7.2.2, the quantification using expert judgement was made by calculating the average value of all expert estimates for each bottom node. This means that the distributions of the collected expert estimates were not taken into consideration. It is possible that the distributions of the expert estimates would affect the quantification results. An analysis was therefore made to understand how the quantification results are affected if the distributions of the expert estimates are taken into consideration.

The analysis was made by changing the calculated average values to probability distributions for the bottom nodes. The risk assessment software @Risk was used to fit probability distributions to the set of expert estimates for each node. The distributions were selected based on rankings methods (chi-squared statistics, Anderson-Darling statistics) as well as what distributions were considered suitable. Monte Carlo simulations were then performed to estimate the top nodes and PLL and compare the results with the calculated values used in the risk model. The analysis only covered the bottom nodes identified in the sensitivity analysis (cf. section 9.4). These nodes are the most interesting to analyse since they have the largest impact on the output. Only the bottom nodes quantified using expert judgement were included in the analysis. Bottom nodes quantified using values from FIRESAFE II or calculations were not included since the purpose was to analyse the expert estimations. The two bottom nodes:

- Manual extinguishment failure \ Failure by fire-fighting group \ Accessibility problems; and
- Manual extinguishment failure \ Failure by fire-fighting group \ Tactical failure

were only included for the fault trees following early decision. The fault trees following late decisions were not included as these bottom nodes were quantified using a scaling-factor.

The result, presented in Table 24, Table 25 and Table 26, show that there is no significant difference between the calculated average and the simulated mean for any of the three ship types. The largest difference found for ro-ro passenger ships is for “Failure of containment” for closed spaces following unsuccessful suppression (3.2 percentage points). The largest difference found for ro-ro cargo ships is for “Early detection failure” for weather decks following unsuccessful suppression (5.5 percentage points). The largest difference found for vehicle carriers is for “First response failure” (1.7 percentage points). The results indicate that consideration of the distribution of expert estimates would not yield notable differences in the quantification results.

For ro-ro passenger ships and ro-ro cargo ships, the number of estimates were above 9 for all analysed bottom nodes. For vehicle carriers, the number of estimates for the analysed bottom nodes varied between 5 and 8. In line with the arbitrary criterion set for historical data (cf. section 7.2.1), the results for vehicle carriers have been kept for informational purposes but should be viewed with much more caution.

The 90% confidence intervals (CI) are shown in brackets in Table 24, Table 25 and Table 26. In general, the 90% CI are within 30 percentage points or less. However, some CI’s are larger. For example, the CI for first response failure is close to 60 percentage points for ro-ro passenger ships and ro-ro cargo ships. For vehicle carriers, it is close to 50 percentage points. The first response fault tree consists of three bottom nodes, and all of them were seen to have a high impact on the outcome in the sensitivity analysis. This might explain the larger CI for this fault tree when modelling the bottom nodes as probability distributions.

Table 24. Simulated mean with 90% confidence intervals in brackets and calculated average value for ro-ro passenger ships

Ro-ro Space Type	Top Event	Mean (simulation) [90% confidence interval]	Average value of expert estimations (risk model)
	PLL	1.25E-02 [8.62E-03; 1.77E-02]	1.30E-02
Closed	First response failure	41.5% [17.1%; 75.9%]	41.5%
Open	First response failure	41.6% [17.2%; 76.3%]	41.3%
Weather deck	First response failure	34.1% [15.4%; 60.4%]	32.6%
Closed	Early detection- Late decision to respond	55.0% [48.0%; 77.0%]	56.4%
Closed	Late detection- Late decision to respond	70.1% [59.6%; 85.3%]	70.1%
Open	Early detection - Late decision to respond	55.7% [48.9%; 77.1%]	57.4%
Open	Late detection- Late decision to respond	70.3% [59.6%; 85.6%]	70.1%
Weather deck	Early detection Late decision to respond	48.0% [40.5%; 72.0%]	49.2%
Weather deck	Late detection- Late decision to respond	57.8% [48.9%; 81.1%]	59.4%
Closed	Early decision- Extinguishment/suppression failure	11.6% [6.9%; 18.7%]	12.1%
Open	Early decision- Extinguishment/suppression failure	11.9% [7.0%; 19.1%]	12.3%
Weather deck	Early decision- Extinguishment/suppression failure	46.6% [28.6%; 74.5%]	48.1%
Closed	Successful suppression- Failure of containment	14.1% [12.1%; 18.7%]	13.9%
Closed	Unsuccessful suppression- Failure of containment	56.6% [44.3%; 81.1%]	59.8%
Open	Successful suppression- Failure of containment	23.4% [21.6%; 27.1%]	23.5%
Open	Unsuccessful suppression- Failure of containment	89.4% [86.1%; 95.9%]	90.1%
Closed	Successful suppression- Unsuccessful evacuation	29.1% [19.5%; 42.9%]	26.5%
Closed	Unsuccessful suppression- Unsuccessful Evacuation	37.3% [31.9%; 48.7%]	37.8%
Open	Successful suppression- Unsuccessful evacuation	59.4% [56.5%; 63.4%]	58.6%
Open	Unsuccessful suppression- Unsuccessful evacuation	63.2% [61.6%; 66.5%]	63.3%
Weather deck	Successful suppression- Unsuccessful evacuation	43.6% [37.3%; 52.8%]	41.9%
Weather deck	Unsuccessful suppression- Unsuccessful evacuation	49.8% [46.3%; 57.1%]	50.2%

Table 25. Simulated mean with 90% confidence intervals in brackets and calculated average value for ro-ro cargo ships

Ro-ro Space Type	Top Event	Mean (simulation) [90% confidence interval]	Average value of expert estimations (risk model)
	PLL	1.33E-04 [1.04E-04; 1.64E-04]	1.29E-04
Closed	Early detection failure	23.2% [11.4%; 31.2%]	23.6%
Open	Early detection failure	23.9% [11.8%;32.4%]	24.3%
Weather deck	Early detection failure	49.9% [24.9%;67.3%]	55.4%
Closed	First response failure	45.3% [21.8%; 78.1%]	41.5%
Open	First response failure	45.3% [21.9%; 78.3%]	41.3%
Weather deck	First response failure	37.4% [19.4%; 62.6%]	32.6%
Closed	Early decision-Extinguishment/suppression failure	17.9% [13.3%; 22.5%]	18.0%
Open	Early decision-Extinguishment/suppression failure	18.2% [13.5%; 22.9%]	18.2%
Weather deck	Early decision-Extinguishment/suppression failure	70.2% [52.9%; 90.8%]	67.7%
Closed	Successful suppression-Failure of containment	18.5% [14.8%; 23.5%]	17.1%
Closed	Unsuccessful suppression- Failure of containment	59.7% [41.7%; 82.6%]	55.4%
Open	Successful suppression-Failure of containment	29.8% [27.1%; 33.3%]	28.9%
Open	Unsuccessful suppression- Failure of containment	75.1% [64.7%; 88.0%]	73.1%
Weather deck	Successful suppression-Failure of containment	81.3% [60.0%; 96.3%]	83.3%
Weather deck	Unsuccessful suppression- Failure of containment	92.6% [82.7%; 99.4%]	94.6%

Table 26. Simulated mean with 90% confidence intervals in brackets and calculated average value for vehicle carriers

Ro-ro Space Type	Top Event	Mean (simulation) [90% confidence interval]	Average value of expert estimations (risk model)
	PLL	1.12E-04 [9.02E-05; 1.33E-04]	1.14E-04
Closed	Early detection failure	40.6% [31.1%; 47.2%]	40.3%
Closed	First response failure	58.2% [34.5%; 82.2%]	59.9%
Closed	Successful suppression Failure of containment	11.9% [7.8%; 15.1%]	12.2%
Closed	Unsuccessful suppression- Failure of containment	45.3% [40.5%; 50.2%]	45.8%

10 Conclusion

Main author of the chapter: Léon Lewandowski, BV.

A risk model focusing on fires originating in ro-ro spaces was developed and quantified.

Several risk modelling techniques were studied and compared. Using those techniques, several draft structures of risk model were developed. It was decided to keep the same structure as the FIRESAFE studies, though as they only focused on ro-ro passenger ships, the structure was enhanced to take into account ro-ro cargo ships and vehicle carriers. The structure of the model was also improved to include new failure modes affected by some of the solutions proposed by the D&D WPs.

For the quantification, different sources of data were used:

- Results from the FIRESAFE studies, when relevant;
- Historical data from the WP04 Casualty database [3] when the number of corresponding cases was sufficient to draw solid conclusions; and
- Expert judgement and inputs from ship operators for the remaining cases.

Expert judgement was conducted following the “individual-based approach”: each expert received a questionnaire dealing with the bottom nodes then to be quantified. Several support sessions were organised by the WP04 in case they needed any help. The agreement amongst experts for all each tier was calculated via a different technique from the one suggested by the IMO FSA guidelines, which was not applicable. The results of the quantification were widely analysed and verified with regards to the available historical data, as well as FIRESAFE studies.

This completed risk model allowed two major objectives to be fulfilled:

- The safety levels regarding life loss, cargo loss and ship loss for the three generic ships were calculated for the reference case (i.e. no solution implemented yet). These results were detailed and analysed, and the following conclusions could be made:
    - The ro-ro ships with the highest risk level in term of life loss are the ro-ro passenger ships;
    - The ro-ro ships with the highest risk level in term of cargo loss are the vehicle carriers;
    - On board the ro-ro passenger ship, the top risk contributor ro-ro spaces in term of life loss are the open ro-ro spaces; and
    - On board the ro-ro cargo ship, the top risk contributor ro-ro spaces in term of life loss are the weather decks.
- The contribution of the bottom nodes to the global risk were computed and analysed, in order to be able to select the most promising solutions proposed by the D&D WPs in term of risk reduction.

The risk model will also be used in the next steps of the FSA led by the WP04. For the selected solutions, using quantitative risk reduction on affected nodes provided afterwards by the D&D WPs and the costs provided by the WP05 (T04.6), it will be possible to assess the cost-effectiveness of each solution (T04.7). A detailed method of use for the risk model can be found in the deliverable D04.4, “*Holistic Risk Model*” [4].

This deliverable is the summary and the conclusion of task T04.4, *'Holistic ro-ro ship fire risk model'* [2]. It contributes to the strategic objective:

> "To provide a **recognized technical basis** for the revision of international **IMO regulations**, which greatly **enhances fire prevention** and **ensures independent management of fires** on ro-ro ships in current and **future** fire safety challenges";

and to the specific objective 3:

> "LASH FIRE will provide a **technical basis** for future revisions of regulations by **assessing risk reduction and economic properties of solutions**".

11 References

[1] IMO, *Revised Guidelines for Formal Safety Assessment (FSA) for the use in the IMO rule-making process, MSC-MEPC.2/Circ.12/Rev.2,* 2018.

[2] LASH FIRE, *LASH FIRE Grant Agreement,* 2019.

[3] M. Gadel, *Ro-ro space fire database and statistical analysis report (D04.2),* LASH FIRE, 2021.

[4] L. Lewandowski, *Holistic risk model (D04.4),* LASH FIRE, 2022.

[5] Society for Risk Analysis, *Glossary,* 2018.

[6] J. Wikman, *Study investigating cost effective measures for reducing the risk from fires on ro-ro passenger ships (FIRESAFE), EMSA/OP/01/2016,* EMSA, 2016.

[7] J. Leroux, *FIRESAFE II Detection and Decision, Final Report, Version 1.1, 2017/EMSA/OP/17/2017,* EMSA, 2018.

[8] J. Leroux, *FIRESAFE II Containment and Evacuation, Final Report, Version 1.1, 2017/EMSA/OP/17/2017,* EMSA, 2018.

[9] IMO, *Review of SOLAS Chapter II-2 [...] to minimize the incidence and consequences of fires on ro-ro spaces [...], Report of the intersessional meeting of the Experts Group on Formal Safety Assessment (FSA), SSE 7/6,* 2019.

[10] IACS, *IACS FSA Training Courses,* 2008.

[11] J. Leroux, *FIRESAFE II Combined Assessment, Final Report, Version 1.1, 2017/EMSA/OP/17/2017,* EMSA, 2018.

[12] IMO, *Casualty statistics and investigation, Report of the Correspondence Group on Casualty Analysis, FSI 21/5,* 2012.

[13] R. Skjong and B. Wentworth, “Expert judgment and risk perception,” in *Proceedings of the International Offshore and Polar Engineering Conference, 4, pp. 537-544*, 2001.

[14] B. Kirwan, G. Basra, G. and S. Taylor-Adams, “CORE-DATA: a computerised human error database for human reliability support,” in *Proceedings of the 1997 IEEE Sixth Conference on Human Factors and Power Plant*, 1997.

[15] E. Vanem and R. Skjong, “Fire and evacuation risk assessment for passenger ship,” in *INTERFLAM 2004, pp. 365-374*, 2004.

[16] IMO, *Formal Safety Assessment, FSA - RoPax ships, MSC 85/INF.3,* SAFEDOR, 2008.

[17] D. Konovessis and al, *Risk Acceptance Criteria and Risk Based Damage Stability, Final Report, part 2: Formal Safety Assessment, EMSA/OP/10/2013,* EMSA, 2015.

[18] M. Rothschild, “Fault Tree and Layer of Protection Hybrid Risk Analysis,” *Process Safety Progress,* vol. 23, no. 3, pp. 185-190, 2004.

[19] R. Casey, C. Keogh and Associates, “Limitations and misuse of LOPA,” *Loss Prevention Bulletin,* vol. 265, pp. 13-16, 2019.

[20] A. Lee and L. Lu, “Petri net modeling for probabilistic safety assessment and its application in the air lock system of a CANDU nuclear power plant,” in *2012 International Symposium on Safety Science and Technology*, 2012.

[21] T. S. Liu and S. B. Chiou, “The application of Petri nets to failure analysis,” *Reliability Engineering and System Safety,* vol. 57, pp. 129-142, 1997.

[22] T. Korhonen, J. Hietaniemi, D. Baroudi and M. Kokkala, “Time- Dependent Event-Tree Method for Fire Risk Analysis: Tentative Results,” in *Fire Safety Science - Proceedings of the seventh international symposium*, 2003.

[23] N. Dalkey, “An Experimental study of group opinion: The Delphi method,” *Futures,* vol. 1, no. 5, pp. 408-426, 1969.

[24] J. Winkler and R. Moser, “Biases in future-oriented Delphi studies; A congative perspective,” *Technological Forecasting & Social Change,* no. 105, pp. 63-76, 2016.

[25] G. Gigerenzer and U. Hoffrage, “Using Natural Frequencies to Improve Diagnostic Interferences,” *Academic Medicine,* vol. 73, no. 5, pp. 538-40, 1998.

[26] J. Becker, D. Brackbill and D. Centola, “Network dynamics of social Influence in the wisdoms of crowds,” *PNAS,* 2017.

[27] A. E. Mannes, J. B. Soll and R. P. Larrick, “The Wisdom of Select Crowds,” *Journal of Personality and Social Psychology,* vol. 107, pp. 276-299, 2014.

[28] IMO, *Electric mobility on ro-ro and ro-pax ships, Report of the Formal Safety Assessment (FSA) study, MSC 96/INF.3,* 2016.

[29] K. Krippendorff, Content Analysis: An Introduction to Its Methodology, 3rd ed., Thousand Oaks, CA: Sage Publications, 2013.

[30] B. Porterie, *Simulation tool for consequence quantification (D04.3),* LASH FIRE.

[31] IMO, *Review of fire protection requirements for on-deck cargo areas, FSA – Container fire on deck, Details of the Formal Safety Assessment, FP 54/INF.2,* 2009.

[32] A. Tversky and D. Kahneman, “Judgment under Uncertanity; Heuristics and Biases,” *Science,* vol. 185, pp. 1124-1131, 1974.

[33] A. O'Hagan, C. E. Buck, A. Daneshkhah, J. R. Eiser, P. H. Garthwaite, D. J. Jenkinson, J. E. Oakley and T. Rakow, *Uncertain Judgements: Eliciting Experts' Probabilities,* John Wiley & Sons, 2006.

[34] U. Hoffrage, S. Krauss, L. Martignon and G. Gigerenzer, “Natural frequencies improve Bayesian reasoning in simple and complex interference tasks,” *Frontiers in Psychology,* vol. 6, 2015.

[35] K. Leung and S. Verga, “Expert Judgement in Risk Assessment,” Defence R&D Canada - CORA, 2007.

[36] IMO, *SOLAS Convention, Consolidated Edition, as amended,* 2014.

[37] Government of Norway, *Sub-section 8.1.4 of ADR, Amendments to the requirements for fire-fighting equipment, Comments on the proposal from Germany in doc. TRANS/WP.15/2002/9,* 2002.

[38] Y. Z. Li and H. Ingason, *Scaling of wood pallet fires, SP Report 2014:57,* RISE, 2014.

[39] NUREG, *Estimating burning characteristics of liquid pool fires, heat release rate, burning duration, and flame height spreadsheets, Version 1805.0 (SI Units),* 2004.

[40] IMO, *Revised guidelines for the design and approval of fixed water-based fire-fighting systems for ro-ro spaces and and special category spaces, MSC.1/Circ.1430/Rev.2,* 2020.

[41] DNV GL, *Fires on ro-ro decks, Paper no. 2016-P012,* 2016.

[42] A. Cassez and P. Mindykowski, “A quantitative criterion to assess early detection for fire safety,” in *1st International Conference on the Stability and Safety (STAB&S)*, Glasgow, Scotland, UK, 2021.

[43] BATPI, “FAQs > EXTINCTEURS > Quelle est la distance d'utilisation d'un extincteur,” [Online]. Available: http://www.batpi.fr/sites/incendie/faq/detail.php/question/distance_utilisation_extincteur. [Accessed 7 December 2021].

[44] European Committee for Standardization, *Eurocode 3: Design of steel structures. Part 1-2: General rules. Structural fire design. (EN Standard EN 1993-1-2:2005),* 2005.

[45] N. Themelis and K. J. Spyrou, *Optimising smoke detectors on passenger ships,* 2012.

[46] N. Themelis and K. J. Spyrou, “Probabilistic fire safety assessment of passenger ships,” *Journal of ship research,* vol. 56, no. 4, pp. 252-275, 2012.

[47] K. J. Spyrou, N. Themelis and N. Nikolaou, “Towards risk-based fire safety assessment of passenger ships,” in *Developments in maritime transportation and exploitation of sea resources*, Guedes Soares & López Peña, 2014.

[48] I. A. Koromila, K. J. Spyrou, N. Themelis and S. Ioannou, “Towards building an attained index of passenger ship fire safety,” in *Technology and Science for the Ships of the Future*, A. Marinò and V. Bucci, 2018.

[49] K. J. Spyrou and I. A. Koromila, “A risk model of passenger ship fire safety and its application,” *Reliability Engineering and System Safety,* vol. 200, 2020.

12 Indexes

12.1 Index of tables

12.2 Index of figures

13 ANNEXES

13.1 ANNEX 1: Short CVs

This annex provides short CVs of persons involved in the development of risk model.

Name: Antoine Cassez

Organisation: BV

Current role: Senior Fire Safety Engineer and Project Manager at BV

Education: Engineering degree, MSc Fire Safety Engineering

Areas of expertise: Fire safety, evacuation, alternative fire safety design, lightweight materials

Past experience: 9 years of advanced safety studies and research projects in maritime industry

Name: Eric De Carvalho

Organisation: BV

Current role: Senior Fire and Gas Safety Engineer at BV – WP04 Formal Safety Assessment leader in LASH FIRE

Education: Engineering degree, MSc in Fluid Dynamics

Areas of expertise: Fire and gas safety, risk analysis

Past experience: 9 years of risk quantification and loss prevention in oil and gas industry, 3 years of advanced safety studies in maritime industry

Name: Léon Lewandowski

Organisation: BV

Current role: Junior Safety Assessment Engineer at BV

Education: General engineering degree, MSc in Fluid Mechanics

Areas of expertise: Risk analysis, new fuels

Past experience: Research on new fuels (ammonia), safety study on ro-ro vessels

Name: Stina Andersson

Organisation: RISE

Current role: Research Engineer, Fire Safe Transport unit at RISE

Education: BSc Fire Protection Engineering & MSc Risk Management and Safety Engineering

Areas of expertise: Fire Safety, Risk Management, Resilience in Infrastructures

Past experience: Fire safety designs and risk assessments for building and maritime industry, research projects on safety of hydrogen in maritime industry

Name: Sixten Dahlbom

Organisation: RISE

Current role: Project manager and PhD student at RISE

Education: MSc Chemical Engineering

Areas of expertise: Process safety, risk analysis, firefighting foam, self-heating (dangerous goods),

Past experience: 7 years of plant operation, plant design and risk assessments and 2 years of industrial fire risks

Name: Kujtim Ukaj

Organisation: RISE

Current role: Research Scientist in Maritime Fire Safety at RISE Safety

Education: Fire Safety Engineering and Risk Management

Areas of expertise: Dangerous goods, alternative fire safety design, lightweight materials, ro-ro ship fire safety

Past experience: Conducted risk assessments of alternative designs, research on fire safety of composite vessels and ro-ro vessels

13.2 ANNEX 2: Structure of LASH FIRE risk model

This annex provides the complete structure of LASH FIRE risk models.

13.2.1 Ro-ro passenger ships

Event tree:

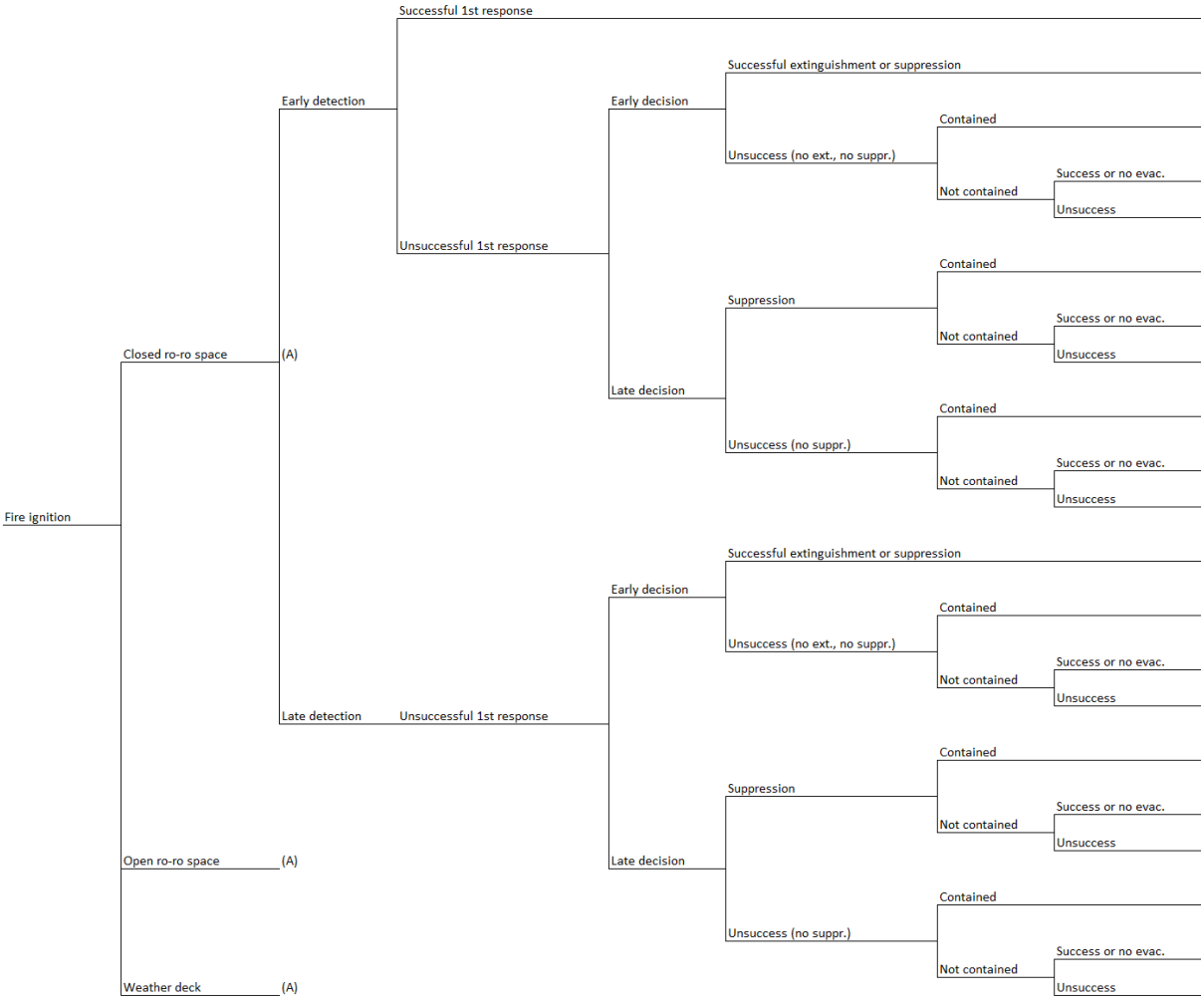


Figure 60. Main event tree – Ro-ro passenger ships.

Ignition:

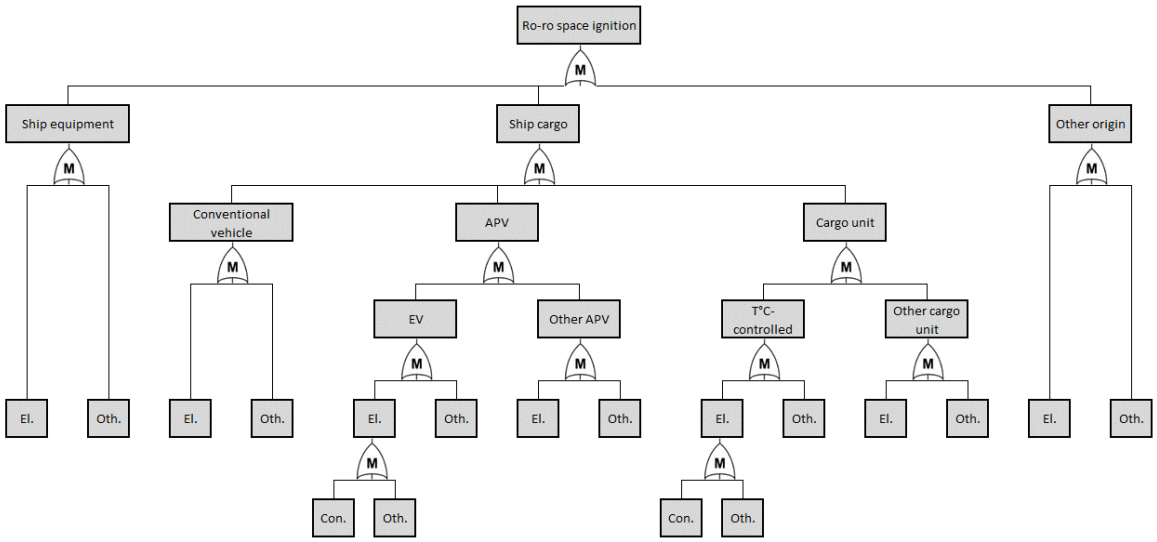


Figure 61. Contribution tree for ignition – Ro-ro passenger ships – Closed and open ro-ro spaces.

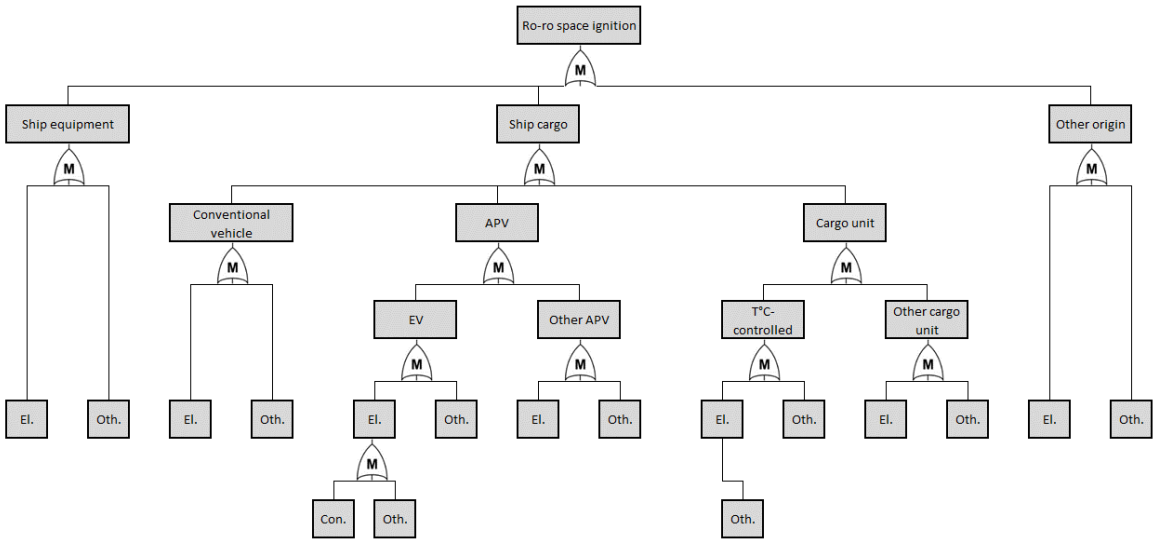


Figure 62. Contribution tree for ignition – Ro-ro passenger ships – Weather decks.

Detection:

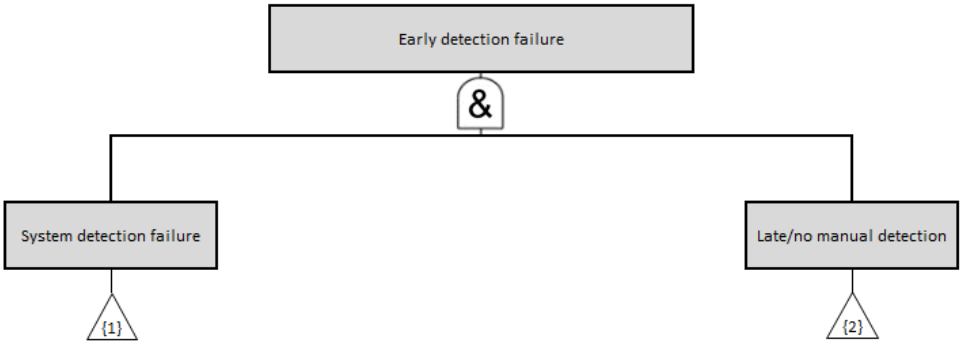


Figure 63. Detection fault tree – Ro-ro passenger ships – Closed, open ro-ro spaces and weather decks.

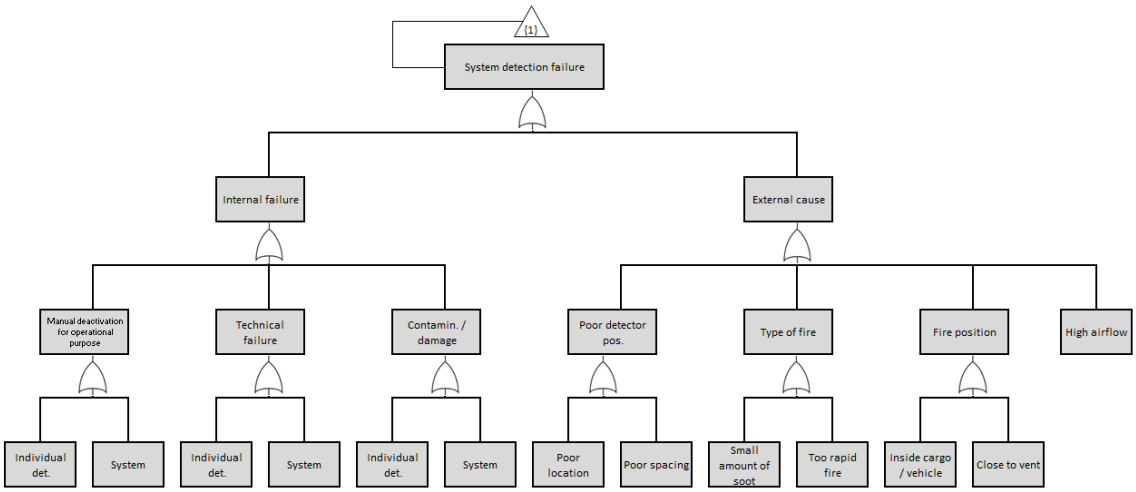


Figure 64. Sub-tree for "System detection failure" – Ro-ro passenger ships – Closed and open ro-ro spaces.

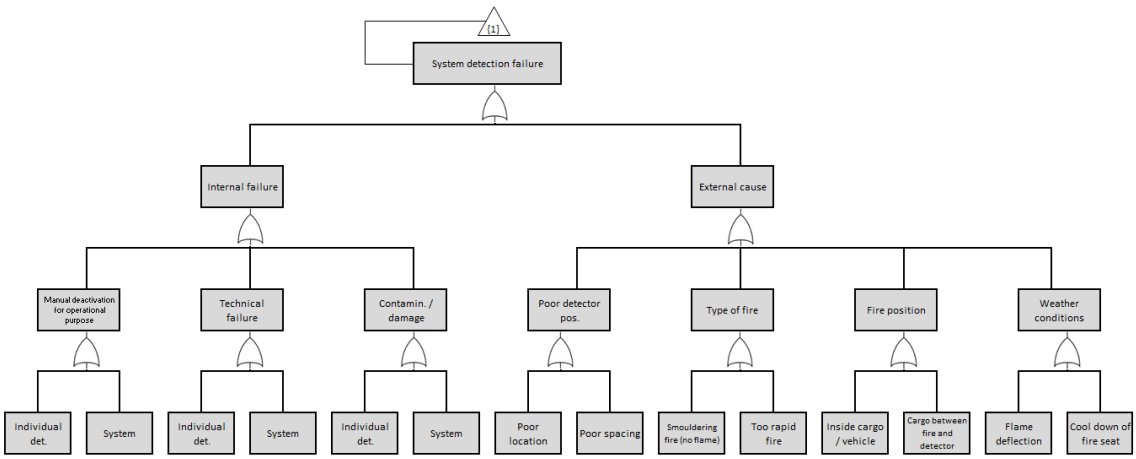


Figure 65. Sub-tree for "System detection failure" – Ro-ro passenger ships – Weather decks.

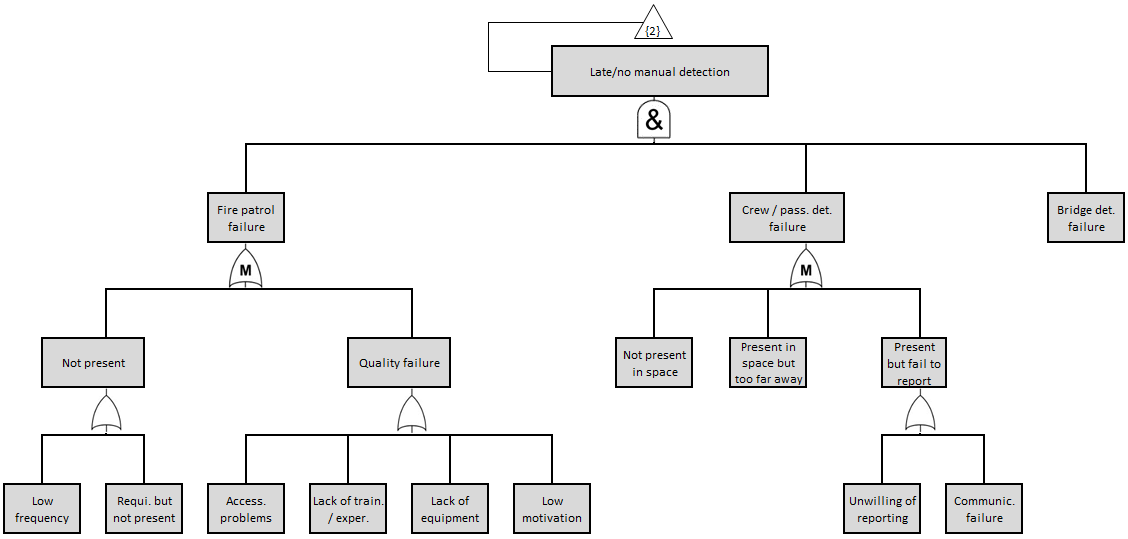


Figure 66. Sub-tree for "Late/no manual detection" – Ro-ro passenger ships – Closed, open ro-ro spaces and weather decks.

First response:

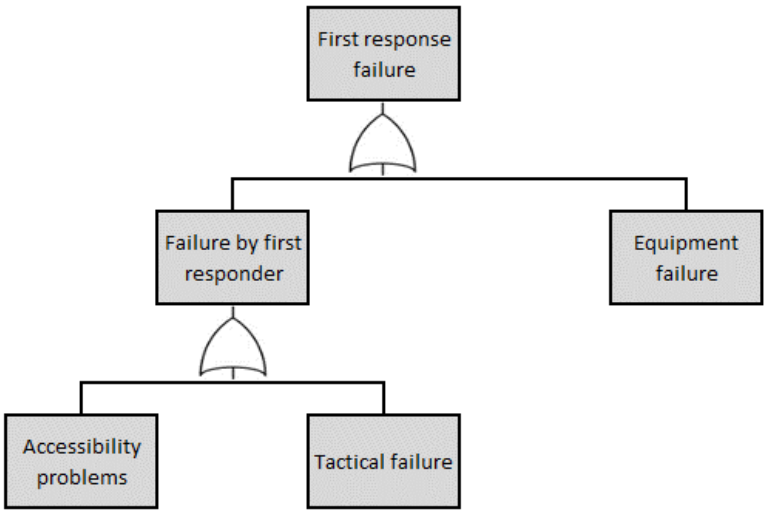


Figure 67. First response fault tree – Ro-ro passenger ships – Closed, open ro-ro spaces and weather decks.

Decision:

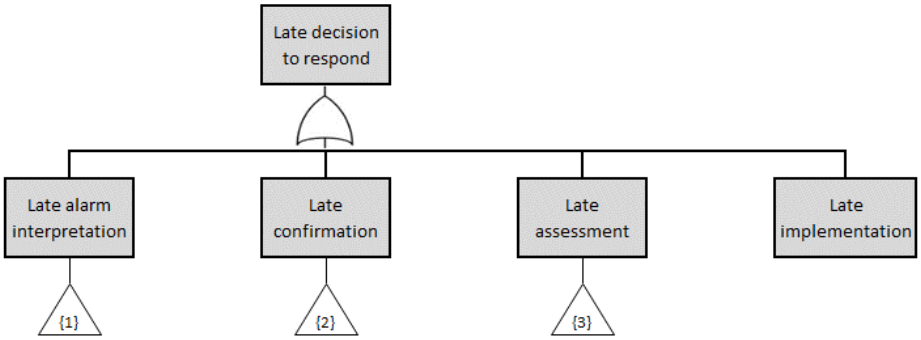


Figure 68. Decision fault tree – Ro-ro passenger ships – Closed, open ro-ro spaces and weather decks.

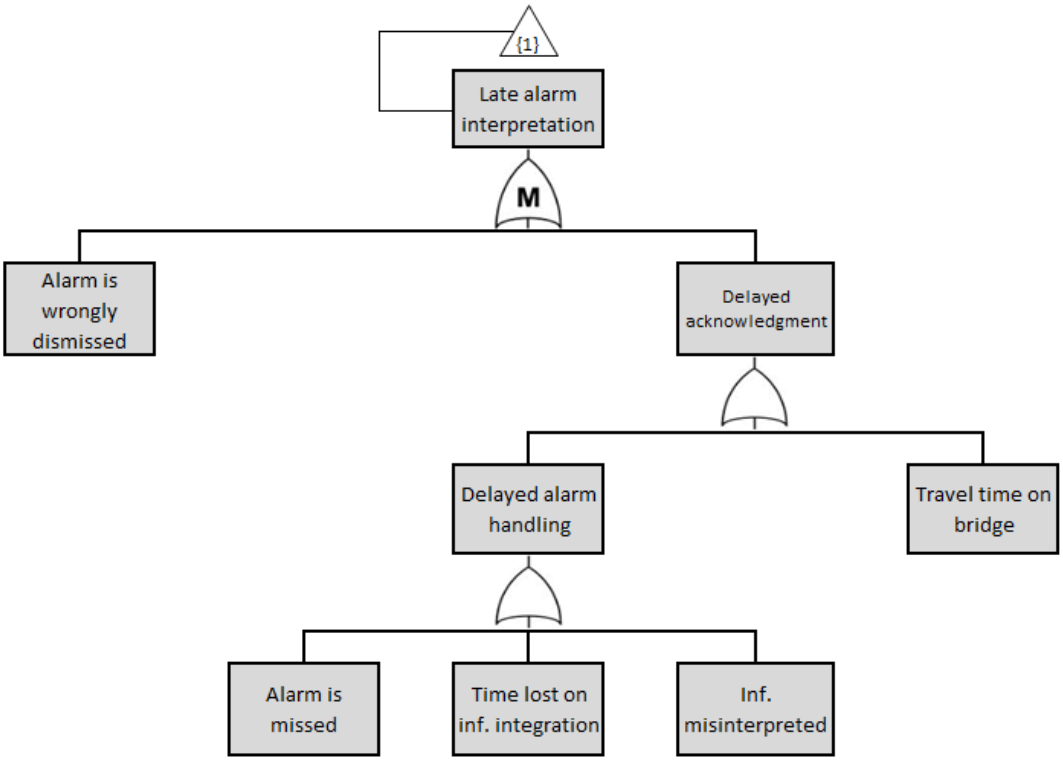


Figure 69. Sub-tree for "Late alarm interpretation" – Ro-ro passenger ships – Closed, open ro-ro spaces and weather decks.

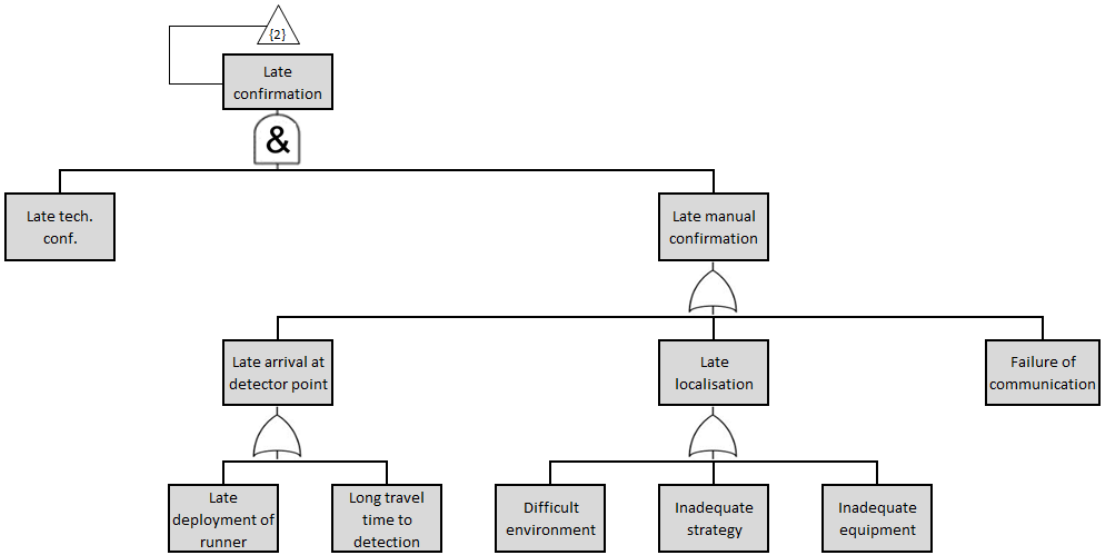


Figure 70. Sub-tree for "Late confirmation" – Ro-ro passenger ships – Closed, open ro-ro spaces and weather decks.

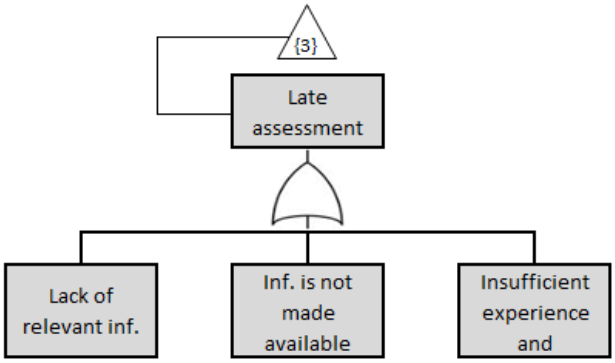


Figure 71. Sub-tree for "Late assessment" – Ro-ro passenger ships – Closed, open ro-ro spaces and weather decks.

Extinguishment:

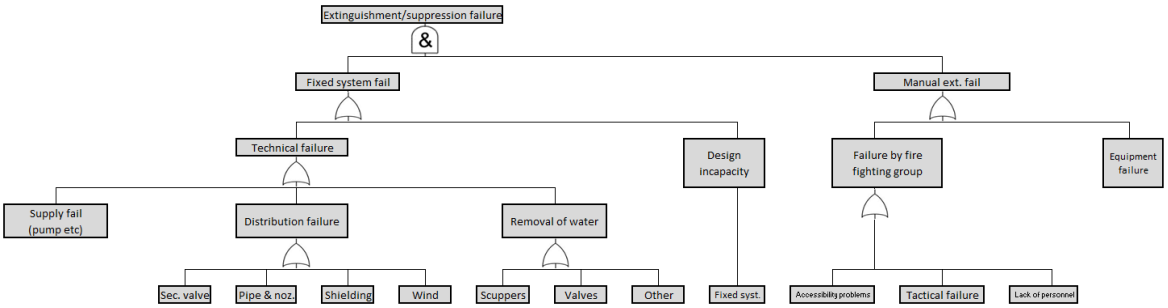


Figure 72. Extinguishment fault tree – Ro-ro passenger ships – Closed and open ro-ro spaces.

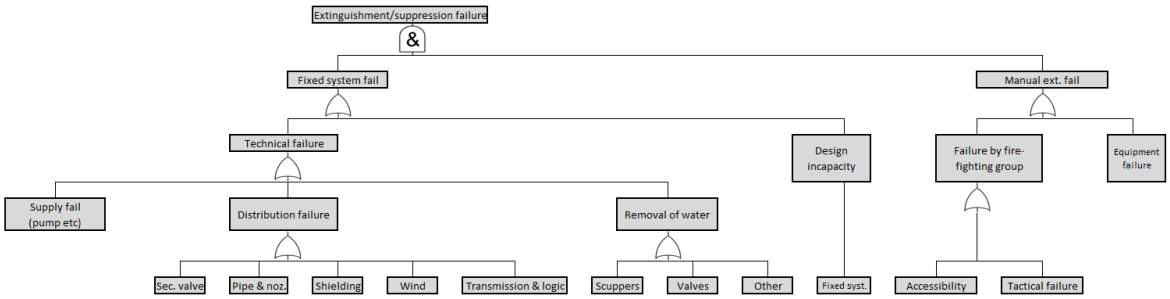


Figure 73. Extinguishment fault tree – Ro-ro passenger ships – Weather decks.

Containment:

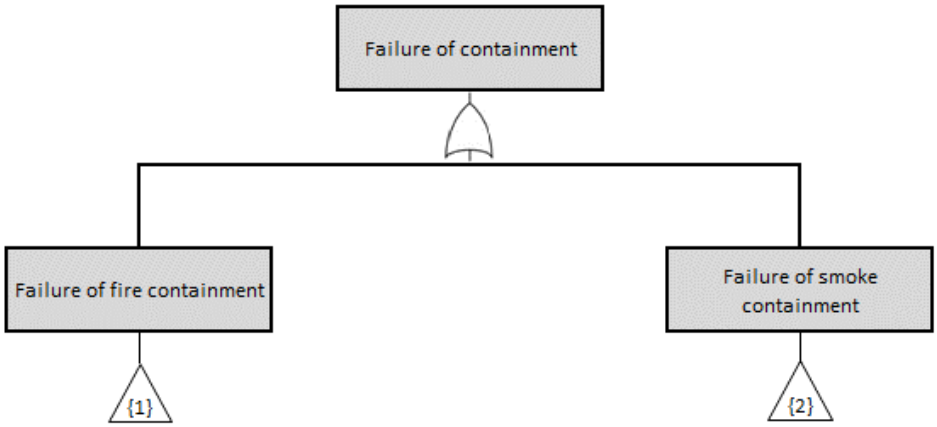


Figure 74. Containment fault tree – Ro-ro passenger ships – Closed and open ro-ro spaces.

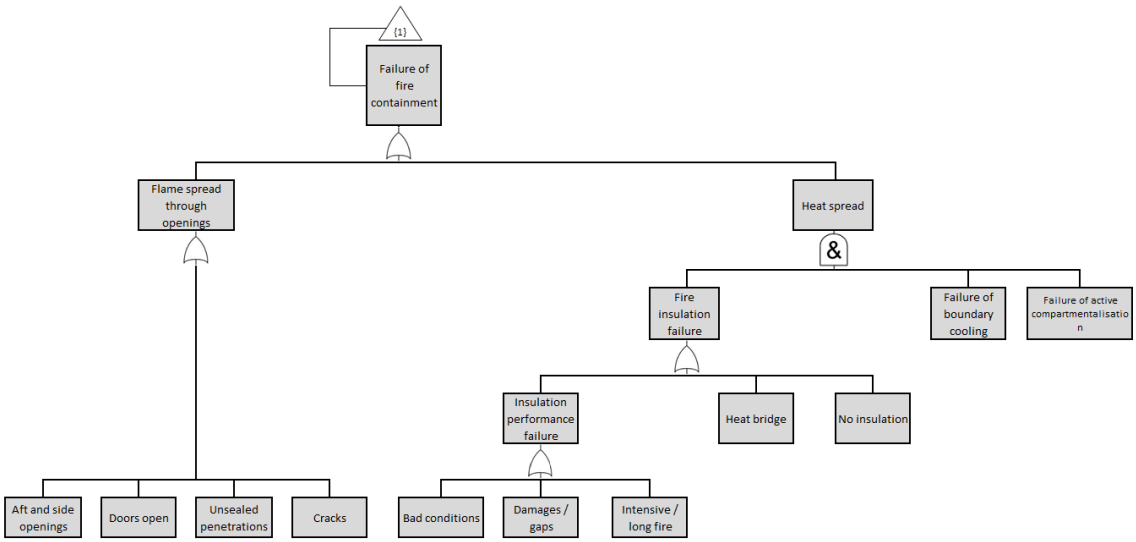


Figure 75. Sub-tree for "Failure of fire containment" – Ro-ro passenger ships – Closed and open ro-ro spaces.

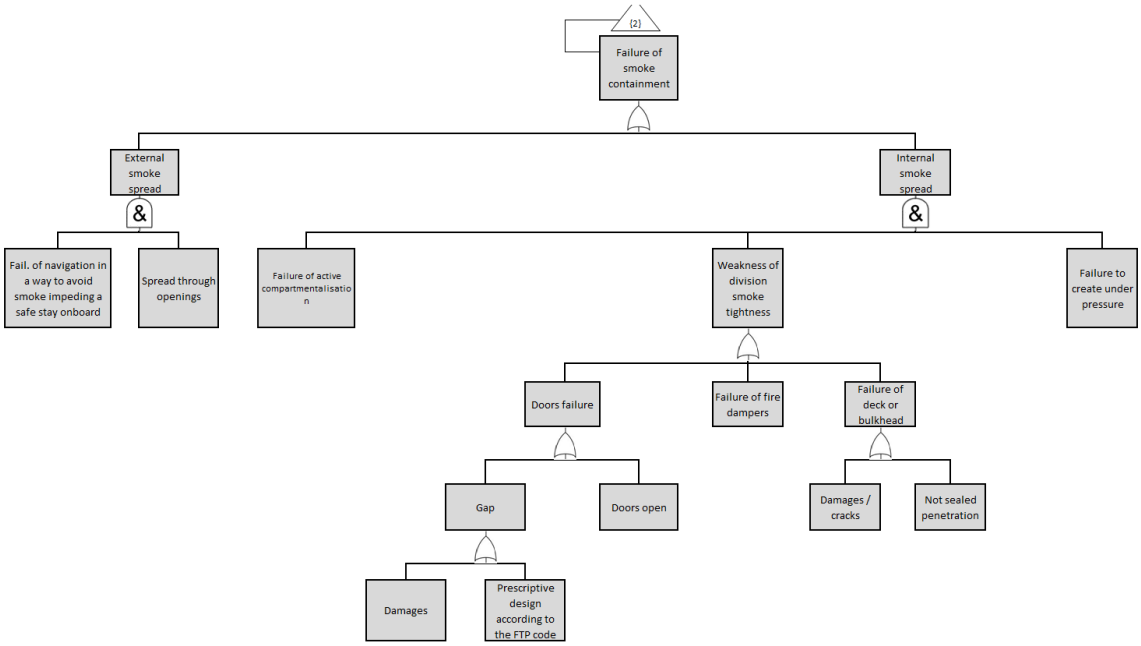


Figure 76. Sub-tree for "Failure of smoke containment" – Ro-ro passenger ships – Closed and open ro-ro spaces.

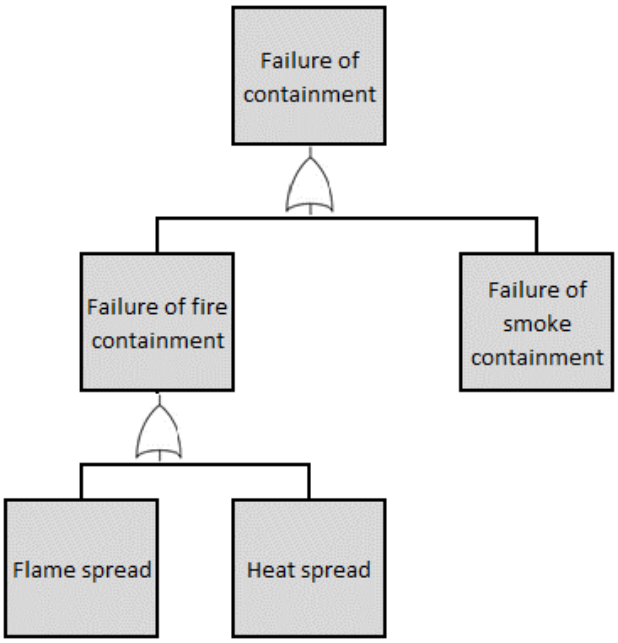


Figure 77. Containment fault tree – Ro-ro passenger ships – Weather decks.

Evacuation:

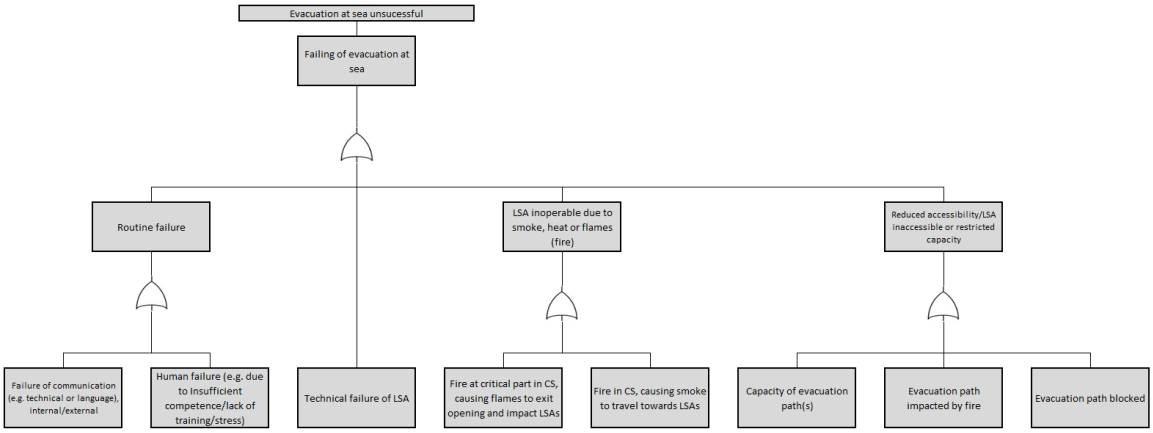


Figure 78. Evacuation at sea fault tree – Ro-ro passenger ships – Closed ro-ro spaces.

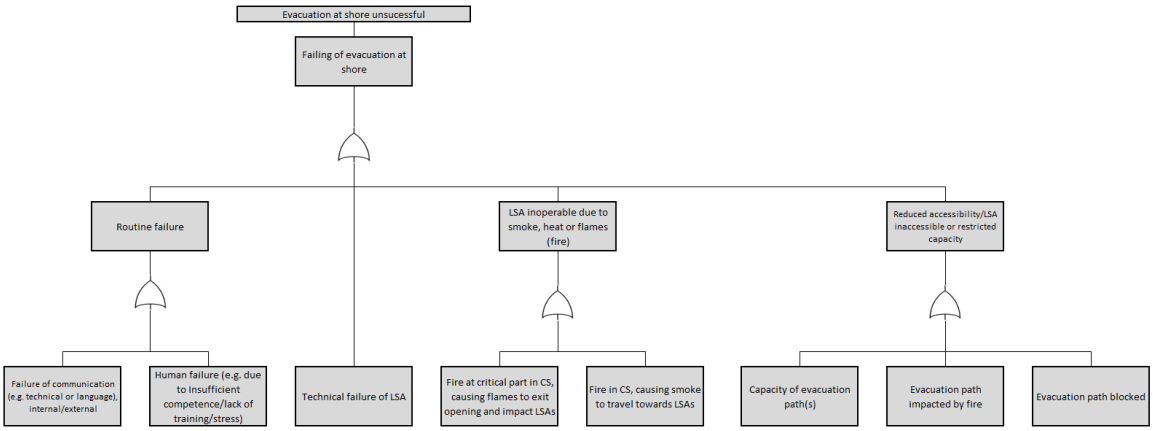


Figure 79. Evacuation at shore fault tree – Ro-ro passenger ships – Closed ro-ro spaces.

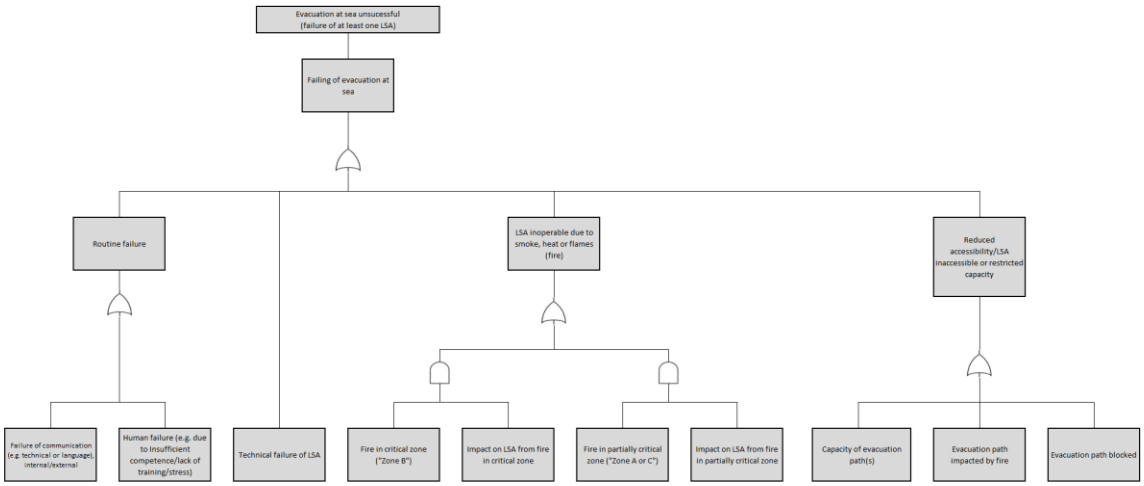


Figure 80. Evacuation at sea fault tree – Ro-ro passenger ships – Open ro-ro spaces.

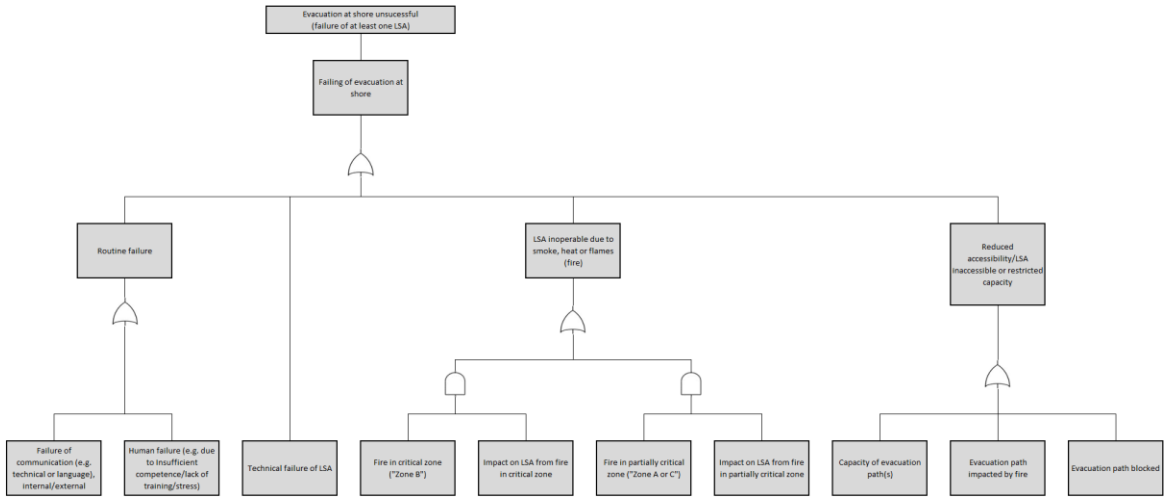


Figure 81. Evacuation at shore fault tree – Ro-ro passenger ships – Open ro-ro spaces.

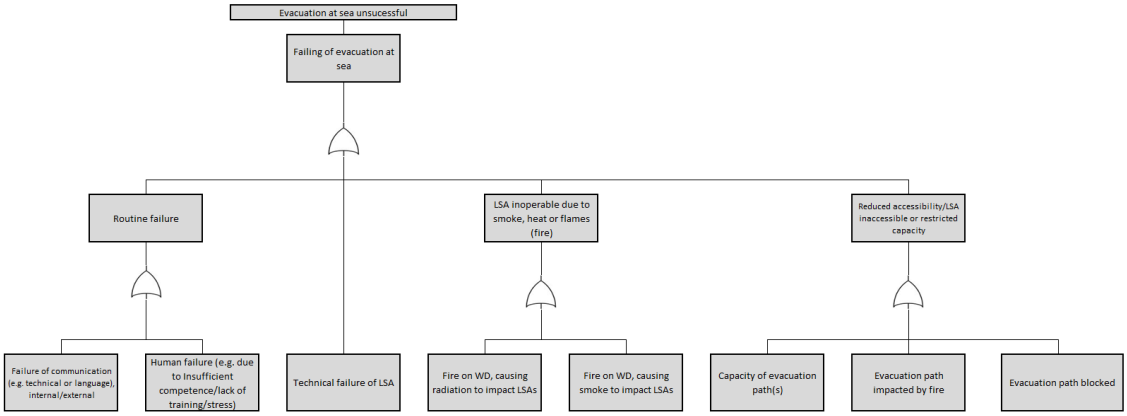


Figure 82. Evacuation at sea fault tree – Ro-ro passenger ships – Weather decks.

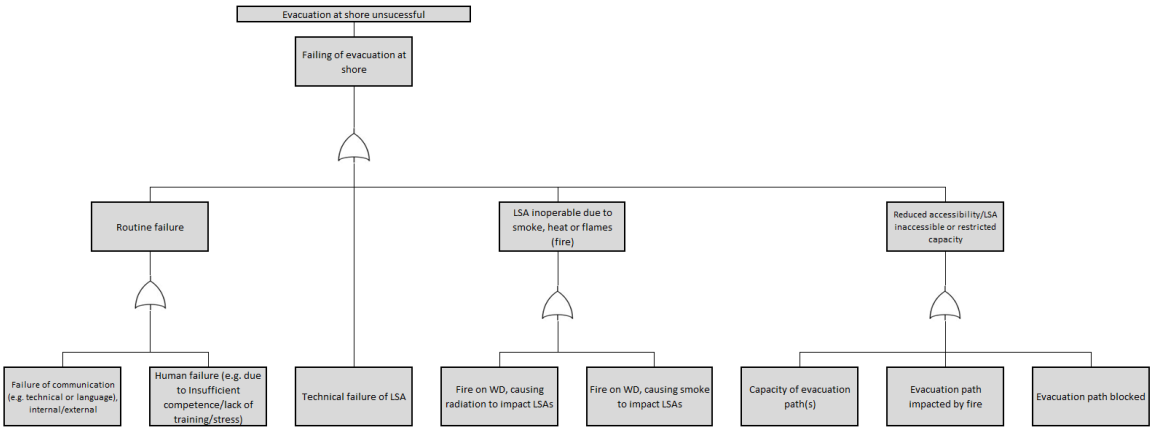


Figure 83. Evacuation at shore fault tree – Ro-ro passenger ships – Weather decks.

13.2.2 Ro-ro cargo ships

Event tree:

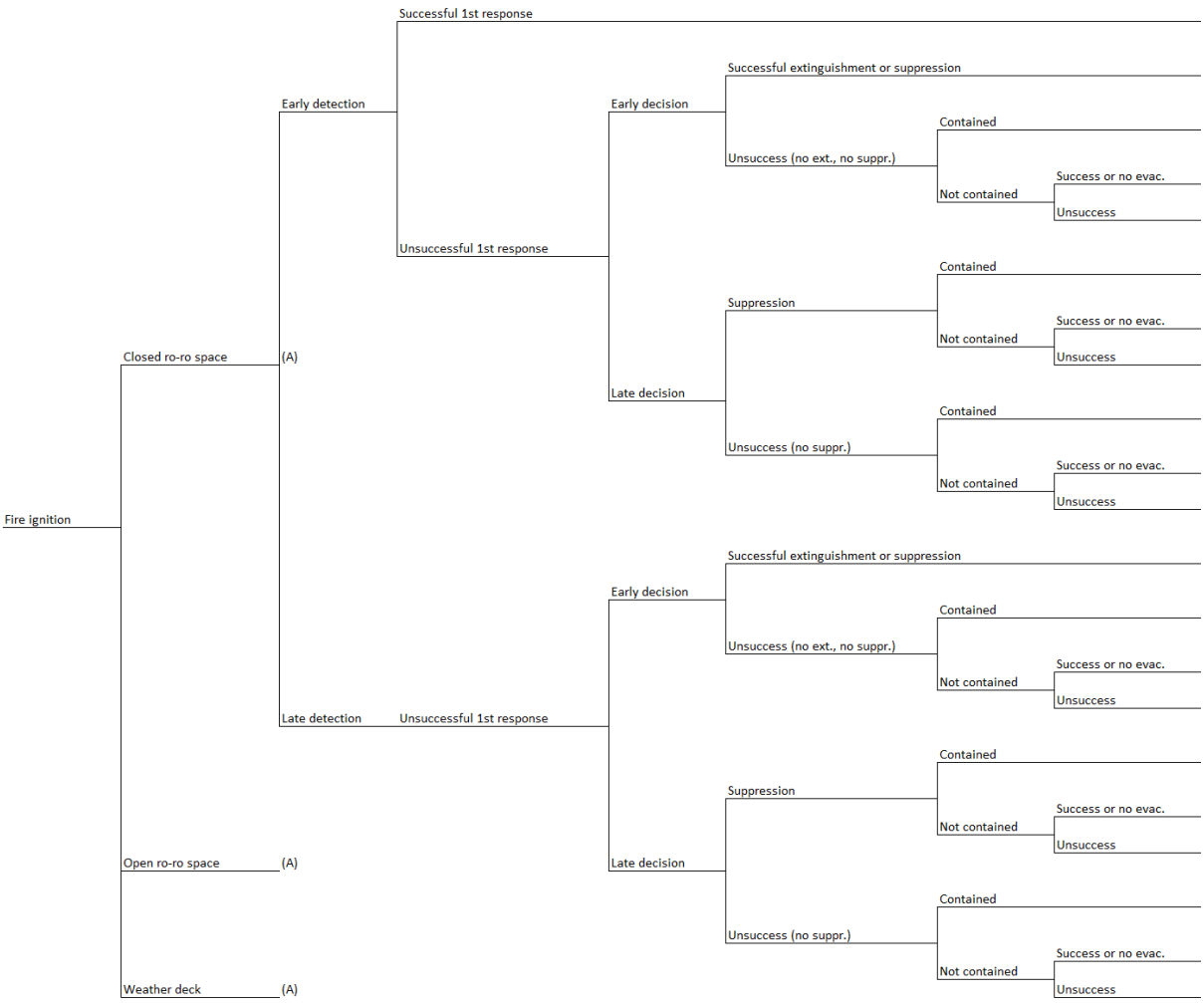


Figure 84. Main event tree – Ro-ro cargo ships.

Ignition:

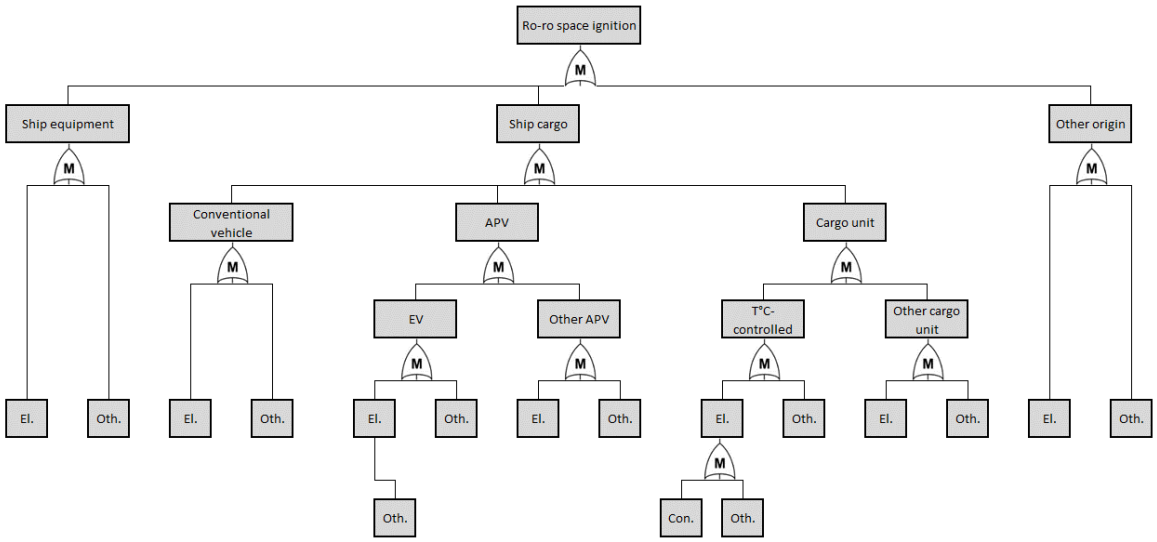


Figure 85. Contribution tree for ignition – Ro-ro cargo ships – Closed and open ro-ro spaces.

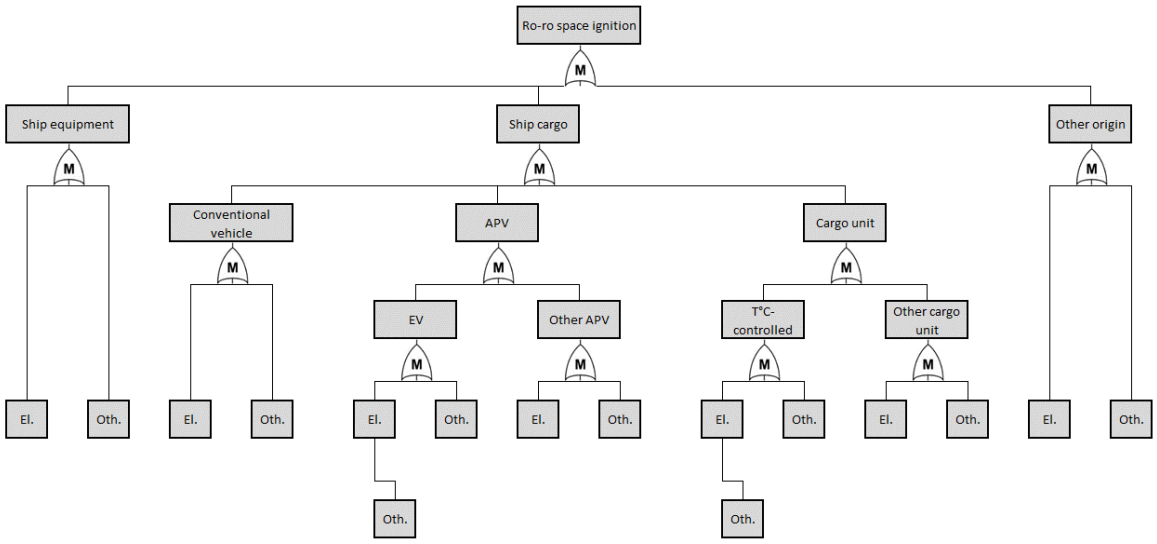


Figure 86. Contribution tree for ignition – Ro-ro cargo ships – Weather decks.

Detection:

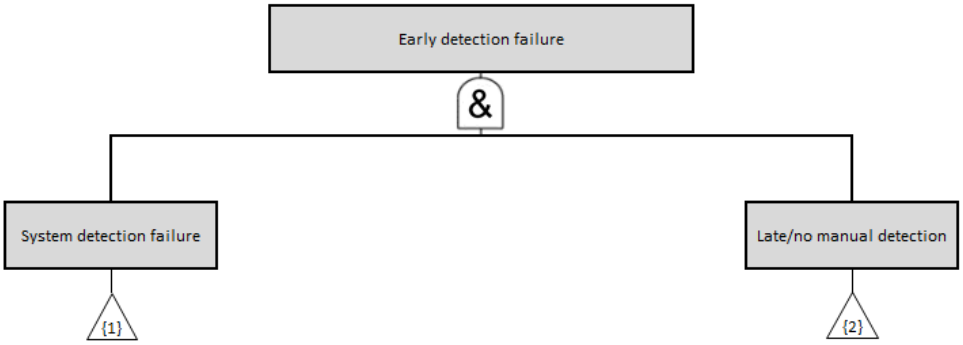


Figure 87. Detection fault tree – Ro-ro cargo ships – Closed, open ro-ro spaces and weather decks.

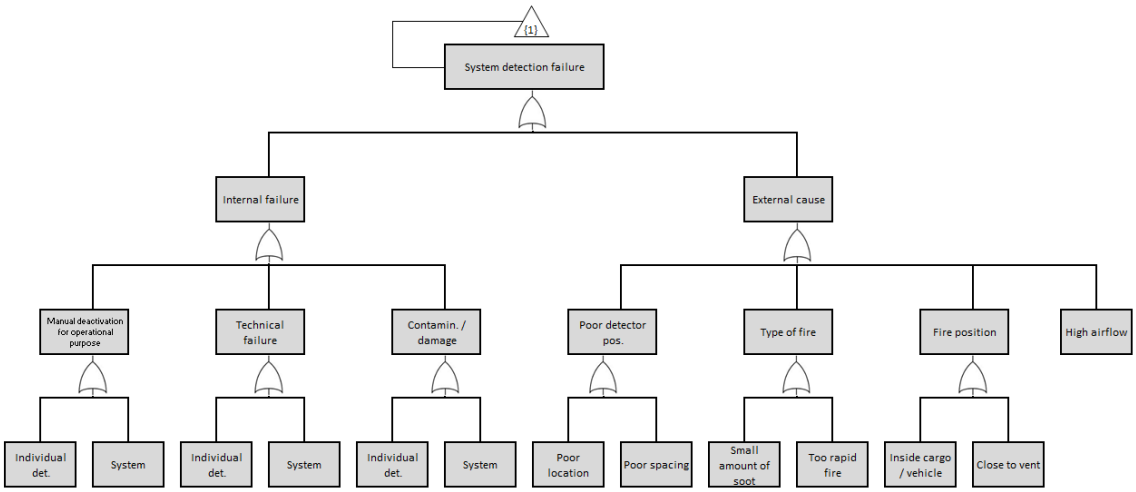


Figure 88. Sub-tree for "System detection failure" – Ro-ro cargo ships – Closed and open ro-ro spaces.

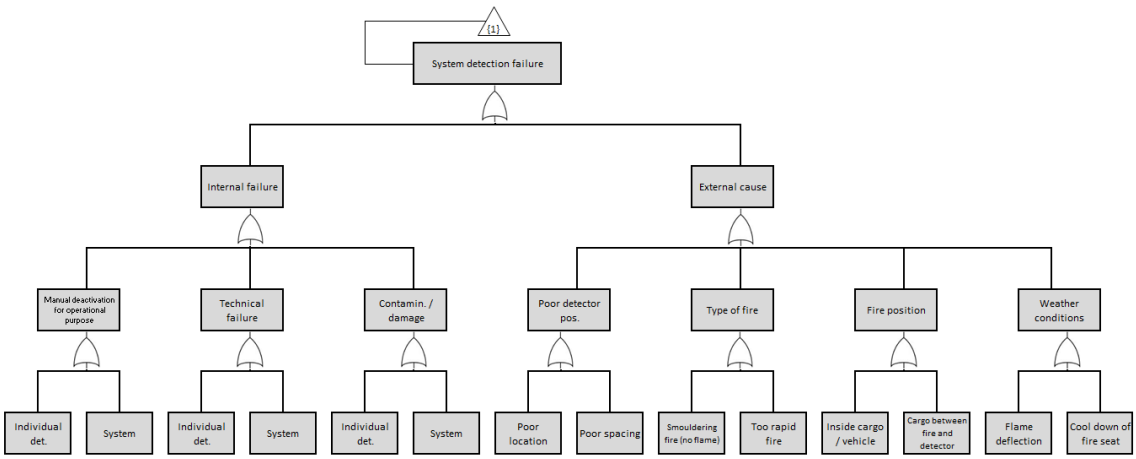


Figure 89. Sub-tree for "System detection failure" – Ro-ro cargo ships – Weather decks.

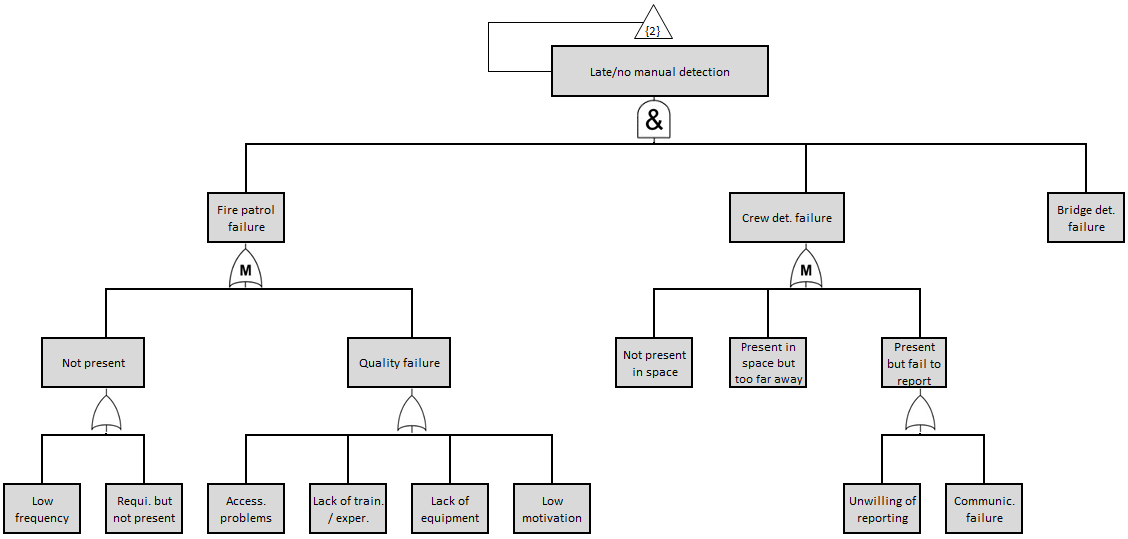


Figure 90. Sub-tree for "Late/no manual detection" – Ro-ro cargo ships – Closed, open ro-ro spaces and weather decks.

First response:

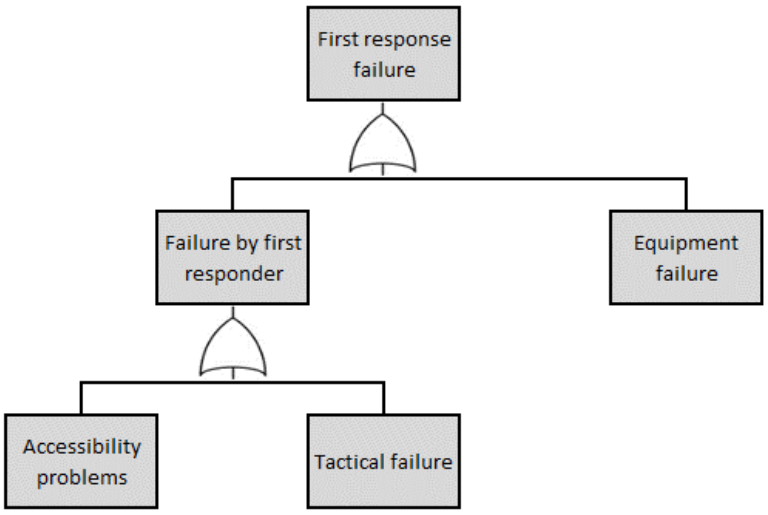


Figure 91. First response fault tree – Ro-ro cargo ships – Closed, open ro-ro spaces and weather decks.

Decision:

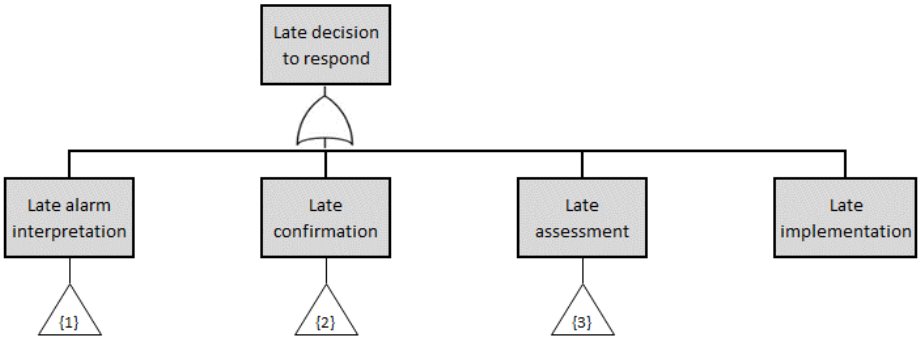


Figure 92. Decision fault tree – Ro-ro cargo ships – Closed, open ro-ro spaces and weather decks.

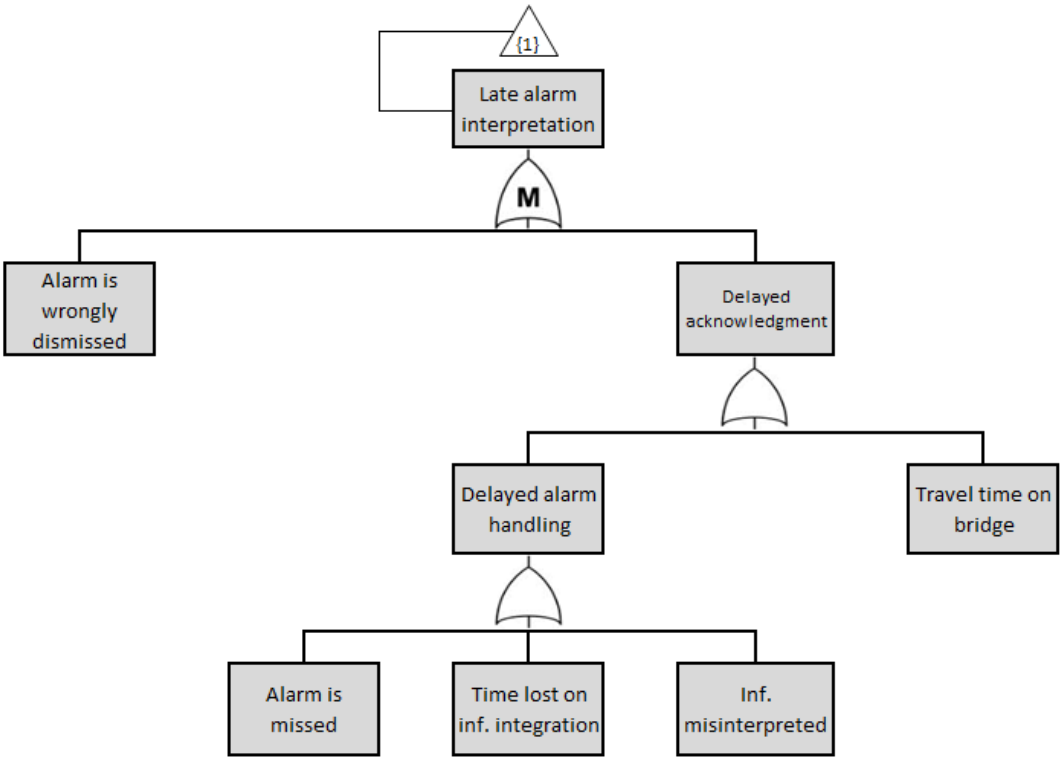


Figure 93. Sub-tree for "Late alarm interpretation" – Ro-ro cargo ships – Closed, open ro-ro spaces and weather decks.

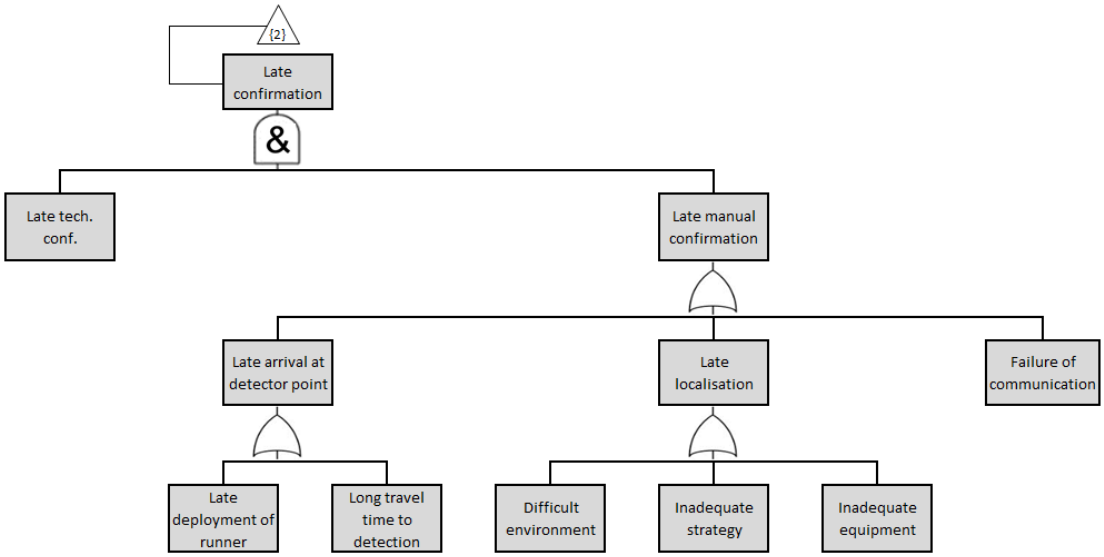


Figure 94. Sub-tree for "Late confirmation" – Ro-ro cargo ships – Closed, open ro-ro spaces and weather decks.

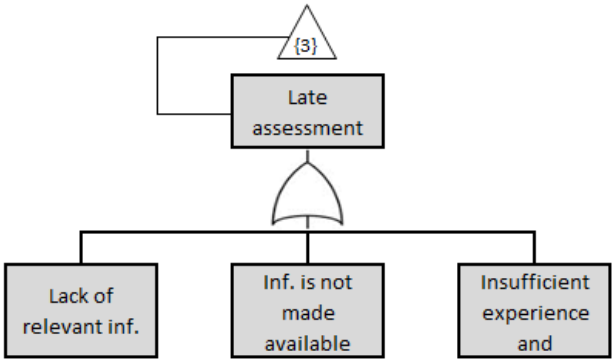


Figure 95. Sub-tree for "Late assessment" – Ro-ro cargo ships – Closed, open ro-ro spaces and weather decks.

Extinguishment:

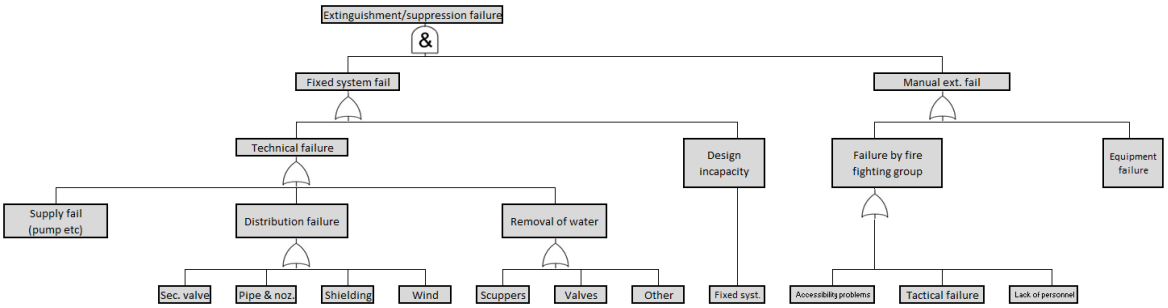


Figure 96. Extinguishment fault tree – Ro-ro cargo ships – Closed and open ro-ro spaces.

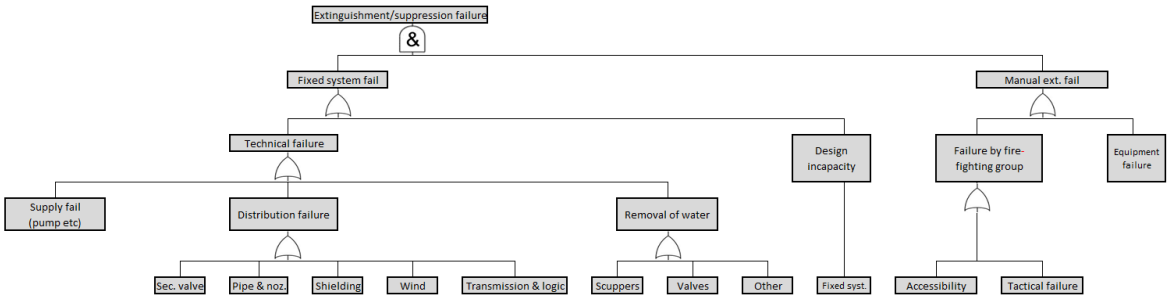


Figure 97. Extinguishment fault tree – Ro-ro cargo ships – Weather decks.

Containment:

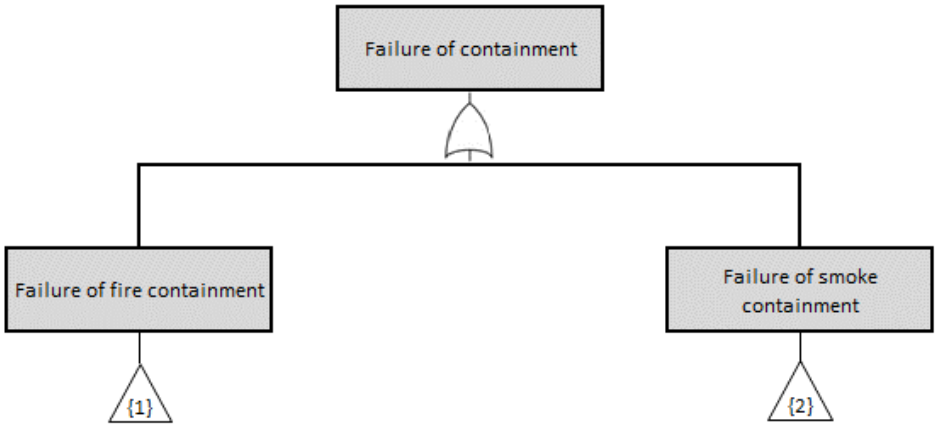


Figure 98. Containment fault tree – Ro-ro cargo ships – Closed and open ro-ro spaces.

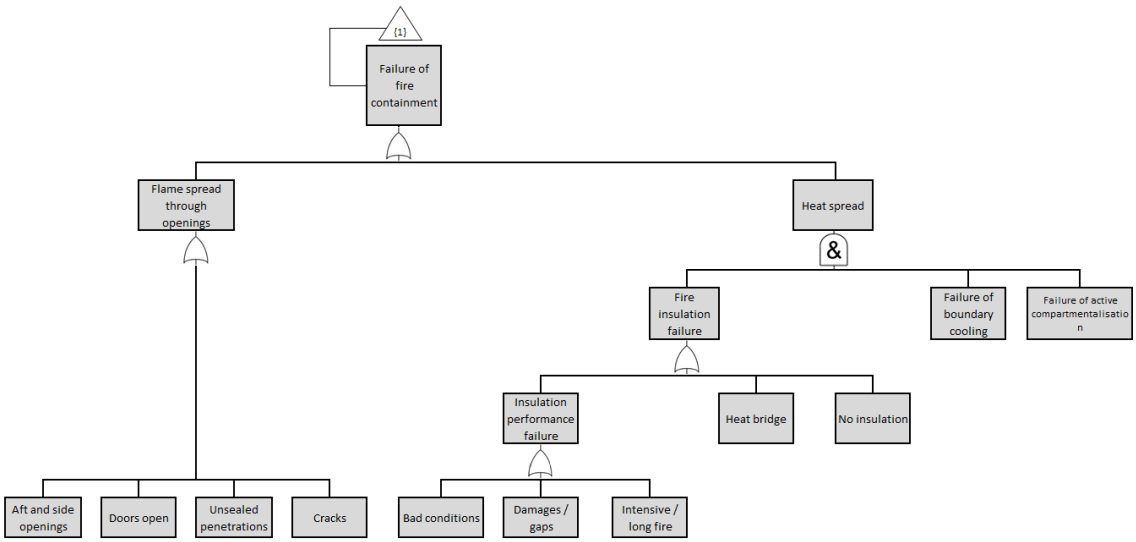


Figure 99. Sub-tree for "Failure of fire containment" – Ro-ro cargo ships – Closed and open ro-ro spaces.

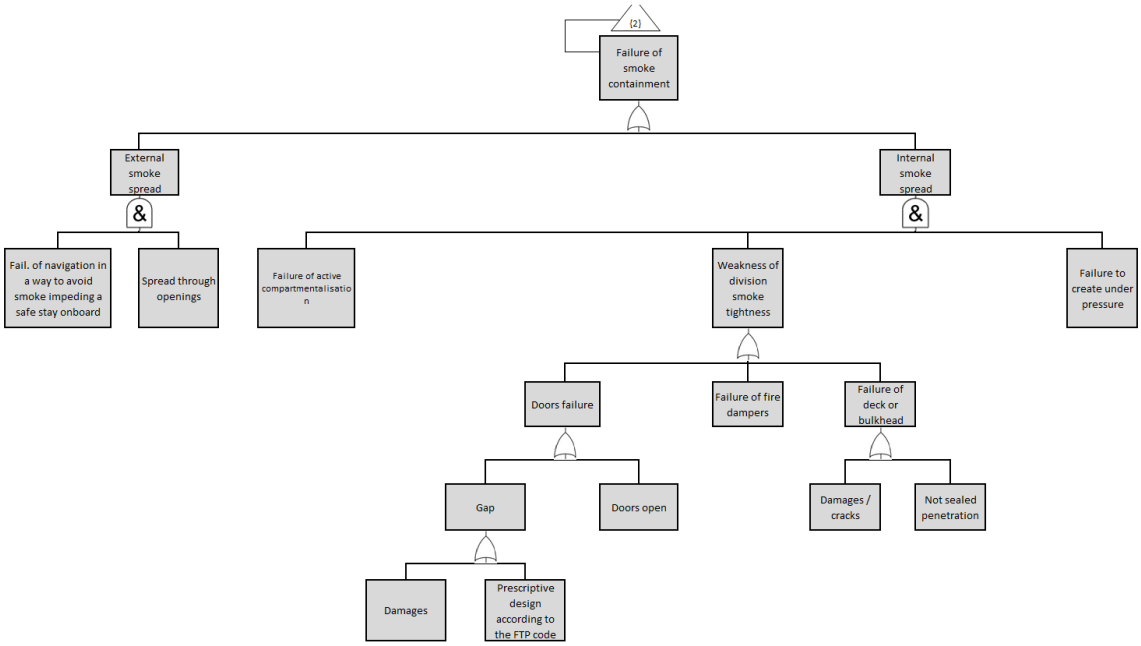


Figure 100. Sub-tree for "Failure of smoke containment" – Ro-ro cargo ships – Closed and open ro-ro spaces.

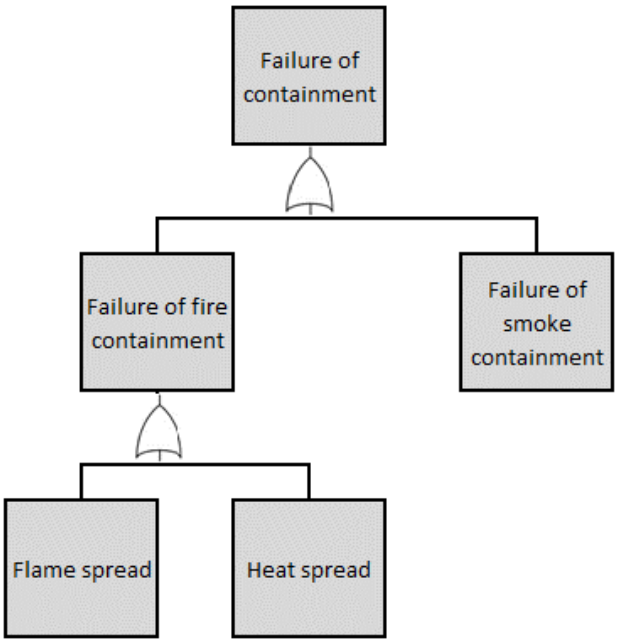


Figure 101. Containment fault tree – Ro-ro cargo ships – Weather decks.

Evacuation:

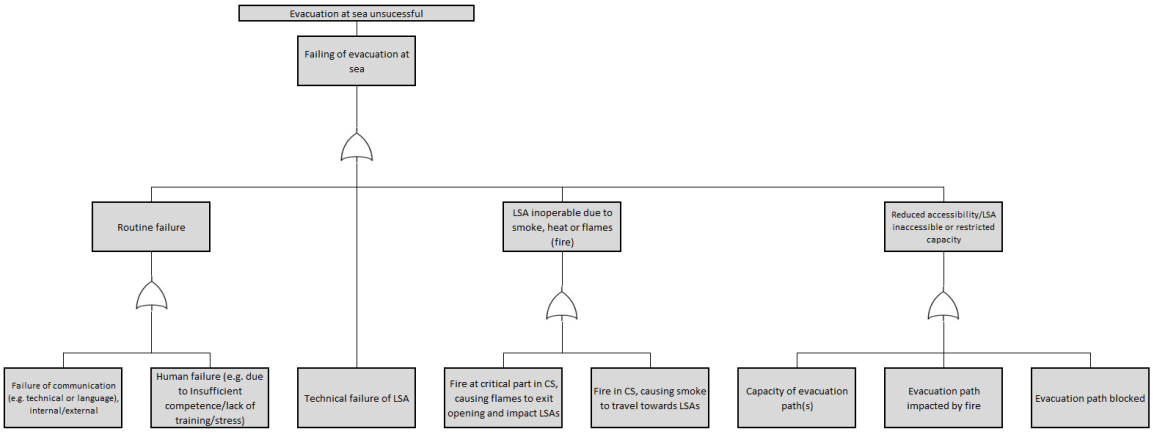


Figure 102. Evacuation at sea fault tree – Ro-ro cargo ships – Closed ro-ro spaces.

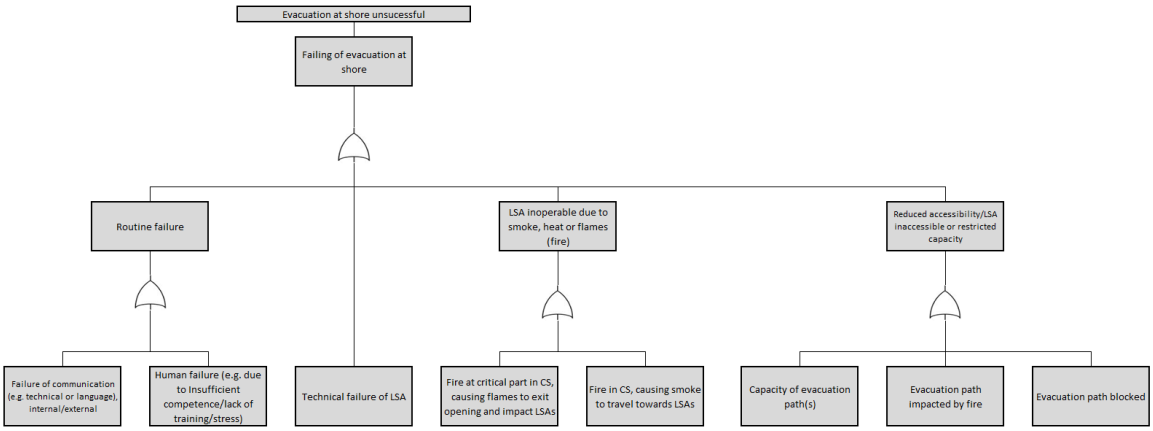


Figure 103. Evacuation at shore fault tree – Ro-ro cargo ships – Closed ro-ro spaces.

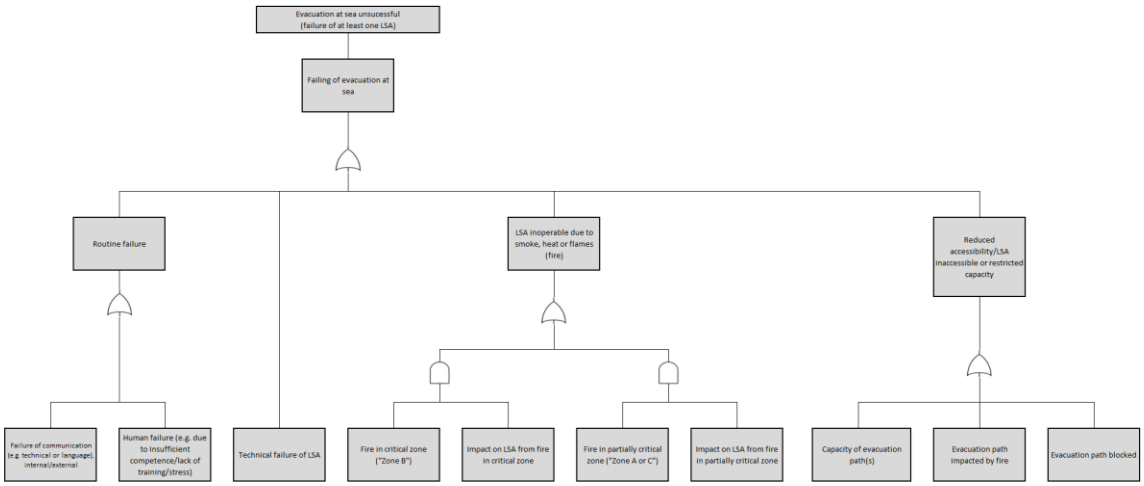


Figure 104. Evacuation at sea fault tree – Ro-ro cargo ships – Open ro-ro spaces.

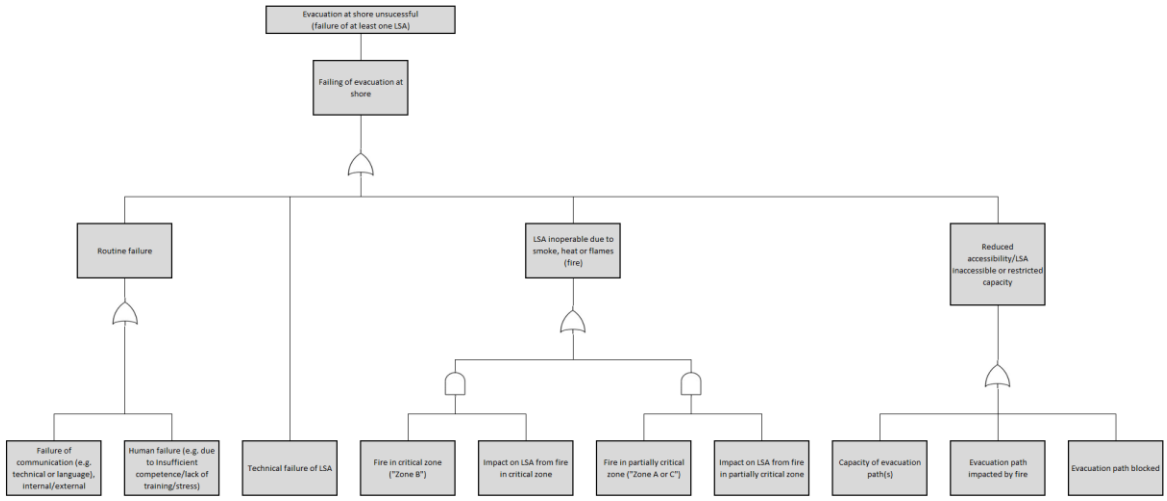


Figure 105. Evacuation at shore fault tree – Ro-ro cargo ships – Open ro-ro spaces.

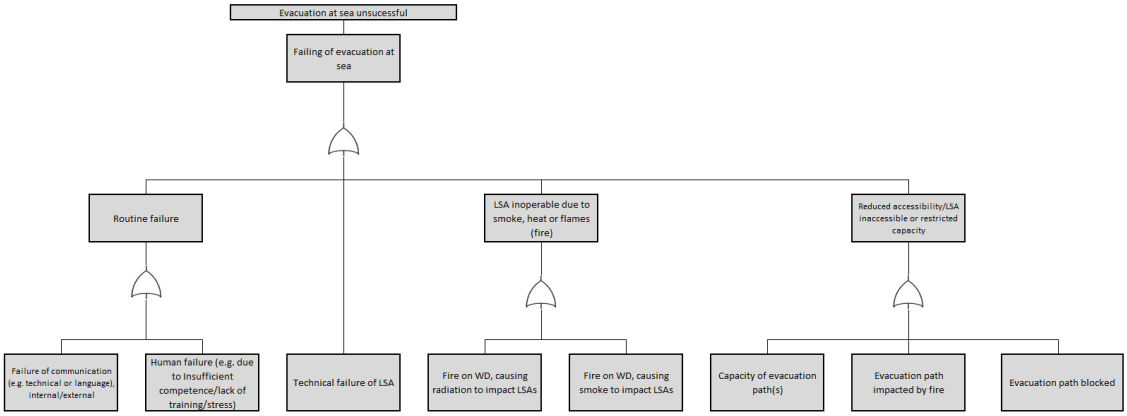


Figure 106. Evacuation at sea fault tree – Ro-ro cargo ships – Weather decks.

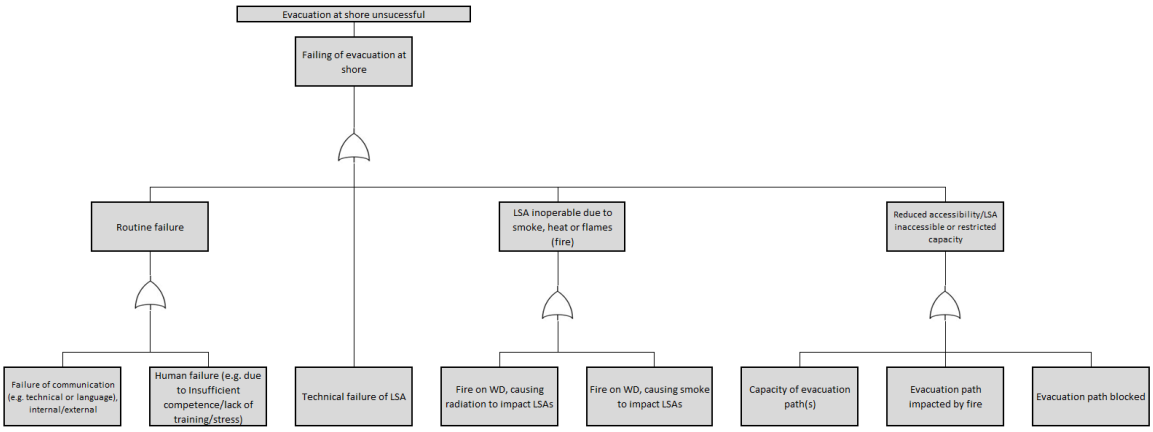


Figure 107. Evacuation at shore fault tree – Ro-ro cargo ships – Weather decks.

13.2.3 Vehicle carriers

Event tree:

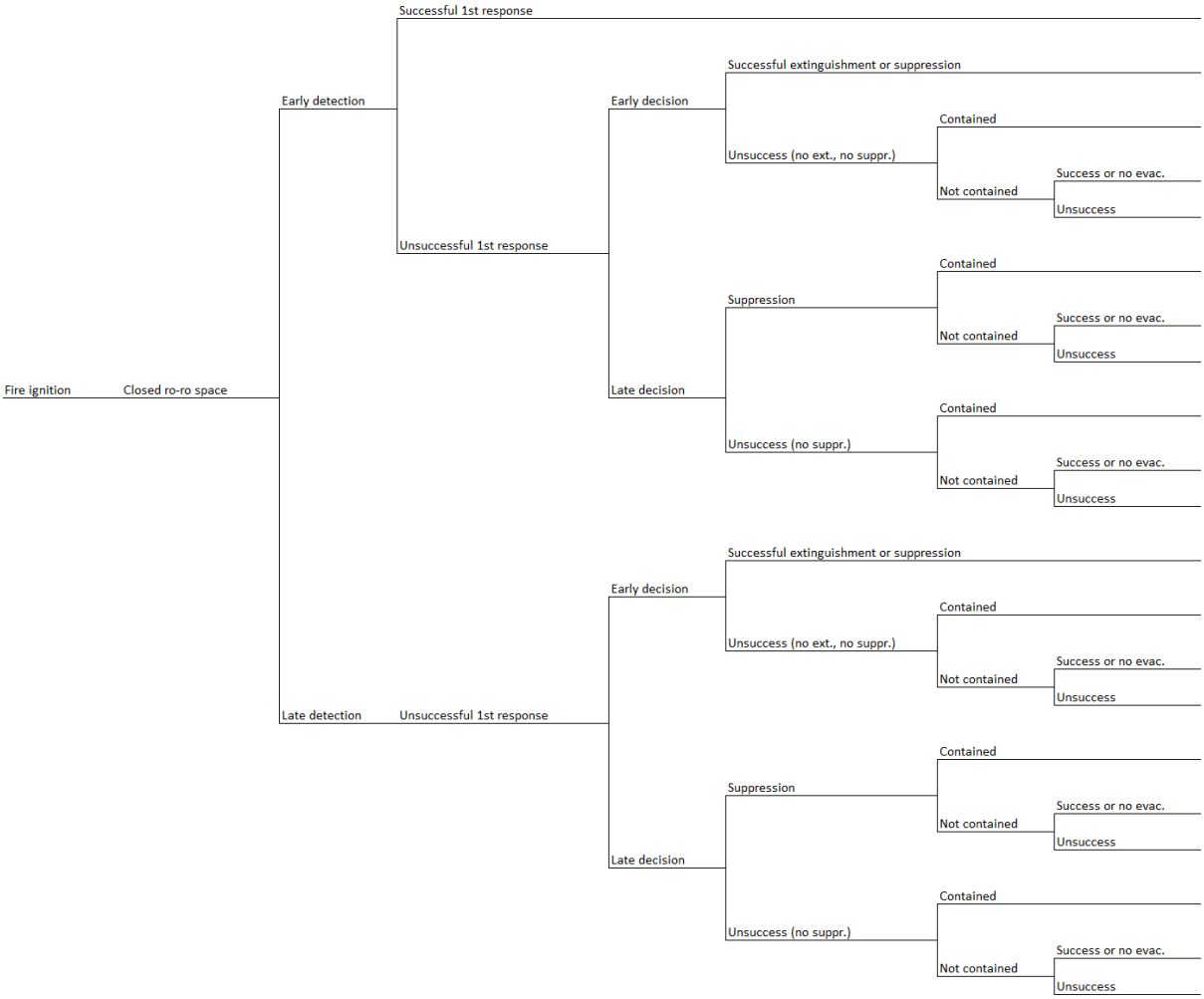


Figure 108. Main event tree – Vehicle carriers.

Ignition:

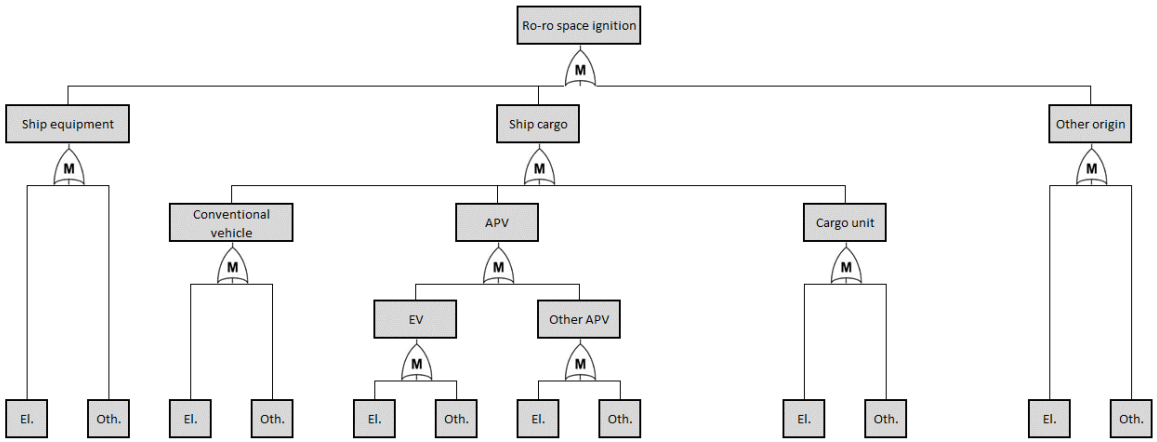


Figure 109. Contribution tree for ignition – Vehicle carriers – Closed ro-ro spaces.

Detection:

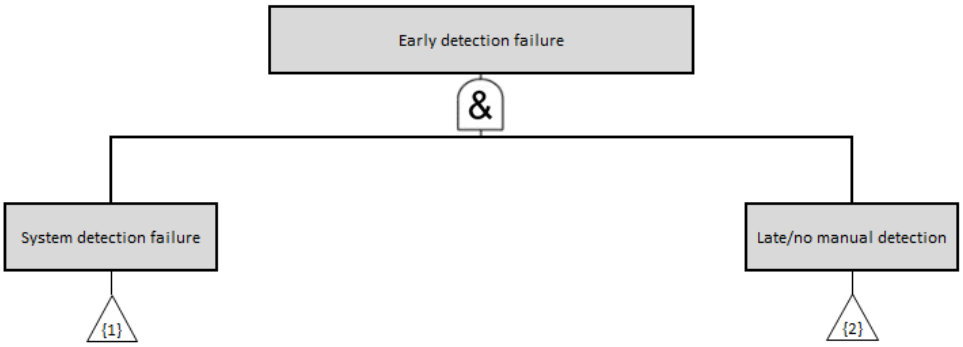


Figure 110. Detection fault tree – Vehicle carriers – Closed ro-ro spaces.

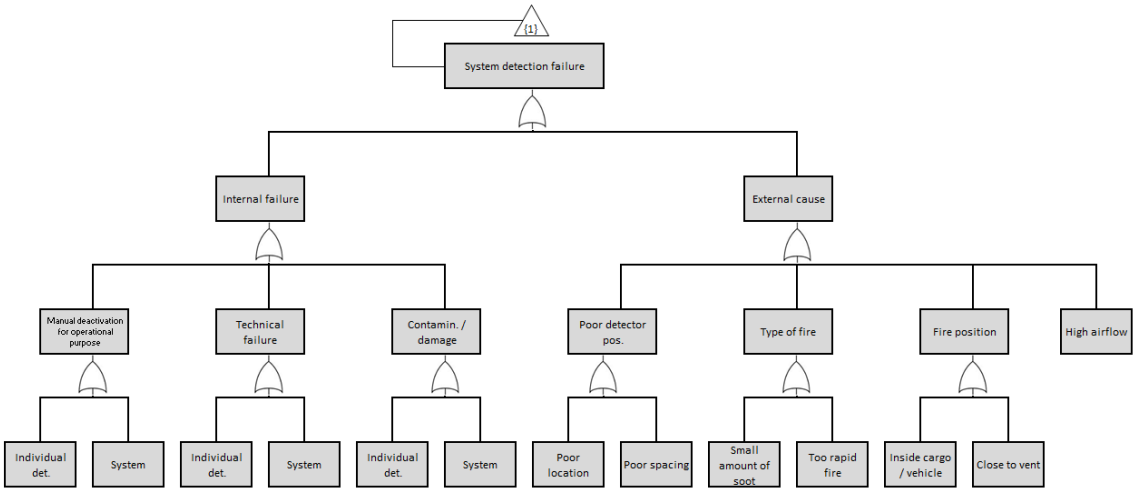


Figure 111. Sub-tree for "System detection failure" – Vehicle carriers – Closed ro-ro spaces.

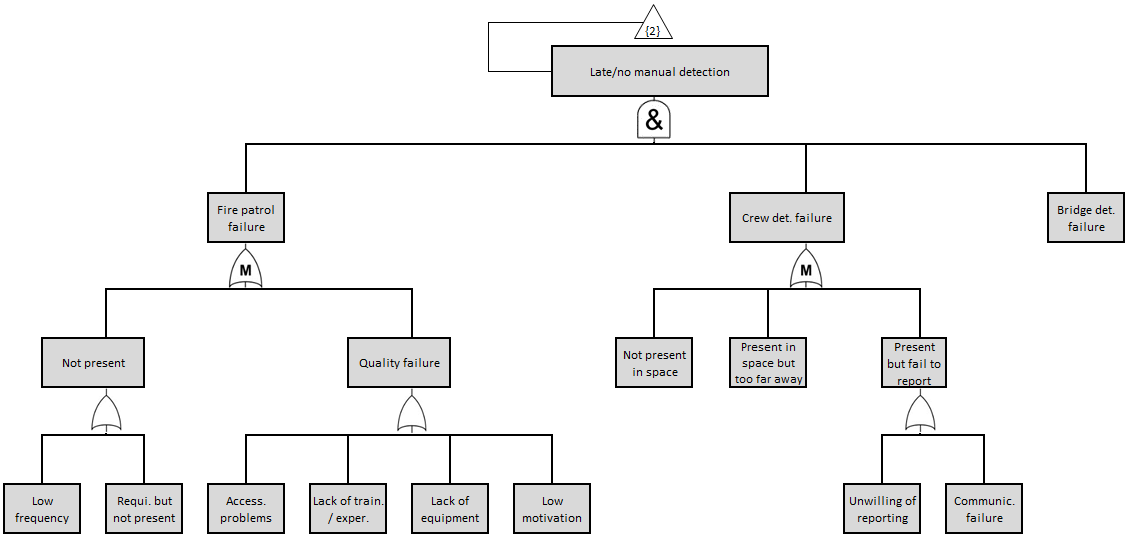


Figure 112. Sub-tree for "Late/no manual detection" – Vehicle carriers – Closed ro-ro spaces.

First response:

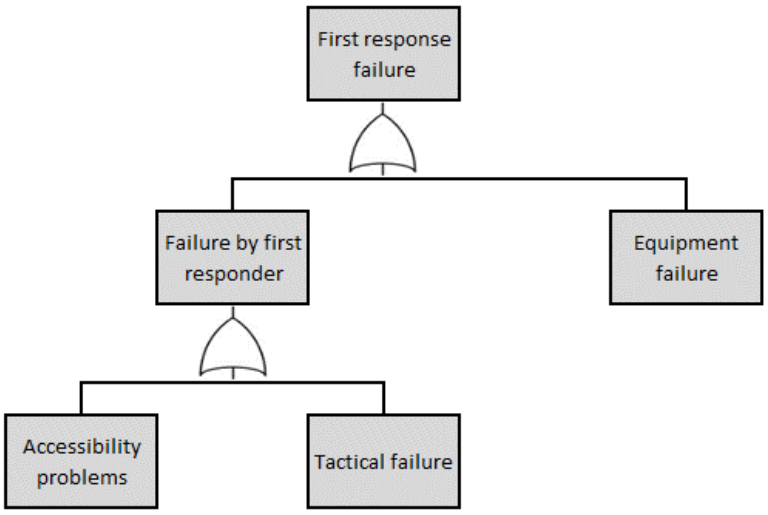


Figure 113. First response fault tree – Vehicle carriers – Closed ro-ro spaces.

Decision:

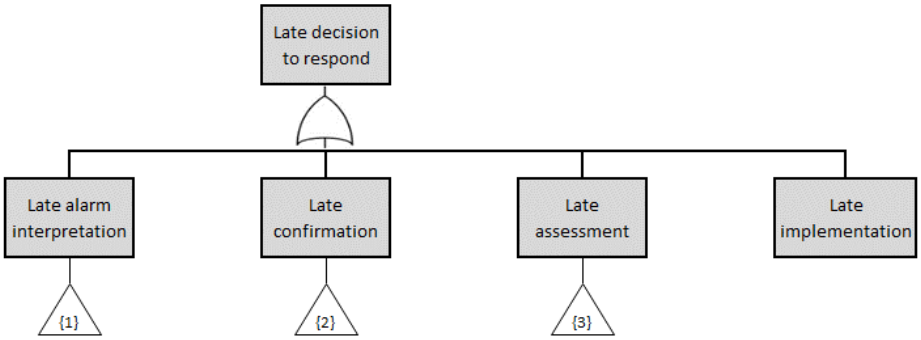


Figure 114. Decision fault tree – Vehicle carriers – Closed ro-ro spaces.

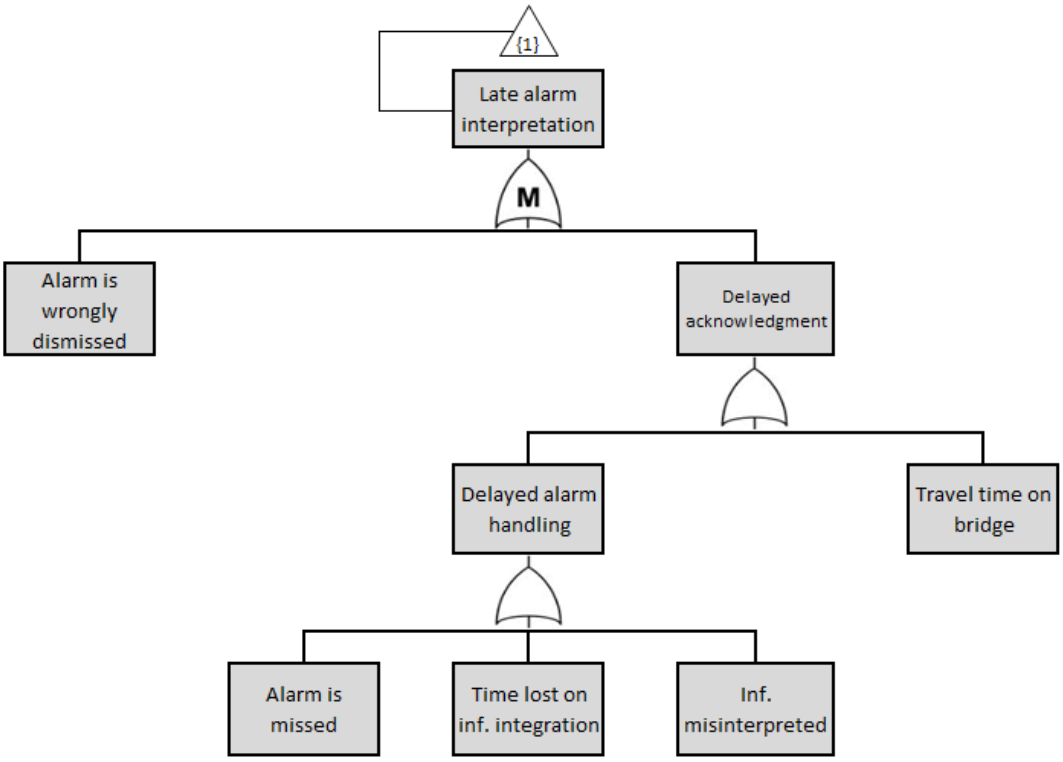


Figure 115. Sub-tree for "Late alarm interpretation" – Vehicle carriers – Closed ro-ro spaces.

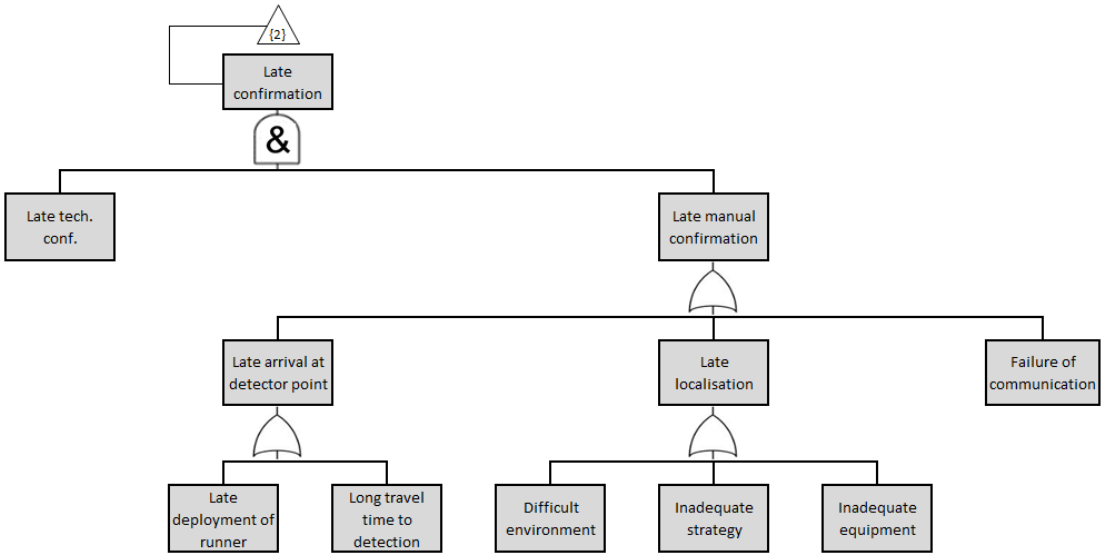


Figure 116. Sub-tree for "Late confirmation" – Vehicle carriers – Closed ro-ro spaces.

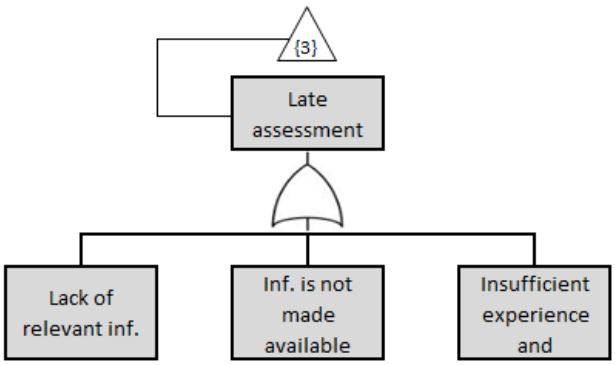


Figure 117. Sub-tree for "Late assessment" – Vehicle carriers – Closed ro-ro spaces.

Extinguishment:

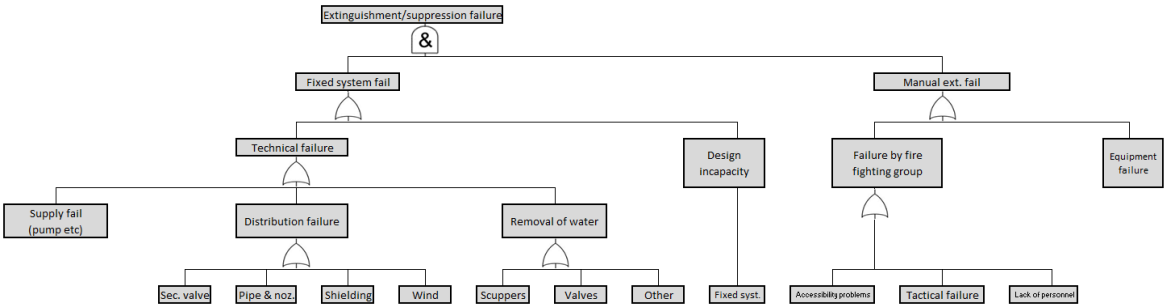


Figure 118. Extinguishment fault tree – Vehicle carriers – Closed ro-ro spaces.

Containment:

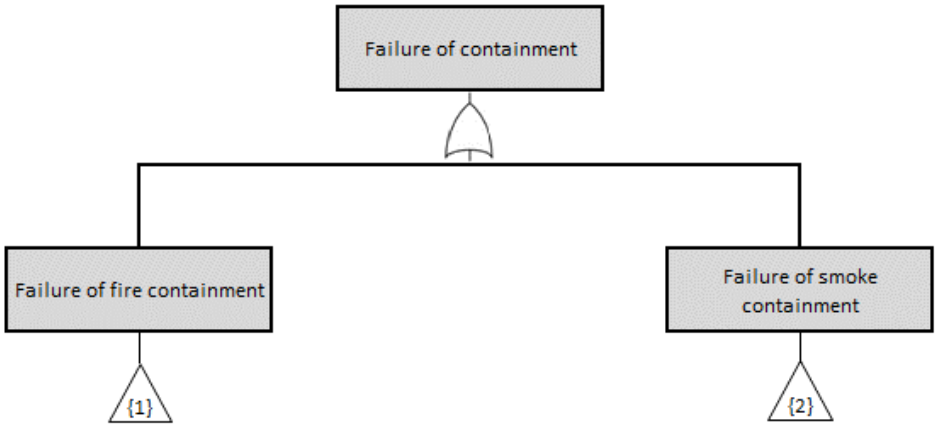


Figure 119. Containment fault tree – Vehicle carriers – Closed ro-ro spaces.

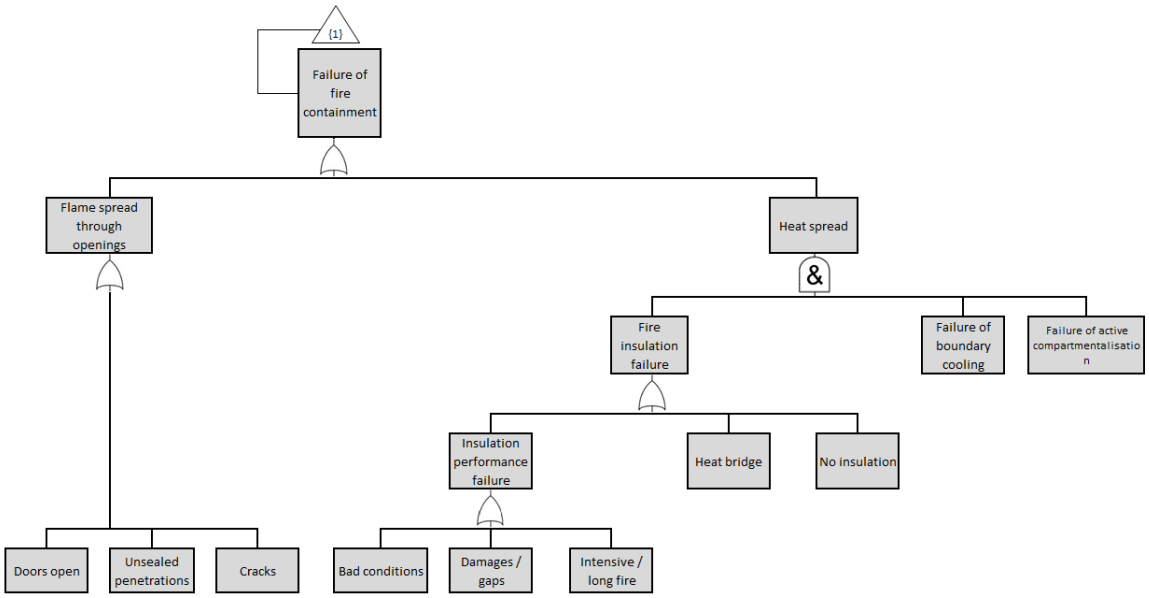


Figure 120. Sub-tree for "Failure of fire containment" – Vehicle carriers – Closed ro-ro spaces.

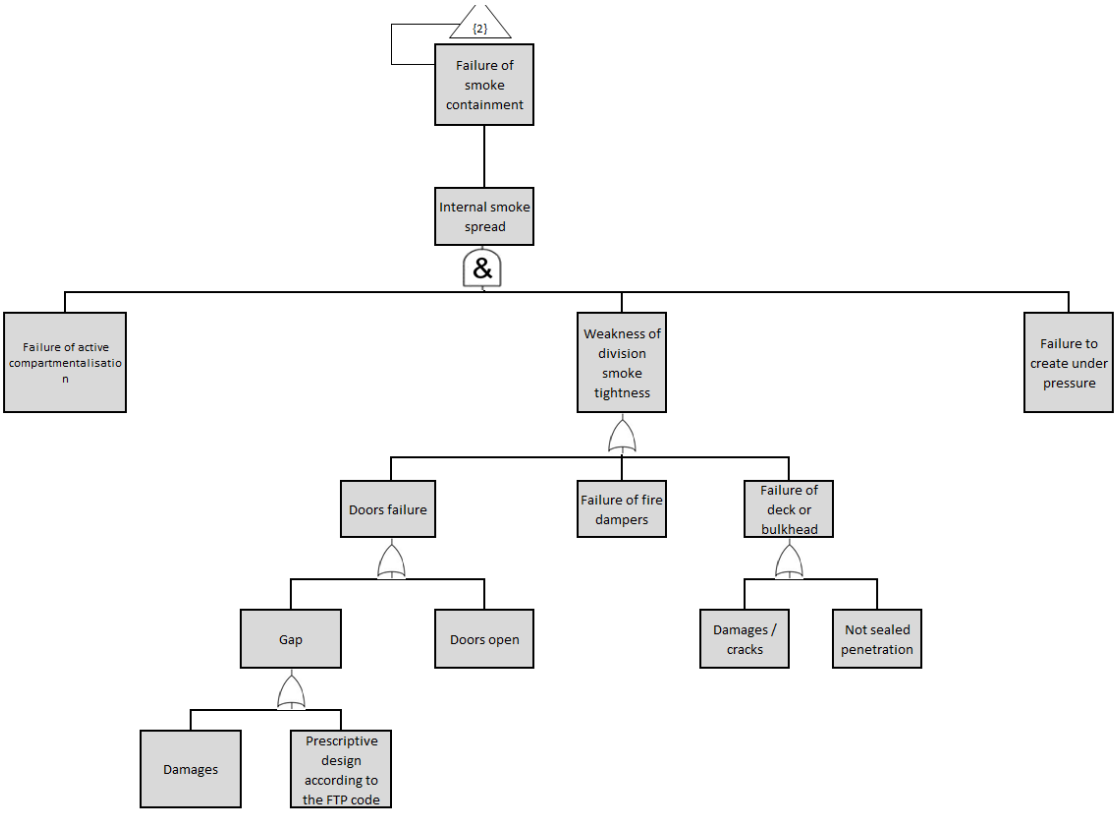


Figure 121. Sub-tree for "Failure of smoke containment" – Vehicle carriers – Closed ro-ro spaces.

Evacuation:

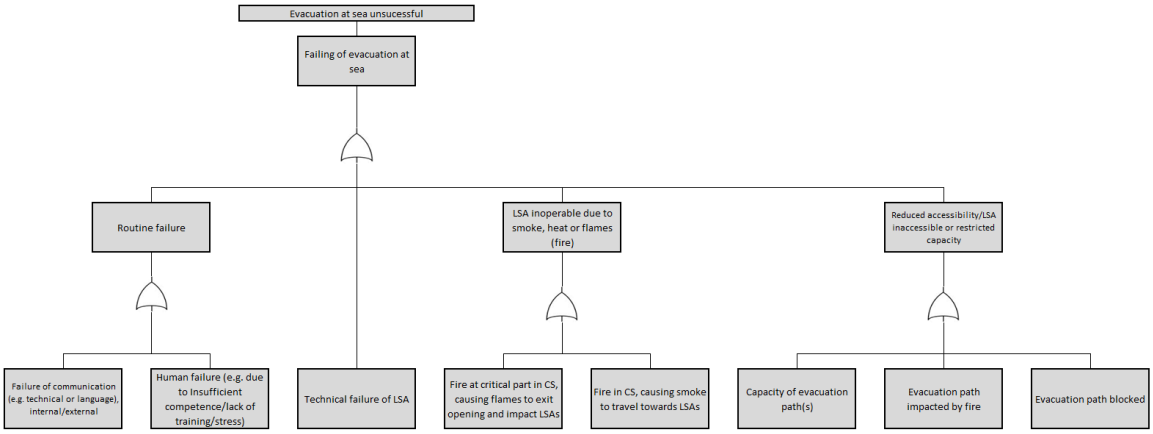


Figure 122. Evacuation at sea fault tree – Vehicle carriers – Closed ro-ro spaces.

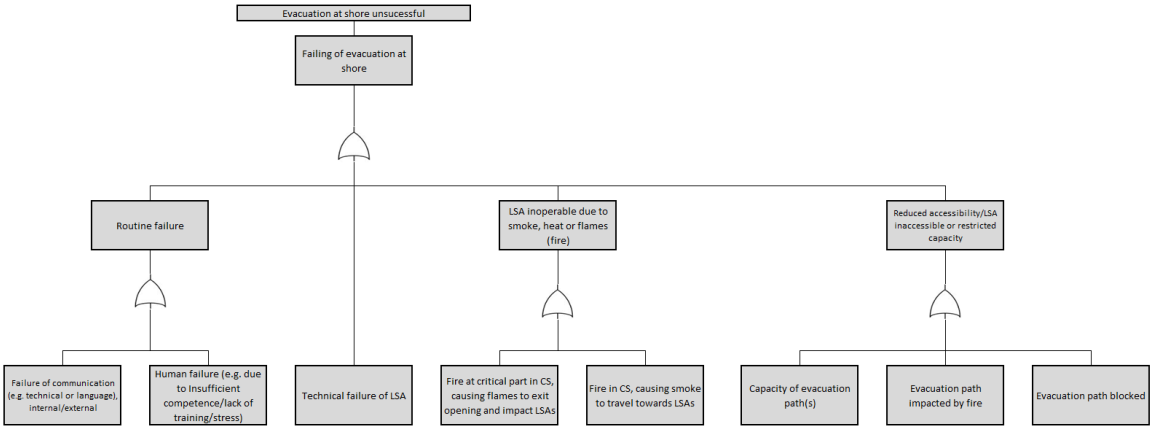


Figure 123. Evacuation at shore fault tree – Vehicle carriers – Closed ro-ro spaces.

13.3 ANNEX 3: Corrigendum D04.2

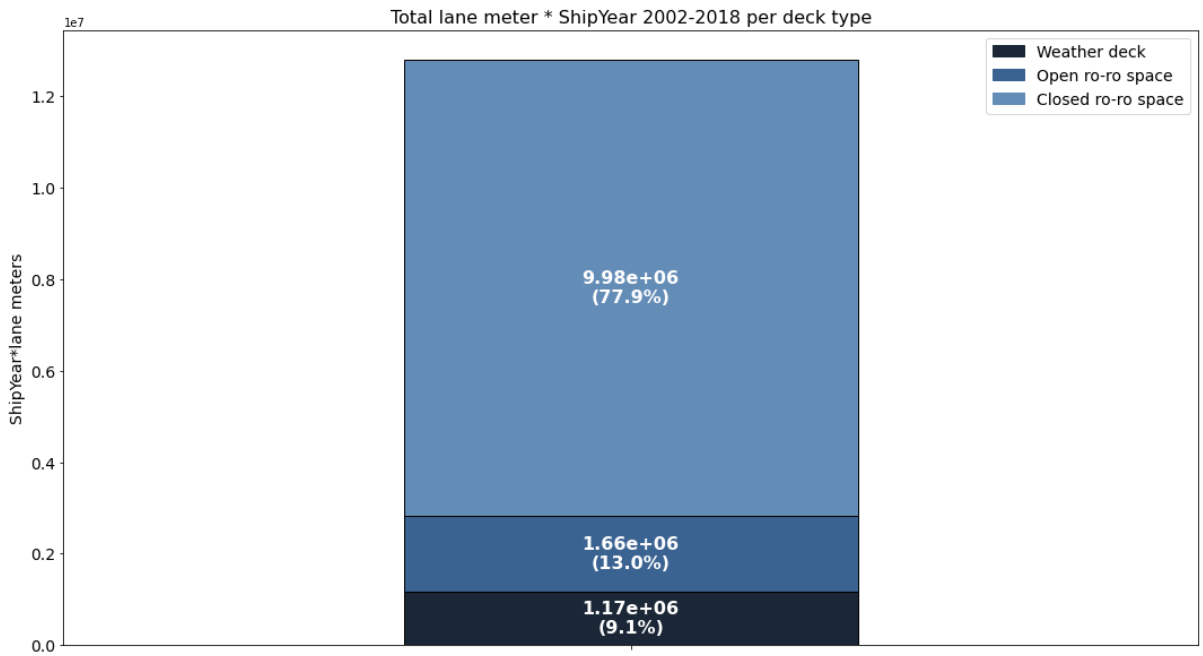
This annex provides a corrigendum of LASH FIRE deliverable D04.2 “Ro-ro space fire database and statistical analysis report” [3], issued in March 2021. Only corrected tables and figure are provided. They are labelled with their original number.

D04.2\Table 29. Exposure time (in lane meter-years) for ro-ro passenger and ro-ro cargo ships, for the period 2002-2018

	Ro-pax ships	Ro-ro cargo ships	TOTAL
Exposure time	12 806 663	16 206 516	29 013 180

D04.2\Table 30. Fire frequencies in ro-ro spaces per type of ro-ro ships, per lane meter-year

Ships type	Exposure Time (LMyear)	Number of accidents	Number of serious accidents	Fire frequency – All accidents ($LMyear^{-1}$)	Fire frequency – Serious accidents ($LMyear^{-1}$)
Ro-pax ships	12 806 663	30	22	2.34E-6	1.72E-6
Ro-ro cargo ships	16 206 516	12	10	7.40E-7	6.17E-7
TOTAL	29 013 180	42	32	1.45E-6	1.10E-6



D04.2\Figure 67. Distribution of lane meter-years for the three types of ro-ro spaces in the ro-ro passenger fleet.

D04.2\Table 33. Frequency of fires per type of ro-ro space in ro-ro passenger ships, per lane meter-year

Type of space	Exposure time (LMyear)	Number of accidents	Space dependent-fire frequency – All accidents ($LMyear^{-1}$)
Closed ro-ro space	9.98E6	24	2.40E-6
Open ro-ro space	1.66E6	5	3.01E-6
Weather deck	1.17E6	1	8.57E-7

13.4 ANNEX 4: Frequency of fires in ro-ro spaces per ro-ro space type – Ro-ro cargo ships

Main author of the chapter: Eric De Carvalho, BV.

In LASH FIRE D04.2 "Ro-ro space fire database and statistical analysis report" [3], the fire frequencies per ro-ro space type and unit were only determined for the ro-ro passenger ships and vehicle carriers. Indeed, at that time, the available MOAG dataset was not representative of the world fleet of ro-ro cargo ships. Therefore, it was not deemed accurate to estimate the distribution of ro-ro space for ro-ro cargo ships based on this dataset.

After D04.2, a new ship operator (MOAG member) offered to share lane meter data and distribution for its ro-ro cargo fleet, which significantly increased the population of the dataset and provided new ro-ro space arrangements.

Due to the limited time frame and the remaining budget, it was decided to develop a simple and coarse approach (not as much as sophisticated as the one used in D04.2) in order to estimate the fire frequencies per ro-ro space type and unit for the ro-ro cargo ships.

Altogether, the MOAG dataset counted 64 ro-ro cargo ships. Ro-ro cargo ships with missing data, not found in the WP04 Fleet General database or deemed to be domestic were excluded from the dataset. Then, the dataset counted 52 ro-ro cargo ships. The sister ships were removed. Finally, the dataset counted 24 different ro-ro cargo ships. The 24 ships were categorised into three different classes, each class with a given percentage of closed, open ro-ro spaces and weather decks. The class percentages were set to the average of the ships constituting a same class. A visual check of the ro-ro space arrangement of all the 24 ships was performed in order to verify the consistency within a class. A criterion based on gross tonnage (GT) was developed to sort out the ships in each class (Table 27). By that means, it was possible to assign a class and so the percentage of closed, open ro-ro spaces and weather decks to each ro-ro cargo ship of the world fleet, and then to calculate the exposure time in lane meter-year and the fire frequencies per lane meter-year (Table 28).

Table 27. Categorisation of ro-ro cargo ships into three classes, percentage of ro-ro spaces and range of gross tonnage

Class	Closed	Open	Weather	GT
A	65%	0%	35%	0 < GT < 20 000
B	45%	30%	25%	20 000 ≤ GT < 40 000
C	85%	5%	10%	40 000 ≤ GT

As verification, a comparison of the exposure time of MOAG fleet (52 ro-ro cargo ships) calculated with the exact percentages provided by MOAG versus calculated with the rulesets (Table 27) was performed. A very good matching was obtained (difference < 10%).

The main identified biases or uncertainties in this approach were:

- It was not sure that the dataset provided by MOAG is representative of the world fleet of ro-ro cargo; and
- The "unidentified" fire in ro-ro spaces (in reference to casualty analysis in D04.2 [3]) was assigned to "fire in open ro-ro spaces" (Table 28) because, initially, there was not reported fires in open ro-ro paces for ro-ro cargo ships.

Despite those uncertainties, it was thought that approach is still better than simply assigning 33%/33%/33% per ro-ro space. And based on the visual review of ro-ro cargo arrangements, it was not surprising that the exposure of open ro-ro spaces in the fleet is low (about 15%) and that the exposure of weather decks is non-negligible (about 30% versus 10% for ro-ro passenger ships) (Table 28). For ro-ro cargo ships, it seems that there is more balance between closed and weather deck, which can be explained by less accommodation onboard ro-ro cargo ships and so more space for weather decks. The results are interesting since quite different than the ones for ro-ro passenger ships.

Table 28. Frequency of fires per type of ro-ro space in ro-ro cargo ships, per lane meter-year

Type of space	**Exposure time (LMyear)**	**Number of accidents**	**Space dependent-fire frequency ($LMyear^{-1}$)**	**Space dependent-fire frequency (%)**
Closed ro-ro space	9.05E+06	8	8.84E-07	56%
Open ro-ro space	2.32E+06	1	4.30E-07	14%
Weather deck	4.83E+06	3	6.21E-07	30%

13.5 ANNEX 5: List of accident investigation reports

Table 29. List of accident investigation reports related to fires originating in ro-ro spaces

Ship Name	IMO No.	Ship Type	Casualty Date	Author	Available on	Downloadable on GISIS MCI?
JOSEPH AND CLARA SMALLWOOD	8604797	Ro-pax	12/05/2003	Canada (TSB)	http://www.tsb.gc.ca/eng/rapports-reports/marine/2003/m03n0050/m03n0050.pdf	Yes
CONFIDENTIAL_RP_1[(3)]		Ro-pax	2003			
CONFIDENTIAL_RP_2		Ro-pax	2004			
VINCENZO FLORIO	9144732	Ro-pax	19/12/2004	Italy	-	Yes
AMORELLA	8601915	Ro-pax	19/05/2005	Finland	http://www.turvallisuustutkinta.fi/material/attachments/otkes/tutkintaselostukset/en/vesiliikenneonnettomuuksientutkinta/2005/b12005m_tutkintaselostus/b12005m_tutkintaselostus.pdf	No[(1)]
AL SALAM BOCCACCIO 98	6921282	Ro-pax	03/02/2006	Panama	-	Yes
CONFIDENTIAL_RP_3		Ro-pax	2007			

CONFIDENTIAL_RP_4		Ro-pax	2009			
CONFIDENTIAL_RP_5		Ro-pax	2009			
COMMODORE CLIPPER	9201750	Ro-pax	16/06/2010	The United Kingdom (MAIB)	https://assets.digital.cabinet-office.gov.uk/media/547c6fb0e5274a428d000037/CommodoreClipperReport.pdf	Yes
LISCO GLORIA	9212151	Ro-pax	09/10/2010	Germany (BSU) / Lithuania	http://www.bsu-bund.de/SharedDocs/pdf/EN/Investigation_Report/2012/Investigation_Report_445_10.pdf?__blob=publicationFile	Yes
PEARL OF SCANDINAVIA	8701674	Ro-pax	17/11/2010	Denmark (DMAIB)	https://dmaib.dk/media/9155/pearl-of-scandinavia-fire-on-17-november-2010.pdf	Yes
MECKLENBURG-VORPOMMERN	9131797	Ro-pax	19/11/2010	Germany (BSU)	http://www.bsu-bund.de/SharedDocs/pdf/EN/Investigation_Report/2012/Investigation_Report_515_10.pdf?__blob=publicationFile	Yes
KRITI II	7814058	Ro-pax	19/11/2012	Greece (HBMCI)	http://www.hbmci.gov.gr/js/investigation%20report/final/01-2012%20KRITI%20II.pdf	Not available for download[2]
CONFIDENTIAL_RP_6		Ro-pax	2013			

VICTORIA SEAWAYS	9350721	Ro-pax	23/04/2013	Lithuania	http://www.bsu-bund.de/SharedDocs/pdf/EN/Investigation_Report/2014/Investigation_Report_MARINE_SHIP_ACCIDENT.pdf?__blob=publicationFile	Yes
CONFIDENTIAL_RP_7		Ro-pax	2013			
URD	7826855	Ro-pax	04/03/2014	Denmark (DMAIB)	https://dmaib.com/media/9102/urd-fire-on-4-march-2014.pdf	Yes
CONFIDENTIAL_RP_8		Ro-pax	2014			
NORMAN ATLANTIC	9435466	Ro-pax	28/12/2014	Italy (MIT)	http://hbmci.gov.gr/js/investigation%20report/Final%20as%20Interested%20Authority/2014-NORMAN%20ATLANTIC.pdf	Yes
SORRENTO	9264312	Ro-pax	28/04/2015	Italy (MIT)	https://www.mitma.es/recursos_mfom/comodin/recursos/sorrento_final_investigation_report_en_def.pdf	Yes
STENA SPIRIT	7907661	Ro-pax	31/08/2016	Bahamas / Poland (SMAIC)	https://www.bahamasmaritime.com/wp-content/uploads/2017/12/M.v-Stena-Spirit-Marine-Safety-Investigation-Report-Published.pdf	Yes
SCHIEBORG	9188233	Ro-ro cargo	08/01/2005	The Netherlands	https://zoek.officielebekendmakingen.nl/stcrt-2006-86-URS452.pdf	No

UND ADRIYATIK	9215488	Ro-ro cargo	06/02/2008	Turkey	http://www.ubak.gov.tr/BLSM_WIYS/KAIK/en/en_Doc/20180629_110537_76347_2_64.pdf	Not available for download
BRITANNIA SEAWAY	9153032	Ro-ro cargo	16/11/2013	Denmark (DMAIB)	https://dmaib.com/media/9120/britannia-seaways-fire-on-16-nov-2013.pdf	Yes
CORONA SEAWAYS	9357597	Ro-ro cargo	04/12/2013	The United Kingdom (MAIB)	https://assets.digital.cabinet-office.gov.uk/media/547c6f1f40f0b60244000005/CoronaSeaways.pdf	Yes
REPUBBLICA DI ROMA	9009504	Ro-ro cargo	10/04/2014	Italy (MIT)	-	Yes
PYXIS	8514083	Vehicle carrier	14/10/2008	Japan	https://www.mlit.go.jp/jtsb/eng-mar_report/2011/2008tk0006e.pdf	Yes
ALLIANCE NORFOLK	9332547	Vehicle carrier	10/03/2012	The United States of America (NTSB)	https://www.ntsb.gov/investigations/AccidentReports/Reports/MAB1305.pdf	No
GOLDEN FAN	8511263	Vehicle carrier	22/06/2013	Panama	-	Yes
COURAGE	8919922	Vehicle carrier	02/06/2015	The United States of America (NTSB)	https://www.ntsb.gov/investigations/AccidentReports/Reports/MAB1724.pdf	No

SILVER SKY	8519722	Vehicle carrier	19/10/2016	Panama	-	Yes
HONOR	9126297	Vehicle carrier	24/02/2017	The United States of America (NTSB)	https://www.ntsb.gov/investigations/AccidentReports/Reports/MAB1807.pdf	No
AUTO BANNER	8608066	Vehicle carrier	21/05/2018	Republic of Korea	-	Yes

(1) "No" = Casualty event not found in GISIS MCI or casualty event found but with no accident investigation report.

(2) "Not available for download" = accident investigation report found in GISIS MCI but not available for download with a public access at the time of the search (01-10-2021).

(3) Confidential reports = no further details about the accident will be provided.

13.6 ANNEX 6: Literature review of heuristics and biases during expert judgement

Main author of the chapter: Stina Andersson, RISE.

The following describes the main result of the literature review that was made as part of the expert judgement process.

Since expert judgement was only used to quantify parts of the risk model where neither historical data nor fire simulations are available, it is likely that the nodes that the experts were asked to quantify are prone to uncertainty. When making judgements under uncertainty people tend to rely on easy-to-use strategies, referred to as heuristics [32] [33]. These heuristics often help people make effective, good-enough decision in uncertain situations but may lead to systematic errors, so called biases. Even experts have been shown to be prone to biases, especially when relying on intuition when making decisions [32]. Below is a description of some of the most common biases, how they might affect expert judgement and what has been done to limit these biases in the expert judgement process in LASH FIRE.

Availability bias

The availability bias occurs when people assess the frequency/probability of an event based on how easy it is for them to imagine the event [32]. For example, one might estimate the probability of a pump failing by thinking about how many times one has personally experienced a pump failing. This bias is often useful when estimating probabilities/frequencies since common events in general are easier to recall than rare events. However, availability can lead to systematic errors if left unchecked. For example, an expert who recently experienced a rare accident will likely overestimate the probability of the same event happening again, if relying on intuition rather than analytical thinking. By aggregating estimates from several experts using individual questionnaires, any potential effect of the availability bias is likely to be diluted or cancel each other out.

Representative bias

Representative bias occurs when people make estimations based on how representative they think the outcome is of the input [32]. A systematic error that has been attributed to the representativeness bias is people's inaccuracy when estimating conditional probabilities, i.e. the probability P(A|B) of event A, given information B. It has been shown that the estimates of conditional probabilities become more accurate when problems are described in natural frequencies (1 out of 100) rather than probabilities (0.01 or 1%) [25] [34]. Based on this, the questionnaire was designed to only include questions relating to observations of fires (x out of 100 fires).

Anchoring bias

The anchoring bias occurs when people make estimations by intuitively using a previously known value as a starting point from which they then adjust their estimate. This strategy can be very efficient but might lead to errors since the starting value have been shown to act as an "anchor", making the final estimate biased towards the starting value [32] [35]. The anchoring bias means that different starting values will result in different final estimations, since, as Winkler & Moser puts it on page 66 in their article, "*persons provided with an anchor above (below) the true value*

systematically come to an estimate higher (lower) than the true value." [24]. By using an individual-based process there will be no anchoring bias due to a starting value being provided during discussion with others. Anchoring due to experts' own previous knowledge has been addressed in the expert judgement process by creating heterogeneity among the experts so that different anchors are in play, cancelling each other out. However, information about values used in the FIRESAFE studies were provided in the questionnaire. This means that the anchoring bias was purposefully used to anchor the experts in the values used in the FIRESAFE studies, as a way of ensuring compatibility between LASH FIRE and the FIRESAFE studies.

Motivational bias

Motivational bias is likely to occur when people have an interest in a certain outcome of an analysis. On page 3 in their conference proceedings, Skjong & Wentworth [13] gives the following example to illustrate motivational bias: *"…an individual involved in the design of a system, even though an expert with respect to that system, is likely to imply that the system is safer than it actually may be*." This bias is relevant in the quantification of the risk model since some of the experts might have an interest in a certain outcome of the assessment. To prevent this bias, the expert group was made as diverse as possible to reflect different incentives and cancel out any motivational bias (cf. Figure 40).

Bandwagon effect

Apart from biases, other factors such as dominant individuals and the bandwagon effect [24] have been considered when designing the expert judgement process. By having an individual-based process without a group discussion, influence from dominant individuals has been removed. Having an individual-based process will also likely decrease the bandwagon effect compared to group-based processes.

13.7 ANNEX 7: Questionnaire Template

A screenshot of part of the questionnaire is presented below. The part of the questionnaire shown in the figure is for ro-ro passenger ships and concerns the bottom nodes of the first response fault tree, refer to Figure 67.

		1. Fire started in a closed ro-ro space	**2.** Fire started in an open ro-ro space	**3.** Fire started on a weather deck
General background to questions below: If the fire has been detected early it is possible for a person to attempt a first response to extinguish the fire in its initial stage. A first reponse can either fail because the first responder is unable to access the fire, tactical failure, or because the equipment malfunctions/fails.				
Make the following assumption: There have been 100 incidents of fire onboard a ro-ro passenger ship				
1.	In how many of those incidents would you estimate that the first responder were unable to extinguish the fire due accessibility problems? Accessibility problem means that the first responder for some reason can not get to the fire as needed to use the first reponse equipment (usually portable fire extinguisher or fire hose). This could for example be due to tight stowage of cargo, or the fire being confined making it difficult to apply the extinguishing agent as needed.	*times out of 100*	This cell will be automatically updated times out of 100	*times out of 100*
	I cannot/do not want want to answer			
	Leave a comment to question 1			
2.	In how many of those incidents would you estimate that the first responder were unable to extinguish the fire because of tactical failure? Tactical failure includes the first responder using inefficient tactics (for example due to lack of training or self-conficence), or not being available to carry out the first response.	*times out of 100*	This cell will be automatically updated times out of 100	*times out of 100*
	I cannot/do not want want to answer			
	Leave a comment to question 2			
3.	In how many of those incidents would you estimate that the first responder were unable to extinguish the fire because the equipment malfunctioned/failed? First response equipment usually consists of a portable fire extinguisher or a hose.	*times out of 100*	*times out of 100*	This cell will be automatically updated times out of 100
	I cannot/do not want want to answer			
	Leave a comment to question 3			

13.8 ANNEX 8: Tables showing quantification method for all fault trees

This annex provides in details for each bottom nodes the methodology used for quantification.

Ignition
The detail about ignition quantification can be found in section 7.3.1.

Late Detection								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
20	System detection failure \ Internal failure \ Manual deactivation for operational purpose \ Individual detector	FSII	FSII	N/A	EJ	EJ	N/A	EJ
21	System detection failure \ Internal failure \ Manual deactivation for operational purpose \ System	FSII	FSII	N/A	EJ	EJ	N/A	EJ
22	System detection failure \ Internal failure \ Technical failure \ Individual detector	FSII	FSII	N/A	FSII	FSII	N/A	EJ
23	System detection failure \ Internal failure \ Technical failure \ System	FSII	FSII	N/A	FSII	FSII	N/A	EJ
24	System detection failure \ Internal failure \ Contamination/damage \ Individual detector	FSII	FSII	N/A	FSII	FSII	N/A	EJ
25	System detection failure \ Internal failure \ Contamination/damage \ System	FSII	FSII	N/A	FSII	FSII	N/A	EJ
26	System detection failure \ External cause \ Poor detector positioning \ Poor location	FSII	FSII	N/A	FSII	FSII	N/A	EJ
27	System detection failure \ External cause \ Poor detector positioning \ Poor spacing	FSII	FSII	N/A	FSII	FSII	N/A	EJ
28	System detection failure \ External cause \ Type of fire \ Small amount of soot	FSII	FSII	N/A	FSII	FSII	N/A	FSII
29	System detection failure \ External cause \ Type of fire \ Smouldering fire (no flame)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30	System detection failure \ External cause \ Type of fire \ Too rapid fire	FSII	FSII	N/A	FSII	FSII	N/A	FSII
31	System detection failure \ External cause \ Fire position \ Inside cargo/vehicle	FSII	FSII	N/A	FSII	FSII	N/A	EJ
32	System detection failure \ External cause \ Fire position \ Close to vent	FSII	FSII	N/A	FSII	FSII	N/A	FSII

Late Detection								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
33	System detection failure \ External cause \ Fire position \ Cargo between fire and detector	N/A	N/A	N/A	N/A	N/A	N/A	N/A
34	System detection failure \ External cause \ High airflow	FSII	FSII	N/A	FSII	FSII	N/A	EJ
35	System detection failure \ External cause \ Weather conditions \ Flame deflection	N/A	N/A	N/A	N/A	N/A	N/A	N/A
36	System detection failure \ External cause \ Weather conditions \ Cool down of fire seat	N/A	N/A	N/A	N/A	N/A	N/A	N/A
37	Late/no manual detection \ Fire patrol failure \ Not present \ Low frequency	Calcul-ations	Calcul-ations	Calcul-ations	Calcul-ations	Calcul-ations	Calcul-ations	Calcul-ations
38	Late/no manual detection \ Fire patrol failure \ Not present \ Required but not present	FSII	FSII	FSII	EJ	EJ	EJ	EJ
39	Late/no manual detection \ Fire patrol failure \ Quality failure \ Accessibility problems	FSII	FSII	FSII	EJ	EJ	EJ	EJ
40	Late/no manual detection \ Fire patrol failure \ Quality failure \ Lack of training / experience	FSII	FSII	FSII	EJ	EJ	EJ	EJ
41	Late/no manual detection \ Fire patrol failure \ Quality failure \ Lack of equipment	FSII	FSII	FSII	EJ	EJ	EJ	EJ
42	Late/no manual detection \ Fire patrol failure \ Quality failure \ Low motivation	FSII	FSII	FSII	EJ	EJ	EJ	EJ
43	Late/no manual detection \ Crew(/passenger) detection failure \ Not present in space	FSII	FSII	FSII	EJ	EJ	EJ	EJ
44	Late/no manual detection \ Crew(/passenger) detection failure \ Present in space but too far away	FSII	FSII	FSII	EJ	EJ	EJ	EJ
45	Late/no manual detection \ Crew(/passenger) detection failure \ Present but fail to report \ Unwilling of reporting	FSII	FSII	FSII	EJ	EJ	EJ	EJ
46	Late/no manual detection \ Crew(/passenger) detection failure \ Present but fail to report \ Communication Failure	FSII	FSII	FSII	EJ	EJ	EJ	EJ
47	Late/no manual detection \ Bridge detection Failure	FSII	FSII	FSII	FSII	FSII	FSII	FSII

First response failure								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
48	Failure by first responder \ Accessibility problems	EJ	EJ	EJ	EJ	EJ	EJ	EJ
49	Failure by first responder \ Tactical failure	EJ	EJ	EJ	EJ	EJ	EJ	EJ
50	Equipment failure	EJ	EJ	EJ	EJ	EJ	EJ	EJ

Late decision								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
51	Late alarm interpretation \ Alarm is wrongly dismissed	FSII	FSII	N/A	FSII	FSII	N/A	EJ
52	Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Alarm is missed	FSII	FSII	N/A	FSII	FSII	N/A	EJ
53	Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Time lost on information integration	FSII	FSII	N/A	FSII	FSII	N/A	EJ
54	Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Information misinterpreted	FSII	FSII	N/A	FSII	FSII	N/A	EJ
55	Late alarm interpretation \ Delayed acknowledgment \ Travel time on bridge	FSII	FSII	N/A	FSII	FSII	N/A	EJ
56	Late confirmation \ Late technical confirmation	FSII	FSII	N/A	FSII	FSII	N/A	FSII
57	Late confirmation \ Late manual confirmation \ Late arrival at detector point \ Late deployment of runner	FSII	FSII	N/A	FSII	FSII	N/A	EJ
58	Late confirmation \ Late manual confirmation \ Late arrival at detector point \ Long travel time to detection point	FSII	FSII	N/A	FSII	FSII	N/A	EJ
59	Late confirmation \ Late manual confirmation \ Late localisation \ Difficult environment	FSII	FSII	FSII	FSII	FSII	FSII	EJ
60	Late confirmation \ Late manual confirmation \ Late localisation \ Inadequate strategy	FSII	FSII	FSII	FSII	FSII	FSII	EJ
61	Late confirmation \ Late manual confirmation \ Late localisation \ Inadequate equipment	FSII	FSII	FSII	FSII	FSII	FSII	EJ

Late decision								
Nodes		**RoPax**			**Ro-ro**			**VC**
		CRS	**ORS**	**WD**	**CRS**	**ORS**	**WD**	**CRS**
62	Late confirmation \ Late manual confirmation \ Failure of communication	FSII	FSII	FSII	FSII	FSII	FSII	EJ
63	Late assessment \ Lack of relevant information	EJ	EJ	EJ	EJ	EJ	EJ	EJ
64	Late assessment \ Information is not made readily	EJ	EJ	EJ	EJ	EJ	EJ	EJ
65	Late assessment \ Insufficient experience and competence	EJ	EJ	EJ	EJ	EJ	EJ	EJ
66	Late implementation	EJ	EJ	EJ	EJ	EJ	EJ	EJ

Extinguishment/suppression failure								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
67	Fixed system fail \ Technical failure \ Supply fail (pump etc.)	FSII	FSII	N/A	FSII	FSII	N/A	EJ
68	Fixed system fail \ Technical failure \ Distribution failure \ Sectioning valves	FSII	FSII	N/A	FSII	FSII	N/A	EJ
69	Fixed system fail \ Technical failure \ Distribution failure \ Pipes & nozzles	FSII	FSII	N/A	FSII	FSII	N/A	EJ
70	Fixed system fail \ Technical failure \ Distribution failure \ Shielding	FSII	FSII	N/A	FSII	FSII	N/A	N/A
71	Fixed system fail \ Technical failure \ Distribution failure \ Wind	FSII	FSII	N/A	FSII	FSII	N/A	N/A
72	Fixed system fail \ Technical failure \ Distribution failure \ Transmission & logic	N/A	N/A	N/A	N/A	N/A	N/A	N/A
73	Fixed system fail \ Technical failure \ Removal of water \ Scuppers	FSII	FSII	N/A	FSII	FSII	N/A	N/A
74	Fixed system fail \ Technical failure \ Removal of water \ Valves	FSII	FSII	N/A	FSII	FSII	N/A	N/A
75	Fixed system fail \ Technical failure \ Removal of water \ Other	FSII	FSII	N/A	FSII	FSII	N/A	N/A
76	Fixed system fail \ Design incapacity \ Fixed system	FSII	FSII	N/A	FSII	FSII	N/A	EJ
77	Manual extinguishment fail \ Failure by fire-fighting group \ Accessibility problems	EJ	EJ	EJ	EJ	EJ	EJ	EJ
78	Manual extinguishment fail \ Failure by fire-fighting group \ Tactical failure	EJ	EJ	EJ	EJ	EJ	EJ	EJ

Extinguishment/suppression failure								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
79	Manual extinguishment fail \ Failure by fire-fighting group \ Lack of personnel	EJ	EJ	EJ	EJ	EJ	EJ	EJ
80	Manual extinguishment fail \ Equipment failure	EJ	EJ	EJ	EJ	EJ	EJ	EJ

Failure of containment								
Nodes		**RoPax**			**Ro-ro**			**VC**
		CRS	**ORS**	**WD**	**CRS**	**ORS**	**WD**	**CRS**
81	Failure of fire containment \ Flame spread through openings \ Aft and side openings	FSII	FSII	N/A	EJ	EJ	N/A	N/A
82	Failure of fire containment \ Flame spread through openings \ Doors open	FSII	FSII	N/A	EJ	EJ	N/A	EJ
83	Failure of fire containment \ Flame spread through openings \ Unsealed penetrations	FSII	FSII	N/A	FSII	FSII	N/A	EJ
84	Failure of fire containment \ Flame spread through openings \ Cracks	FSII	FSII	N/A	FSII	FSII	N/A	FSII
85	Failure of fire containment \ Flame spread	N/A	N/A	FSII	N/A	N/A	EJ	N/A
86	Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Bad condition of insulation	FSII	FSII	N/A	FSII	FSII	N/A	FSII
87	Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Damages/gaps	FSII	FSII	N/A	FSII	FSII	N/A	EJ
88	Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Intensive/long fire	FSII	FSII	N/A	FSII	FSII	N/A	EJ
89	Failure of fire containment \ Heat spread \ Fire insulation failure \ Heat bridge	FSII	FSII	N/A	FSII	FSII	N/A	EJ
90	Failure of fire containment \ Heat spread \ Fire insulation failure \ No insulation	FSII	FSII	N/A	EJ	EJ	N/A	EJ
91	Failure of fire containment \ Heat spread \ Failure of boundary cooling	EJ	EJ	N/A	EJ	EJ	N/A	EJ

Failure of containment								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
92	Failure of fire containment \ Heat spread \ Failure of active compartmentalization	N/A	N/A	N/A	N/A	N/A	N/A	N/A
93	Failure of fire containment \ Heat spread	N/A	N/A	FSII	N/A	N/A	EJ	N/A
94	Failure of smoke containment \ External smoke spread \ Fail. of navigation in a way to avoid smoke impeding a safe stay onboard	FSII	FSII	N/A	EJ	EJ	N/A	N/A
95	Failure of smoke containment \ External smoke spread \ Spread through openings	FSII	FSII	N/A	EJ	EJ	N/A	N/A
96	Failure of smoke containment \ Internal smoke spread \ Failure of active compartmentalization	N/A	N/A	N/A	N/A	N/A	N/A	N/A
97	Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Gap \ Damages	FSII	FSII	N/A	FSII	FSII	N/A	EJ
98	Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Gap \ Prescriptive design according to the FTP code	FSII	FSII	N/A	EJ	EJ	N/A	EJ
99	Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Doors open	FSII	FSII	N/A	EJ	EJ	N/A	EJ
100	Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of fire dampers	FSII	N/A	N/A	FSII	N/A	N/A	FSII
101	Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of deck or bulkhead \ Damages/cracks	FSII	FSII	N/A	FSII	FSII	N/A	FSII

Failure of containment								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
102	Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of deck or bulkhead \ Not sealed penetration	FSII	FSII	N/A	FSII	FSII	N/A	FSII
103	Failure of smoke containment \ Internal smoke spread \ Failure to create under pressure	FSII	FSII	N/A	EJ	EJ	N/A	EJ
104	Failure of smoke containment	N/A	N/A	FSII	N/A	N/A	EJ	N/A

Unsuccessful evacuation								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
105	Failing of evacuation at sea \ Routine failure \ Failure of communication (e.g. technical or language), internal/external	EJ	EJ	EJ	EJ	EJ	EJ	EJ
106	Failing of evacuation at sea \ Routine failure \ Human failure (e.g. due to Insufficient competence/lack of training/stress)	EJ	EJ	EJ	EJ	EJ	EJ	EJ
107	Failing of evacuation at sea \ Technical failure of LSA	EJ	EJ	EJ	EJ	EJ	EJ	EJ
108	Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire at critical part in CS, causing flames to exit opening and impact LSAs	Calcul-ations	N/A	N/A	Calcul-ations	N/A	N/A	Calcul-ations
109	Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in CS, causing smoke to travel towards LSAs	Calcul-ations	N/A	N/A	Calcul-ations	N/A	N/A	Calcul-ations
110	Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in critical zone ("Zone B")	N/A	Calcul-ations	N/A	N/A	Calcul-ations	N/A	N/A
111	Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in critical zone	N/A	Calcul-ations	N/A	N/A	Calcul-ations	N/A	N/A

Unsuccessful evacuation								
Nodes		RoPax			Ro-ro			VC
		CRS	ORS	WD	CRS	ORS	WD	CRS
112	Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in partially critical zone ("Zone A or C")	N/A	Calcul-ations	N/A	N/A	Calcul-ations	N/A	N/A
113	Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in partially critical zone	N/A	Calcul-ations	N/A	N/A	Calcul-ations	N/A	N/A
114	Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire on WD, causing radiation to impact LSAs	N/A	N/A	Calcul-ations	N/A	N/A	Calcul-ations	N/A
115	Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire on WD, causing smoke to impact LSAs	N/A	N/A	Calcul-ations	N/A	N/A	Calcul-ations	N/A
116	Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Capacity of evacuation path(s)	EJ	EJ	EJ	EJ	EJ	EJ	EJ
117	Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path impacted by fire	EJ	EJ	EJ	EJ	EJ	EJ	EJ
118	Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path blocked	EJ	EJ	EJ	EJ	EJ	EJ	EJ
119-132	Failing of evacuation at shore	EJ (scaling factor)	EJ (scaling factor)	EJ (scaling factor)	EJ (scaling factor)	EJ (scaling factor)	EJ (scaling factor)	EJ (scaling factor)

13.9 ANNEX 9: Probabilities of LASH FIRE risk model

This annex provides the probabilities of the bottom nodes of LASH FIRE risk models.

CRS = 'Closed ro-ro space'; ORS = 'Open ro-ro space'; WD = 'Weather deck'.

13.9.1 Ro-ro passenger ships

Ignition	Ro-ro passenger ship		
	CRS	ORS	WD
Ship equipment \ Electrical	3.8%		4.8%
Ship equipment \ Other than electrical	3.8%		4.8%
Ship cargo \ Conventional vehicle \ Electrical	25.0%		31.0%
Ship cargo \ Conventional vehicle \ Other than electrical	12.5%		15.5%
Ship cargo \ APV \ EV \ Electrical \ Connection	0.03%		0.03%
Ship cargo \ APV \ EV \ Electrical \ Other (electrical cause)	0.01%		0.01%
Ship cargo \ APV \ EV \ Other than electrical	0.004%		0.005%
Ship cargo \ APV \ Other APV \ Electrical	0.6%		0.8%
Ship cargo \ APV \ Other APV \ Other than electrical	0.3%		0.4%
Ship cargo \ Cargo unit \ T°C-controlled cargo unit \ Electrical \ Connection	26.0%	18.2%	N.A.
Ship cargo \ Cargo unit \ T°C-controlled cargo unit \ Electrical \ Other (electrical cause)	2.9%		3.6%
Ship cargo \ Cargo unit \ T°C-controlled cargo unit \ Other than electrical	9.6%	17.4%	20.0%
Ship cargo \ Cargo unit \ Other cargo unit \ Electrical	2.9%		3.6%
Ship cargo \ Cargo unit \ Other cargo unit \ Other than electrical	4.8%		6.0%
Other origin \ Electrical	2.3%		2.9%
Other origin \ Other than electrical	5.4%		6.7%

Early detection failure	Ro-Pax		
	CRS	ORS	WD
System detection failure \ Internal failure \ Manual deactivation for operational purpose \ Individual detector	1.0%		N.A.
System detection failure \ Internal failure \ Manual deactivation for operational purpose \ System	24.2%		
System detection failure \ Internal failure \ Technical failure \ Individual detector	0.1%		
System detection failure \ Internal failure \ Technical failure \ System	0.3%		
System detection failure \ Internal failure \ Contamination/damage \ Individual detector	0.7%	1.1%	
System detection failure \ Internal failure \ Contamination/damage \ System	0.3%	0.6%	
System detection failure \ External cause \ Poor detector positioning \ Poor location	0.3%		
System detection failure \ External cause \ Poor detector positioning \ Poor spacing	0.1%		
System detection failure \ External cause \ Type of fire \ Small amount of soot	0.1%		
System detection failure \ External cause \ Type of fire \ Too rapid fire	4.0%		
System detection failure \ External cause \ Fire position \ Inside cargo/vehicle	15.0%		
System detection failure \ External cause \ Fire position \ Close to vent	1.0%	3.0%	
System detection failure \ External cause \ High airflow	0.4%		
Late/no manual detection \ Fire patrol failure \ Not present \ Low frequency	50.0%		
Late/no manual detection \ Fire patrol failure \ Not present \ Required but not present	3.8%		
Late/no manual detection \ Fire patrol failure \ Quality failure \ Accessibility problems	2.0%		
Late/no manual detection \ Fire patrol failure \ Quality failure \ Lack of training / experience	1.0%		
Late/no manual detection \ Fire patrol failure \ Quality failure \ Lack of equipment	0.5%		
Late/no manual detection \ Fire patrol failure \ Quality failure \ Low motivation	3.5%		
Late/no manual detection \ Crew(/passenger) detection failure \ Not present in space	64.9%		
Late/no manual detection \ Crew(/passenger) detection failure \ Present in space but too far away	4.1%		
Late/no manual detection \ Crew(/passenger) detection failure \ Present but fail to report \ Unwilling of reporting	1.2%		
Late/no manual detection \ Crew(/passenger) detection failure \ Present but fail to report \ Communication Failure	4.7%		
Late/no manual detection \ Bridge detection Failure	100.0%	99.9%	99.0%

First response failure	Ro-Pax		
	CRS	ORS	WD
Failure by first responder \ Accessibility problems	25.9%		17.5%
Failure by first responder \ Tactical failure	16.2%		13.7%
Equipment failure	5.67%	5.36%	5.4%

Late decision	Ro-ro passenger ship					
	Early detection			Late detection		
	CRS	ORS	WD	CRS	ORS	WD
Late alarm interpretation \ Alarm is wrongly dismissed	3.0%		N.A.	0.1%		N.A.
Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Alarm is missed	0.5%			0.5%		
Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Time lost on information integration	2.5%			5.0%		
Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Information misinterpreted	1.0%			2.0%		
Late alarm interpretation \ Delayed acknowledgment \ Travel time on bridge	0.1%			0.2%		
Late confirmation \ Late technical confirmation	90.0%			90.0%		
Late confirmation \ Late manual confirmation \ Late arrival at detector point \ Late deployment of runner	1.0%			2.0%		
Late confirmation \ Late manual confirmation \ Late arrival at detector point \ Long travel time to detection point	3.1%			6.2%		
Late confirmation \ Late manual confirmation \ Late localisation \ Difficult environment	3.0%		1.0%	6.0%		2.0%
Late confirmation \ Late manual confirmation \ Late localisation \ Inadequate strategy	2.0%			0%		
Late confirmation \ Late manual confirmation \ Late localisation \ Inadequate equipment	2.0%			0%		
Late confirmation \ Late manual confirmation \ Failure of communication	5.0%			10.0%		
Late assessment \ Lack of relevant information	17.7%		15.6%	28.4%		21.3%
Late assessment \ Information is not made readily	14.4%		13.4%	20.5%		17.6%
Late assessment \ Insufficient experience and competence	11.6%			16.7%		
Late implementation	12.9%	14.8%	12.9%	14.8%		

Exinguishment/Suppression failure	Ro-ro passenger ship					
	Early decision			Late decision		
	CRS	ORS	WD	CRS	ORS	WD
Fixed system fail \ Technical failure \ Supply fail (pump etc.)	6.8%		N.A.	26.0%		N.A.
Fixed system fail \ Technical failure \ Distribution failure \ Sectioning valves	5.6%			22.2%		
Fixed system fail \ Technical failure \ Distribution failure \ Pipes & nozzles	5.6%			22.2%		
Fixed system fail \ Technical failure \ Distribution failure \ Shielding	1.1%			4.4%		
Fixed system fail \ Technical failure \ Distribution failure \ Wind	0%	0.5%		0%	1.8%	
Fixed system fail \ Technical failure \ Removal of water \ Scuppers	2.3%			8.9%		
Fixed system fail \ Technical failure \ Removal of water \ Valves	0.6%			2.2%		
Fixed system fail \ Technical failure \ Removal of water \ Other	0.2%			0.9%		
Fixed system fail \ Design incapacity \ Fixed system	4.0%			40.0%		
Manual extinguishment fail \ Failure by fire-fighting group \ Accessibility problems	21.5%		18.5%	61.0%		55.3%
Manual extinguishment fail \ Failure by fire-fighting group \ Tactical failure	17.8%		15.9%	53.9%		51.8%
Manual extinguishment fail \ Failure by fire-fighting group \ Lack of personnel	18.1%			39.9%		50.0%
Manual extinguishment fail \ Equipment failure	7.5%					

Failure of containment	Ro-ro passenger ship					
	Successful extinguishment			Unsuccessful extinguishment		
	CRS	ORS	WD	CRS	ORS	WD
Failure of fire containment \ Flame spread through openings \ Aft and side openings	0.8%	8.8%	N.A.	4.8%	70.0%	N.A.
Failure of fire containment \ Flame spread through openings \ Doors open	0.2%	0.1%		1.0%	0.8%	
Failure of fire containment \ Flame spread through openings \ Unsealed penetrations	0.2%	0.2%		2.3%	2.2%	
Failure of fire containment \ Flame spread through openings \ Cracks	0.03%	0.1%		0.4%	0.4%	
Failure of fire containment \ Flame spread	N.A.		23.3%	N.A.		45.0%
Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Bad condition of insulation	1.7%	2.5%	N.A.	7.3%	9.5%	N.A.
Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Damages/gaps	2.0%	1.8%		13.0%	8.2%	
Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Intensive/long fire	4.8%	6.5%		83.3%	83.3%	
Failure of fire containment \ Heat spread \ Fire insulation failure \ Heat bridge	3.5%	3.5%		23.3%	20.0%	
Failure of fire containment \ Heat spread \ Fire insulation failure \ No insulation	5.2%	7.8%		61.7%	71.7%	
Failure of fire containment \ Heat spread \ Failure of boundary cooling	13.0%	12.3%		29.9%	31.5%	
Failure of fire containment \ Heat spread \ Failure of active compartmentalization	N.A.			N.A.		
Failure of fire containment \ Heat spread			51.7%			73.3%
Failure of smoke containment \ External smoke spread \ Fail. of navigation in a way to avoid smoke impeding a safe stay onboard	6.3%	13.3%	N.A.	9.0%	50.0%	N.A.
Failure of smoke containment \ External smoke spread \ Spread through openings	7.7%	85.0%		11.0%	98.3%	
Failure of smoke containment \ Internal smoke spread \ Failure of active compartmentalization	N.A.			N.A.		
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Gap \ Damages	2.0%	1.2%		4.0%	2.1%	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Gap \ Prescriptive design according to the FTP code	4.0%	2.0%		20.3%	2.0%	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Doors open	4.3%	2.4%		4.7%	2.4%	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of fire dampers	1.3%	N.A.		6.4%	N.A.	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of deck or bulkhead \ Damages/cracks	0.1%	1.2%		2.0%	1.2%	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of deck or bulkhead \ Not sealed penetration	0.1%	5.7%		9.0%	5.7%	
Failure of smoke containment \ Internal smoke spread \ Failure to create under pressure	93.3%	22.5%		96.7%	26.7%	
Failure of smoke containment	N.A.		86.7%	N.A.		93.3%

Failure of evacuation	Ro-ro passenger ship					
	Successful extinguishment			Unsuccessful extinguishment		
	CRS	ORS	WD	CRS	ORS	WD
Failing of evacuation at sea \ Routine failure \ Failure of communication (e.g. technical or language), internal/external	10.5%					
Failing of evacuation at sea \ Routine failure \ Human failure (e.g. due to Insufficient competence/lack of training/stress)	17.5%			31.3%		
Failing of evacuation at sea \ Technical failure of LSA	1.0%	17.8%		1.0%	17.8%	
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in critical zone ("Zone B")	N.A.	61.3%	N.A.	N.A.	61.3%	N.A.
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in critical zone		100.0%			100.0%	
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in partially critical zone ("Zone A or C")		38.7%			38.7%	
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in partially critical zone		25.0%			25.0%	
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire on WD, causing smoke to impact LSAs		N.A.	21.9%		N.A.	21.9%
Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Capacity of evacuation path(s)	1.0%			2.0%		
Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path impacted by fire	7.1%	7.0%	5.9%	14.1%	13.9%	14.3%
Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path blocked	6.7%	6.7%	6.7%	6.7%	6.7%	6.7%
Failing of evacuation at shore \ Routine failure \ Failure of communication (e.g. technical or language), internal/external	0.7%	0.9%	0.8%	1.4%	1.5%	1.3%
Failing of evacuation at shore \ Routine failure \ Human failure (e.g. due to Insufficient competence/lack of training/stress)	1.2%	1.5%	1.3%	4.1%	4.6%	3.8%
Failing of evacuation at shore \ Technical failure of LSA	0.1%	1.5%	1.3%	0.1%	2.6%	2.2%
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in critical zone ("Zone B")	N.A.	5.1%	N.A.	N.A.	8.9%	N.A.
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in critical zone		100.0%			100.0%	
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in partially critical zone ("Zone A or C")		3.2%			5.6%	
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in partially critical zone		2.1%			3.6%	
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Fire on WD, causing smoke to impact LSAs		N.A.	1.6%		N.A.	2.7%
Failing of evacuation at shore \ Reduced accessibility/LSA inaccessible or restricted capacity \ Capacity of evacuation path(s)	0.1%	0.1%	0.1%	0.3%	0.3%	0.2%
Failing of evacuation at shore \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path impacted by fire	0.5%	0.6%	0.4%	1.9%	2.0%	1.7%
Failing of evacuation at shore \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path blocked	0.4%	0.6%	0.5%	0.9%	1.0%	0.8%

13.9.2 Ro-ro cargo ships

Ignition	Ro-ro cargo ship		
	CRS	ORS	WD
Ship equipment \ Electrical	1.2%		1.2%
Ship equipment \ Other than electrical	1.6%		1.7%
Ship cargo \ Conventional vehicle \ Electrical	39.0%		40.7%
Ship cargo \ Conventional vehicle \ Other than electrical	19.5%		20.3%
Ship cargo \ APV \ EV \ Electrical \ Other (electrical cause)	0.1%		0.1%
Ship cargo \ APV \ EV \ Other than electrical	0.01%		0.01%
Ship cargo \ APV \ Other APV \ Electrical	1.0%		1.1%
Ship cargo \ APV \ Other APV \ Other than electrical	0.5%		0.5%
Ship cargo \ Cargo unit \ T°C-controlled cargo unit \ Electrical \ Connection	5.8%	4.1%	N.A.
Ship cargo \ Cargo unit \ T°C-controlled cargo unit \ Electrical \ Other (electrical cause)	0.6%		0.7%
Ship cargo \ Cargo unit \ T°C-controlled cargo unit \ Other than electrical	2.1%	3.9%	4.0%
Ship cargo \ Cargo unit \ Other cargo unit \ Electrical	9.7%		10.1%
Ship cargo \ Cargo unit \ Other cargo unit \ Other than electrical	16.1%		16.8%
Other origin \ Electrical	1.2%		1.2%
Other origin \ Other than electrical	1.6%		1.7%

Early detection failure	Ro-Ro		
	CRS	ORS	WD
System detection failure \ Internal failure \ Manual deactivation for operational purpose \ Individual detector	7.6%		N.A.
System detection failure \ Internal failure \ Manual deactivation for operational purpose \ System	15.6%		
System detection failure \ Internal failure \ Technical failure \ Individual detector	0.1%		
System detection failure \ Internal failure \ Technical failure \ System	0.3%		
System detection failure \ Internal failure \ Contamination/damage \ Individual detector	0.7%	1.1%	
System detection failure \ Internal failure \ Contamination/damage \ System	0.3%	0.6%	
System detection failure \ External cause \ Poor detector positioning \ Poor location	0.3%		
System detection failure \ External cause \ Poor detector positioning \ Poor spacing	0.1%		
System detection failure \ External cause \ Type of fire \ Small amount of soot	0.1%		
System detection failure \ External cause \ Type of fire \ Too rapid fire	4.0%		
System detection failure \ External cause \ Fire position \ Inside cargo/vehicle	15.0%		
System detection failure \ External cause \ Fire position \ Close to vent	1.0%	3.0%	
System detection failure \ External cause \ High airflow	0.4%		
Late/no manual detection \ Fire patrol failure \ Not present \ Low frequency	75.0%		
Late/no manual detection \ Fire patrol failure \ Not present \ Required but not present	10.3%	8.7%	7.8%
Late/no manual detection \ Fire patrol failure \ Quality failure \ Accessibility problems	23.3%	23.2%	14.7%
Late/no manual detection \ Fire patrol failure \ Quality failure \ Lack of training / experience	8.9%	8.5%	6.4%
Late/no manual detection \ Fire patrol failure \ Quality failure \ Lack of equipment	6.1%	5.6%	5.3%
Late/no manual detection \ Fire patrol failure \ Quality failure \ Low motivation	8.6%	8.9%	8.1%
Late/no manual detection \ Crew(/passenger) detection failure \ Not present in space	66.3%	65.9%	61.5%
Late/no manual detection \ Crew(/passenger) detection failure \ Present in space but too far away	9.0%	8.9%	9.1%
Late/no manual detection \ Crew(/passenger) detection failure \ Present but fail to report \ Unwilling of reporting	1.8%	1.7%	1.5%
Late/no manual detection \ Crew(/passenger) detection failure \ Present but fail to report \ Communication Failure	3.3%	3.3%	3.2%
Late/no manual detection \ Bridge detection Failure	100.0%	99.9%	99.0%

First response failure	Ro-Ro		
	CRS	ORS	WD
Failure by first responder \ Accessibility problems	25.9%		17.5%
Failure by first responder \ Tactical failure	16.2%		13.7%
Equipment failure	5.7%	5.4%	5.4%

Late decision	Ro-ro cargo ship					
	Early detection			Late detection		
	CRS	ORS	WD	CRS	ORS	WD
Late alarm interpretation \ Alarm is wrongly dismissed	3.0%		N.A.	0.1%		N.A.
Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Alarm is missed	0.5%			0.5%		
Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Time lost on information integration	2.5%			5.0%		
Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Information misinterpreted	1.0%			2.0%		
Late alarm interpretation \ Delayed acknowledgment \ Travel time on bridge	0.1%			0.2%		
Late confirmation \ Late technical confirmation	90.0%			90.0%		
Late confirmation \ Late manual confirmation \ Late arrival at detector point \ Late deployment of runner	1.0%			2.0%		
Late confirmation \ Late manual confirmation \ Late arrival at detector point \ Long travel time to detection point	3.1%			6.2%		
Late confirmation \ Late manual confirmation \ Late localisation \ Difficult environment	3.0%		1.0%	6.0%		2.0%
Late confirmation \ Late manual confirmation \ Late localisation \ Inadequate strategy	2.0%		1.0%	0%		
Late confirmation \ Late manual confirmation \ Late localisation \ Inadequate equipment	2.0%			0%		
Late confirmation \ Late manual confirmation \ Failure of communication	5.0%			10.0%	5.0%	10.0%
Late assessment \ Lack of relevant information	26.2%		24.7%	31.8%		30.7%
Late assessment \ Information is not made readily	27.4%		24.9%	33.2%		28.7%
Late assessment \ Insufficient experience and competence	12.6%			14.1%		
Late implementation	12.0%			10.6%		

Exinguishment/Suppression failure	Ro-ro cargo ship					
	Early decision			Late decision		
	CRS	ORS	WD	CRS	ORS	WD
Fixed system fail \ Technical failure \ Supply fail (pump etc.)	6.8%		N.A.	26.0%		N.A.
Fixed system fail \ Technical failure \ Distribution failure \ Sectioning valves	5.6%			22.2%		
Fixed system fail \ Technical failure \ Distribution failure \ Pipes & nozzles	5.6%			22.2%		
Fixed system fail \ Technical failure \ Distribution failure \ Shielding	1.1%			4.4%		
Fixed system fail \ Technical failure \ Distribution failure \ Wind	0%	0.5%		0%	1.8%	
Fixed system fail \ Technical failure \ Removal of water \ Scuppers	2.3%			8.9%		
Fixed system fail \ Technical failure \ Removal of water \ Valves	0.6%			2.2%		
Fixed system fail \ Technical failure \ Removal of water \ Other	0.2%			0.9%		
Fixed system fail \ Design incapacity \ Fixed system	4.0%			40.0%		
Manual extinguishment fail \ Failure by fire-fighting group \ Accessibility problems	50.6%		35.8%	71.9%		65.9%
Manual extinguishment fail \ Failure by fire-fighting group \ Tactical failure	17.8%		15.2%	30.4%		32.1%
Manual extinguishment fail \ Failure by fire-fighting group \ Lack of personnel	30.7%			40.3%		49.7%
Manual extinguishment fail \ Equipment failure	14.4%					

Failure of containment	Ro-ro cargo ship					
	Successful extinguishment			Unsuccessful extinguishment		
	CRS	ORS	WD	CRS	ORS	WD
Failure of fire containment \ Flame spread through openings \ Aft and side openings	4.5%	14.8%	N.A.	12.0%	43.9%	N.A.
Failure of fire containment \ Flame spread through openings \ Doors open	1.8%	1.6%		3.3%	3.3%	
Failure of fire containment \ Flame spread through openings \ Unsealed penetrations	0.2%	0.2%		2.3%	2.2%	
Failure of fire containment \ Flame spread through openings \ Cracks	0.0%	0.1%		0.4%	0.4%	
Failure of fire containment \ Flame spread	N.A.		16.5%	N.A.		37.2%
Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Bad condition of insulation	1.7%	2.5%	N.A.	7.3%	9.5%	N.A.
Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Damages/gaps	2.0%	1.8%		13.0%	8.2%	
Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Intensive/long fire	4.8%	6.5%		83.3%	83.3%	
Failure of fire containment \ Heat spread \ Fire insulation failure \ Heat bridge	3.5%	3.5%		23.3%	20.0%	
Failure of fire containment \ Heat spread \ Fire insulation failure \ No insulation	5.1%	6.4%		34.4%	37.8%	
Failure of fire containment \ Heat spread \ Failure of boundary cooling	20.2%	15.7%		28.5%	29.2%	
Failure of fire containment \ Heat spread \ Failure of active compartmentalization	N.A.			N.A.		
Failure of fire containment \ Heat spread			39.1%			60.4%
Failure of smoke containment \ External smoke spread \ Fail. of navigation in a way to avoid smoke impeding a safe stay onboard	5.6%	15.5%	N.A.	10.2%	34.4%	N.A.
Failure of smoke containment \ External smoke spread \ Spread through openings	9.9%	58.0%		23.2%	74.9%	
Failure of smoke containment \ Internal smoke spread \ Failure of active compartmentalization	N.A.			N.A.		
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Gap \ Damages	2.0%	1.2%		4.0%	2.1%	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Gap \ Prescriptive design according to the FTP code	5.2%	4.2%		13.1%	7.8%	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Doors open	5.1%	3.9%		8.8%	5.4%	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of fire dampers	1.3%	N.A.		6.4%	N.A.	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of deck or bulkhead \ Damages/cracks	0.1%	1.2%		2.0%	1.2%	
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of deck or bulkhead \ Not sealed penetration	0.1%	5.7%		9.0%	5.7%	
Failure of smoke containment \ Internal smoke spread \ Failure to create under pressure	60.5%	24.6%		67.8%	29.1%	
Failure of smoke containment	N.A.		67.1%	N.A.		78.4%

Failure of evacuation	Ro-ro cargo ship					
	Successful extinguishment			Unsuccessful extinguishment		
	CRS	ORS	WD	CRS	ORS	WD
Failing of evacuation at sea \ Routine failure \ Failure of communication (e.g. technical or language), internal/external	20.7%					
Failing of evacuation at sea \ Routine failure \ Human failure (e.g. due to Insufficient competence/lack of training/stress)	17.5%			31.3%		
Failing of evacuation at sea \ Technical failure of LSA	1.0%	17.8%		1.0%	17.8%	
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in critical zone ("Zone B")	N.A.	81.0%	N.A.	N.A.	81.0%	N.A.
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in critical zone		100.0%			100.0%	
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in partially critical zone ("Zone A or C")		19.0%			19.0%	
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in partially critical zone		28.2%			28.2%	
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire on WD, causing radiation to impact LSAs		N.A.	64.1%		N.A.	71.6%
Failing of evacuation at sea \ LSA inoperable due to smoke, heat or flames (fire) \ Fire on WD, causing smoke to impact LSAs			25.0%			50.0%
Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Capacity of evacuation path(s)	0.8%			1.5%		
Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path impacted by fire	8.0%	9.2%	8.5%	15.3%	15.8%	15.0%
Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path blocked	12.9%					
Failing of evacuation at shore \ Routine failure \ Failure of communication (e.g. technical or language), internal/external	1.7%	0.9%	1.0%	3.8%	2.3%	2.1%
Failing of evacuation at shore \ Routine failure \ Human failure (e.g. due to Insufficient competence/lack of training/stress)	1.4%	0.8%	0.8%	5.8%	3.5%	3.2%
Failing of evacuation at shore \ Technical failure of LSA	0.1%	0.8%	0.8%	0.2%	2.0%	1.8%
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in critical zone ("Zone B")	N.A.	3.6%	N.A.	N.A.	9.0%	N.A.
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in critical zone		100.0%			100.0%	
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Fire in partially critical zone ("Zone A or C")		0.8%			2.1%	
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Impact on LSA from fire in partially critical zone		1.3%			3.1%	
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Fire on WD, causing radiation to impact LSAs		N.A.	3.0%		N.A.	7.3%
Failing of evacuation at shore \ LSA inoperable due to smoke, heat or flames (fire) \ Fire on WD, causing smoke to impact LSAs			1.2%			5.1%
Failing of evacuation at shore \ Reduced accessibility/LSA inaccessible or restricted capacity \ Capacity of evacuation path(s)	0.1%	0.03%	0.03%	0.3%	0.2%	0.2%
Failing of evacuation at shore \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path impacted by fire	0.7%	0.4%	0.4%	2.8%	1.8%	1.5%
Failing of evacuation at shore \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path blocked	1.0%	0.6%	0.6%	2.4%	1.4%	1.3%

13.9.3 Vehicle carriers

Ignition	Vehicle carrier
	CRS
Ship equipment \ Electrical	3.8%
Ship equipment \ Other than electrical	3.8%
Ship cargo \ Conventional vehicle \ Electrical	65.9%
Ship cargo \ Conventional vehicle \ Other than electrical	7.3%
Ship cargo \ APV \ EV \ Electrical	0.1%
Ship cargo \ APV \ EV \ Other than electrical	0.01%
Ship cargo \ APV \ Other APV \ Electrical	1.3%
Ship cargo \ APV \ Other APV \ Other than electrical	0.6%
Ship cargo \ Cargo unit \ Electrical	3.5%
Ship cargo \ Cargo unit \ Other than electrical	5.9%
Other origin \ Electrical	2.3%
Other origin \ Other than electrical	5.4%

Early detection failure	VC
	CRS
System detection failure \ Internal failure \ Manual deactivation for operational purpose \ Individual detector	4.7%
System detection failure \ Internal failure \ Manual deactivation for operational purpose \ System	15.7%
System detection failure \ Internal failure \ Technical failure \ Individual detector	8.2%
System detection failure \ Internal failure \ Technical failure \ System	4.7%
System detection failure \ Internal failure \ Contamination/damage \ Individual detector	5.6%
System detection failure \ Internal failure \ Contamination/damage \ System	1.6%
System detection failure \ External cause \ Poor detector positioning \ Poor location	1.5%
System detection failure \ External cause \ Poor detector positioning \ Poor spacing	1.4%
System detection failure \ External cause \ Type of fire \ Small amount of soot	0.1%
System detection failure \ External cause \ Type of fire \ Too rapid fire	4.0%
System detection failure \ External cause \ Fire position \ Inside cargo/vehicle	22.1%
System detection failure \ External cause \ Fire position \ Close to vent	1.0%
System detection failure \ External cause \ High airflow	1.4%
Late/no manual detection \ Fire patrol failure \ Not present \ Low frequency	90.0%
Late/no manual detection \ Fire patrol failure \ Not present \ Required but not present	12.8%
Late/no manual detection \ Fire patrol failure \ Quality failure \ Accessibility problems	8.9%
Late/no manual detection \ Fire patrol failure \ Quality failure \ Lack of training / experience	4.2%
Late/no manual detection \ Fire patrol failure \ Quality failure \ Lack of equipment	2.2%
Late/no manual detection \ Fire patrol failure \ Quality failure \ Low motivation	3.3%
Late/no manual detection \ Crew(/passenger) detection failure \ Not present in space	77.8%
Late/no manual detection \ Crew(/passenger) detection failure \ Present in space but too far away	6.6%
Late/no manual detection \ Crew(/passenger) detection failure \ Present but fail to report \ Unwilling of reporting	1.4%
Late/no manual detection \ Crew(/passenger) detection failure \ Present but fail to report \ Communication Failure	6.6%

First response failure	VC
	CRS
Failure by first responder \ Accessibility problems	43.6%
Failure by first responder \ Tactical failure	24.9%
Equipment failure	5.36%

Late decision	Vehicle carrier	
	Early detection	Late detection
	CRS	CRS
Late alarm interpretation \ Alarm is wrongly dismissed	6.7%	12.1%
Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Alarm is missed	2.5%	3.0%
Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Time lost on information integration	6.7%	9.5%
Late alarm interpretation \ Delayed acknowledgment \ Delayed alarm handling \ Information misinterpreted	3.7%	5.2%
Late alarm interpretation \ Delayed acknowledgment \ Travel time on bridge	2.6%	3.1%
Late confirmation \ Late technical confirmation	90.0%	90.0%
Late confirmation \ Late manual confirmation \ Late arrival at detector point \ Late deployment of runner	1.2%	2.2%
Late confirmation \ Late manual confirmation \ Late arrival at detector point \ Long travel time to detection point	5.0%	7.7%
Late confirmation \ Late manual confirmation \ Late localisation \ Difficult environment	4.2%	7.2%
Late confirmation \ Late manual confirmation \ Late localisation \ Inadequate strategy	3.3%	4.0%
Late confirmation \ Late manual confirmation \ Late localisation \ Inadequate equipment	1.8%	1.7%
Late confirmation \ Late manual confirmation \ Failure of communication	7.0%	10.3%
Late assessment \ Lack of relevant information	26.0%	33.0%
Late assessment \ Information is not made readily	18.8%	24.7%
Late assessment \ Insufficient experience and competence	12.6%	14.1%
Late implementation	5.8%	8.5%

Exinguishment/Suppression failure	Vehicle carrier	
	Early decision	Late decision
	CRS	CRS
Fixed system fail \ Technical failure \ Supply fail (pump etc.)	5.9%	13.0%
Fixed system fail \ Technical failure \ Distribution failure \ Sectioning valves	4.3%	12.8%
Fixed system fail \ Technical failure \ Distribution failure \ Pipes & nozzles	4.9%	13.3%
Fixed system fail \ Technical failure \ Distribution failure \ Shielding	N.A.	
Fixed system fail \ Technical failure \ Distribution failure \ Wind		
Fixed system fail \ Technical failure \ Removal of water \ Scuppers		
Fixed system fail \ Technical failure \ Removal of water \ Valves		
Fixed system fail \ Technical failure \ Removal of water \ Other		
Fixed system fail \ Design incapacity \ Fixed system	4.8%	40.6%
Manual extinguishment fail \ Failure by fire-fighting group \ Accessibility problems	31.4%	67.9%
Manual extinguishment fail \ Failure by fire-fighting group \ Tactical failure	16.1%	36.6%
Manual extinguishment fail \ Failure by fire-fighting group \ Lack of personnel	26.6%	44.8%
Manual extinguishment fail \ Equipment failure	11.1%	

Failure of containment	Vehicle carrier	
	Success. ext.	Unsuccess. ext.
	CRS	CRS
Failure of fire containment \ Flame spread through openings \ Aft and side openings	N.A.	
Failure of fire containment \ Flame spread through openings \ Doors open	1.0%	1.0%
Failure of fire containment \ Flame spread through openings \ Unsealed penetrations	1.3%	2.3%
Failure of fire containment \ Flame spread through openings \ Cracks	0.03%	0.4%
Failure of fire containment \ Flame spread	N.A.	
Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Bad condition of insulation	1.7%	7.3%
Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Damages/gaps	2.8%	10.7%
Failure of fire containment \ Heat spread \ Fire insulation failure \ Insulation performance failure \ Intensive/long fire	7.0%	20.3%
Failure of fire containment \ Heat spread \ Fire insulation failure \ Heat bridge	4.0%	19.2%
Failure of fire containment \ Heat spread \ Fire insulation failure \ No insulation	5.8%	55.8%
Failure of fire containment \ Heat spread \ Failure of boundary cooling	4.8%	18.0%
Failure of fire containment \ Heat spread \ Failure of active compartmentalization	N.A.	
Failure of fire containment \ Heat spread		
Failure of smoke containment \ External smoke spread \ Fail. of navigation in a way to avoid smoke impeding a safe stay onboard		
Failure of smoke containment \ External smoke spread \ Spread through openings		
Failure of smoke containment \ Internal smoke spread \ Failure of active compartmentalization		
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Gap \ Damages	2.1%	5.2%
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Gap \ Prescriptive design according to the FTP code	4.0%	18.8%
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Doors failure \ Doors open	6.5%	11.0%
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of fire dampers	1.3%	6.4%
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of deck or bulkhead \ Damages/cracks	0.1%	2.0%
Failure of smoke containment \ Internal smoke spread \ Weakness of division smoke tightness \ Failure of deck or bulkhead \ Not sealed penetration	0.1%	9.0%
Failure of smoke containment \ Internal smoke spread \ Failure to create under pressure	69.0%	81.2%
Failure of smoke containment	N.A.	

Failure of evacuation	Vehicle carrier	
	Success. ext.	Unsuccess. ext.
	CRS	CRS
Failing of evacuation at sea \ Routine failure \ Failure of communication (e.g. technical or language), internal/external	20.7%	
Failing of evacuation at sea \ Routine failure \ Human failure (e.g. due to Insufficient competence/lack of training/stress)	17.5%	31.3%
Failing of evacuation at sea \ Technical failure of LSA	1.0%	1.0%
Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Capacity of evacuation path(s)	0.8%	1.5%
Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path impacted by fire	6.2%	10.3%
Failing of evacuation at sea \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path blocked	12.9%	12.9%
Failing of evacuation at shore \ Routine failure \ Failure of communication (e.g. technical or language), internal/external	0.9%	2.2%
Failing of evacuation at shore \ Routine failure \ Human failure (e.g. due to Insufficient competence/lack of training/stress)	0.7%	3.4%
Failing of evacuation at shore \ Technical failure of LSA	0.04%	0.1%
Failing of evacuation at shore \ Reduced accessibility/LSA inaccessible or restricted capacity \ Capacity of evacuation path(s)	0.03%	0.2%
Failing of evacuation at shore \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path impacted by fire	0.3%	1.1%
Failing of evacuation at shore \ Reduced accessibility/LSA inaccessible or restricted capacity \ Evacuation path blocked	0.5%	1.4%

13.10 ANNEX 10: Compilation of event trees probabilities

This annex provides the probabilities of the different event trees from the following sources:

- LASH FIRE, i.e. final values in the risk models;
- FIRESAFE II; and
- Historical data.

For length and readability purposes, only the unsuccessful case is displayed for each tier.

13.10.1 Late detection

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	15.4%	24.0%	32.1%
	Open space	16.0%	25.0%	32.1%
	Weather space	37.3%	58.0%	
Ro-ro cargo ship	Closed space	23.6%	28.0%	32.1%
	Open space	24.3%		32.1%
	Weather deck	55.4%	68.0%	
Vehicle carrier	Closed space	40.3%		32.1%

13.10.2 Unsuccessful first response

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	41.5%	70.0%	93.1%
	Open space	41.3%	70.0%	93.1%
	Weather space	32.6%	70.0%	93.1%
Ro-ro cargo ship	Closed space	41.5%	70.0%	93.1%
	Open space	41.3%		93.1%
	Weather deck	32.6%	70.0%	93.1%
Vehicle carrier	Closed space	59.9%		93.1%

13.10.3 Late decision

Following early detection:

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	56.4%	28.0%	38.5%
	Open space	57.4%	28.0%	38.5%
	Weather space	49.2%	19.0%	
Ro-ro cargo ship	Closed space	66.9%	28.0%	
	Open space	66.9%		
	Weather deck	60.4%	19.0%	
Vehicle carrier	Closed space	68.3%		

Following late detection:

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	70.1%	41.0%	
	Open space	70.1%	41.0%	
	Weather space	59.4%	30.0%	
Ro-ro cargo ship	Closed space	74.1%	41.0%	
	Open space	72.9%		
	Weather deck	66.5%	30.0%	
Vehicle carrier	Closed space	79.9%		

13.10.4 Unsuccessful extinguishment

Following early decision:

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	12.1%	16.6%	
	Open space	12.3%	16.8%	
	Weather space	48.1%	70.0%	
Ro-ro cargo ship	Closed space	18.0%	16.6%	
	Open space	18.2%		
	Weather deck	67.7%	70.0%	
Vehicle carrier	Closed space	11.5%		

Following late decision:

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	69.7%	77.4%	
	Open space	70.0%	77.8%	
	Weather space	90.0%	90.0%	
Ro-ro cargo ship	Closed space	69.6%	77.4%	
	Open space	70.0%		
	Weather deck	90.0%	90.0%	
Vehicle carrier	Closed space	54.9%		

13.10.5 Unsuccessful containment

Following successful suppression:

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	13.9%	12.8%	
	Open space	23.5%	22.4%	
	Weather space	95.1%	95.1%	
Ro-ro cargo ship	Closed space	17.1%	22.1%	
	Open space	28.9%		
	Weather deck	83.3%	88.3%	
Vehicle carrier	Closed space	12.2%		

Following unsuccessful suppression:

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	59.8%	85.7%	
	Open space	90.1%	90.6%	
	Weather space	99.0%	99.0%	
Ro-ro cargo ship	Closed space	55.4%	54.5%	
	Open space	73.1%		
	Weather deck	94.6%	94.7%	
Vehicle carrier	Closed space	45.8%		

13.10.6 Unsuccessful evacuation

Following successful suppression:

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	26.5%	23.0%	9.1%
	Open space	58.6%	48.0%	
	Weather space	41.9%	29.0%	
Ro-ro cargo ship	Closed space	26.2%	24.0%	
	Open space	49.2%		
	Weather deck	47.4%	33.0%	
Vehicle carrier	Closed space	21.7%		

Following unsuccessful suppression:

		LASH FIRE	FIRESAFE II	Historical data (if relevant)
Ro-ro passenger ship	Closed space	37.8%	23.0%	9.1%
	Open space	63.3%	48.0%	
	Weather space	50.2%	29.0%	
Ro-ro cargo ship	Closed space	35.9%	24.0%	
	Open space	54.3%		
	Weather deck	55.6%	33.0%	
Vehicle carrier	Closed space	29.0%		

13.11 ANNEX 11: Swift detection

Main author of the chapter: Eric De Carvalho, BV.

Swift detection (terminology used in the H2020 call) is identified as a parameter of paramount importance for early fire response. However, there is no commonly agreed definition of a "swift detection" in the current regulations. An attempt in this section is to discuss about a clear definition of swift detection, that should increase the intelligibility and the transparency of fire risk models, as originally planned in the project description.

This definition is a concept and may be re-used in future risk models or any other analyses. But this definition cannot be used in an operational context nor in a real onboard fire situation.

13.11.1 Regulation review

In IMO regulation, there is no occurrence of the terminology "swift detection".

SOLAS II-2/2.2.1.4 [36] provides the functional requirement:

"detection of any fire in the zone of origin".

SOLAS II-2/7.1 [36] about the regulation on fire detection and alarm specifies that:

"The purpose of this regulation is to detect a fire in the space of origin and to provide for alarm for safe escape and fire-fighting activity. For this purpose, the following functional requirements shall be met:

.1 fixed fire detection and fire alarm system installations shall be suitable for the nature of the space, fire growth potential and potential generation of smoke and gases;

.2 manually operated call points shall be placed effectively to ensure a readily accessible means of notification; and

.3 fire patrols shall provide an effective means of detecting and locating fires and alerting the navigation bridge and fire teams."

In SOLAS II-2/20.4.1 [36] applicable to vehicle spaces, special category spaces and ro-ro spaces, the terminology "rapidly" is introduced with the term "onset of fire":

"The fixed fire detection system shall be capable of rapidly detecting the onset of fire."

This requirement targets a certain stage of the fire, i.e. the fire development shall be further addressed.

13.11.2 Fire development versus fire response

In general, a compartment fire starts with an incipient phase (Figure 124). The fire is "small", with no or little flames and a certain amount a smoke released. The duration of the incipient phase depends on fuel characteristics, local airfields, ignition source location and physical arrangements.

In ro-ro spaces, many fires are caused by electrical faults, which often start as smouldering fires with long incipient phase. They may produce too little smoke as compared to the large space volume to be detected by smoke detectors. As a matter of fact, the fire patrols are more likely to detect this type of fires [7].

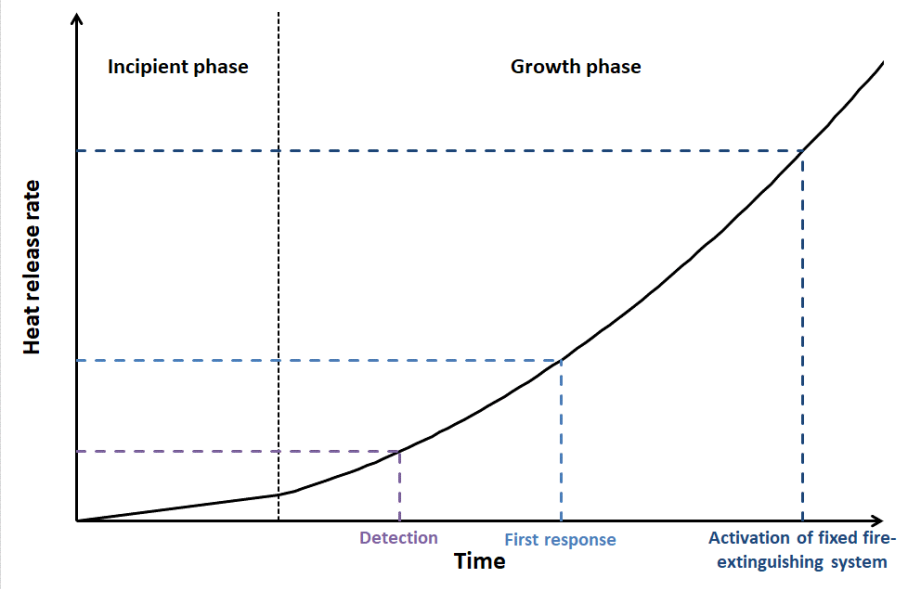


Figure 124. Fire development versus response.

After the incipient phase, the fire development can continue with a growth phase (Figure 124): the flames and the smoke production increase. The fire is likely to be detected by either standard smoke or heat detectors. Consequently, an AB is sent on site to confirm the fire and attempt the first response. In case the fire is firstly detected by a crew member, the first response is directly attempted by the person noting the fire and the fire is reported to the bridge. It is generally accepted that a fire of 500 kW (heat release rate or HRR) can be extinguished by a powder fire extinguisher (according to WP05 and Norway [37]). For illustration, 500 kW is the power of a fire of about 2-3 European wood pallets [38] (Figure 125). A fire of 1 MW is much more difficult to be extinguished with a portable fire extinguisher (according to WP05). For illustration, 1 MW is the power of a diesel pool fire of about 0.5 m^2 [39]. According to WP05, the ship operators recommend that the first response should be ready to take action to put out the fire in early stage and report the situation preferably within 60 seconds from the fire alarm, and not more than 3 minutes.

Figure 125. Wood pallets fire (about 2 MW) [38].

After confirmation, the general alarm is sounded. A decision-making process is initiated, potentially resulting in the activation of the fixed fire-extinguishing system. Fire suppression tests conducted by WP10 have demonstrated that wood pallets fire of 2.5 MW and standard plastic commodity fire of

4 MW can be extinguished by a drencher system. Based on the IMO test method and the theory [40], the drencher systems in ro-ro spaces should be capable to control a wood pallets fire of about 10 MW ("fire scenario 1: cargo fire in a simulated freight truck"). For vehicle carriers, no data were found about the performance requirements of CO_2 systems. Based on lesson learnt from past accidents, DNV recommends that the ship operators implement defined goal for release time of fixed fire-extinguishing systems: for instance, 3 minutes for drencher systems and 15 minutes for CO_2 systems [41]. The time of release starts from the fire alarm signal.

Finding data about the performance of fire-extinguishing systems against bigger fires is a nontrivial task. For obvious reasons, it is hard to scale up the actual fire suppression tests. Another means to find this information is to review accident investigation reports. Unfortunately, no or very few data about the fire development is found in those reports (and if they exist, they will be too few, partial or too qualitative).

In summary of this section, it is really important to superpose the timeline of the fire response (time of detection, of first response and of activation of fixed fire-extinguishing system) with the timeline of the fire spread (Figure 124). Early detection of fire is often considered as one of the key parameters to successful fire management, allowing to prevent loss of life and damage to the ship and cargo [7]. A fire handled at its early stage is much easier to be extinguished or suppressed. Therefore, the concept of swift detection cannot be addressed without addressing the residual potential performance of first response and fixed fire-extinguishing system.

13.11.3 Concept of early detection

13.11.3.1 Early detection as regards as first response

13.11.3.1.1 FIRESAFE II study

The FIRESAFE II study introduced the concept of early/late detection (Figure 126), which is related to whether it is possible to carry out the first response successfully and safely. This concept served the development of the fire risk model. More specifically, a quantitative criterion was developed.

Early detection is defined to have occurred if:

> Required Time for Safe First Response (RTSFR), i.e. the time to detect the fire and to set up actions for the first response, ≤ Available Time for Safe First Response (ATSFR), i.e. the time available until conditions become untenable around the fire, disallowing the first response, at a distance equal to the effective range of portable fire extinguishers.

The proposed criterion was built to be applicable no matter what fire scenarios are considered, i.e. independent from the possible influencing factors. A detailed description of the concept can be found in [42] and [7].

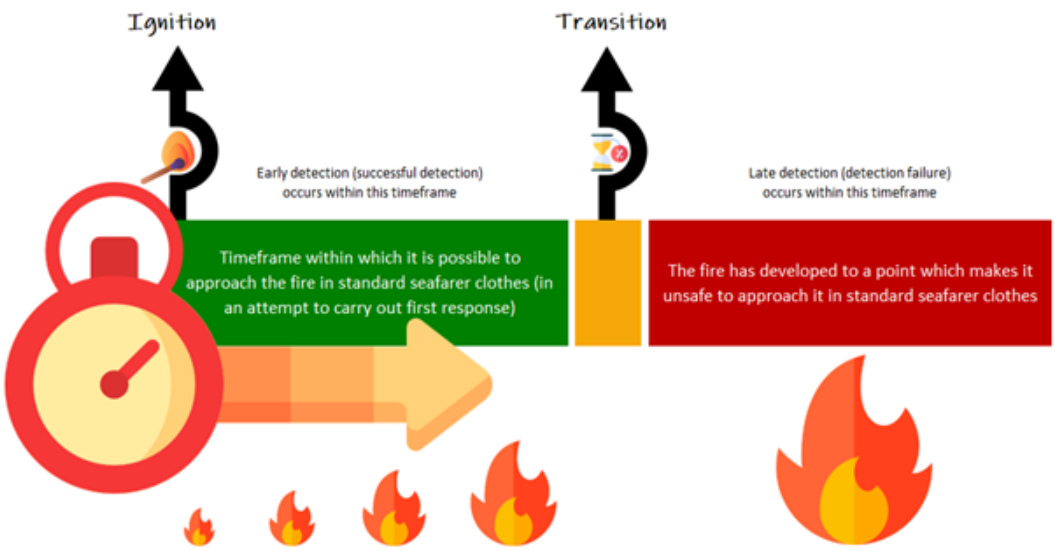


Figure 126. A schematic summarising the difference between early and late detection (RISE).

13.11.3.1.2 New simulations – LASH FIRE

Re-starting from the simple test case (Figure 127) used in the FIRESAFE II study to test ATSFR, new FDS simulations were run. Several parameters were studied, such as HRR curve, height of the fire seat, height of the simulation domain, CO and soot yield. Such parameters were deemed to be the ones the most representative of different fire scenarios and configurations. The purpose was to analyse the impact of different fire scenarios on the tenability around the fire (i.e. ATSFR) and to check if a general and simple law can be found.

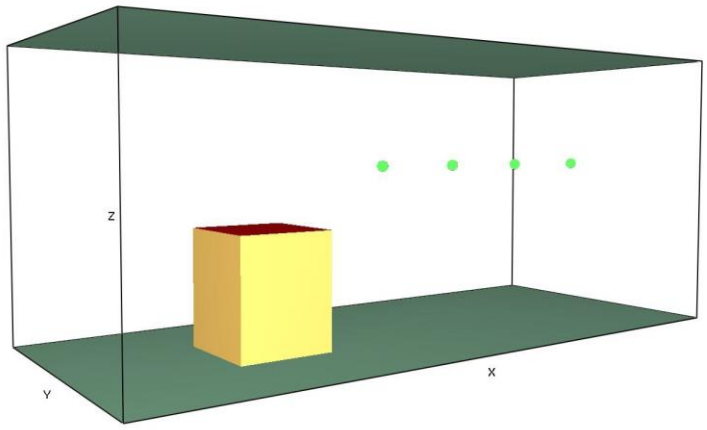


Figure 127. Simulation domain – Simple case test from FIRESAFE II [7].

In the FIRESAFE II study, the radiant heat flux was found to be the governing parameter in the vicinity of the fire. Therefore, only the time when the radiant heat flux threshold value (2.5 kW/m^2) is exceeded is monitored at a distance of 3 m and 4 m from the fire. Indeed, the general effective range of a powder fire extinguishers is between 3-4 m [43].

Table 30 presents the time from the ignition to exceed 2.5 kW/m^2 for different fire growing speeds. For the different growing speeds, the conditions become untenable for the same HRR values.

Table 30. Time to exceed 2.5 kW/m² depending on HRR curve

	3 m from fire		4 m from fire	
Simulation	Time (s)	HRR (kW) at time	Time (s)	HRR (kW) at time
Slow	592	1 027	815	1 947
Medium	305	1 090	418	2 048
Fast	148	1 027	209	2 048
Ultra-fast	76	1 083	104	2 029

Table 31 presents the time from the ignition to exceed 2.5 kW/m², varying different parameters. The parameter with the highest sensitivity is the height of the simulation domain. Indeed, the interaction of the flame with the ceiling influences the flame view factor, and so the radiant heat flux received at 3 m and 4 m from the fire.

Table 31. Time to exceed 2.5 kW/m² depending on the difference between the height of the simulation domain and of the fire seat (Δh) and the CO and soot yields (y_{CO} and y_{soot}). Base case: Δh = 1.8 m, y_{CO} = 0.036, y_{soot} = 0.12

	3 m from fire		4 m from fire	
Simulation	Time (s)	HRR (kW) at time	Time (s)	HRR (kW) at time
Base case	305	1090	418	2048
Δh = 3.0 m	310	1127	413	1999
Δh = 1.0 m	303	1076	408	1951
Δh = 0.8 m	392	1801	556	3624
Δh = 4.8 m	320	1200	440	2269
y_{CO} = 0.5, y_{soot} = 0.15	317	1178	406	1932
y_{CO} = 0.01, y_{soot} = 0.01	294	1013	398	1857

Those new simulations confirm that ATSFR is sensitive to several parameters. No simple law that can be used directly without simulations was found.

13.11.3.2 Early detection as regards as activation of fixed fire-extinguishing system

In LASH FIRE, several CFD simulations were run using SAFIR code in order to model the spread of fire from one vehicle to another in a ro-ro space. Fire scenarios were selected in order to challenge the containment and evacuation. Indeed, worst credible scenarios were modelled. The selected HRR curves are based on experimental data and represent severe but realistic fires. The fire spread model is based on ignition of rubber tyres, which are the vehicle components that are most likely to ignite first. More details in LASH FIRE deliverable D04.3 [30]. The results of the simulations are analysed to provide information about the fire spread in ro-ro spaces.

Table 32 presents the main results in terms of damage to cargo of the simulations run for the Stena Flavia (SF) and Magnolia Seaways (MS). Only the results of the fires started in open ro-ro spaces are presented because they resulted in the quicker fire spread. After 5 minutes from the ignition, there is still only 1 truck burning. After 8 minutes, the fire spreads to a 6th truck, which correspond to the layer of vehicles not initially exposed to the fire seat (Figure 128). After 15 minutes, the fire spreads to trucks located in the adjacent drencher zone (DZ).

Table 32. Damage to cargo

	Time to ignite (min.)			Number of ignited trucks			
Simulations	**2nd truck**	**6th truck**	**Truck in next DZ**	**At 3 min.**	**At 5 min.**	**At 10 min.**	**At 15 min.**
SF1	5.8	8.0	16.4	1	1	11	17
SF2	5.9	7.8	14.5	1	1	10	16
SF3	5.6	8.3	15.5	1	1	10	18
SF4	5.9	8.2	15.0	1	1	8	18
SF5	5.4	7.5	14.7	1	1	11	18
MS8	6.8	13.9	18.8	1	1	5	11
MS9	7.2	16.9	20.2	1	1	3	4
MS10	7.2	16.9	20.2	1	1	3	4

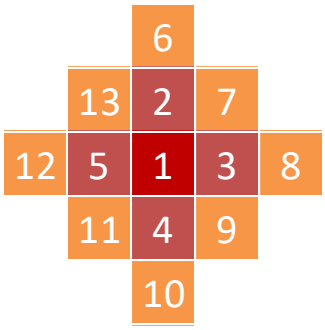


Figure 128. Layers of vehicles (principle).

Table 33 presents the main results in terms of damage to ship of the simulations run for the Stena Flavia (SF) and Magnolia Seaways (MS). Only the results of the fires started in open ro-ro spaces are presented because they resulted in the quicker fire spread. The time to ignite PVC is selected to represent the damage to ceiling elements, e.g. cable trays, and the time when the bulkhead reaches 500°C is selected to represent the hull deformation [44]. The ceiling elements in the drencher zone of fire origin starts to be ignited after 4 minutes from the ignition and after 12 minutes in the adjacent drencher zone. The bulkhead starts to be deformed in the drencher zone of fire origin after 11 minutes and after 21 minutes in the adjacent drencher zone.

Table 33. Damage to ship

	Time to ignite PVC (min.)		Time when the bulkhead reaches 500°C (min.)	
Simulations	**In DZ of origin**	**In next DZ**	**In DZ of origin**	**In next DZ**
SF1	6.1	14.7	21.1	22.5
SF2	5.6	12.8	25.4	27.9
SF3	5.9	12.7	23.6	26.8
SF4	5.8	14.5	26.7	27.8
SF5	4.1	14.2	18.1	20.5
MS8	3.9	N/A	> 60	N/A
MS9	6.0	25.6	11.1	41.2
MS10	6.3	17.6	17.9	36.0

Despite the high severity of the selected fire (1 MW in less than one minute), the simulations underline that there is still one single vehicle burning and no significant damages to the ship after 5 minutes from the ignition. Activating the fixed fire-extinguishing system (i.e. drencher system) within this time frame should have a high probability of success.

Therefore, for this specific design fire (where first response is likely not possible), early detection can be defined as the detection time that will enable the activation of the drencher system within this time frame.

It shall be noted that this can be consistent with DNV's recommendations [41] (i.e. release time of drencher system 3 minutes after the fire alarm, providing the fire alarm was sounded 2 minutes after the ignition).

13.11.4 Conclusion

As a conclusion, swift detection can be defined as a concept relative to the fire scenario and may be re-used in future risk models or any other analyses. The performance criterion for swift detection can be to detect the fire early enough to be able to prevent any loss of life and limit damage to the ship and cargo. And its corollary can be to detect the fire early enough to be able to extinguish the fire, whatever the fire, whatever the means of fire-fighting used.

As a way forward, this concept can be standardised using a design fire. The design fire can be defined by a deterministic approach (e.g. truck fire) or by a probabilistic approach (e.g. a stochastic generation of fire scenarios). The latter approach will be able to provide the early detection as the 90th percentile of the distribution generated by the set of fire scenarios (for example). NTUA has conducted promising research related to the probabilistic generation of design fires. The readers may refer to their work as a start [45], [46], [47], [48] and [49].

Another way forward can be to extend the calculations done previously to new hazards arising from Alternatively Powered Vehicles (APVs), e.g. a thermal runaway or a PRV release.