CARGOSAFE REPORT

Study investigating cost-efficient measures for reducing the risk of cargo fires on container vessels (CARGOSAFE)

EMSA/CARGOSAFE – 2022-2023

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EMSA

About this study:

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Executive Summary

CARGOSAFE is a safety study developed in accordance with the Formal Safety Assessment, MSC-MEPC.2/Circ. 12/Rev. 2 Revised Guidelines for Formal Safety Assessment (FSA) for use in IMO rule-making process. The study is tendered and commissioned by European Maritime Safety Agency (EMSA). Its goal is to identify cost-effective measures for reducing the risk of cargo fires on containerships. The study encompasses both newbuilds and existing containerships and has been done per the instructions in the Tender Specifications (EMSA/OP/17/2021) and in dialogue with EMSA during the work.

Fires on containerships, in particular originating in containerized cargo, have been increasingly called to attention by maritime stakeholders within the last five years. This aligns with a general increase in the size of containerships ships, with a fleet which has seen a close to 30% capacity increase in the very large and ultra large containership (VLCS/ULCS) categories over the last two years.

Fire safety of cargo onboard containerships can be considered a topic with two essential dimensions requiring consideration in a safety risk analysis:

- The ship systems for detection and response to fires.
- The carriage, handling, declaration, and segregation of cargo - especially dangerous goods (DGs) and the declaration of these.

Both topics have been broken down and considered in the work carried out.
The work was divided into five tasks according to MSC-MEPC.2/Circ.12/Rev.2 guidelines on Formal Safety Assessment:

- Hazard Identification.
- Risk-Analysis.
- Risk Control Options.
- Cost-effectiveness Assessment.
- Decision-making recommendations.

Task 1 – Hazard identification

In Task 1 (Hazard identification), four hazard identification (HAZID) workshops were conducted online (via Microsoft Teams) in combination with the internet whiteboard tool MIRO.

The first HAZID was on detection, which pointed out that detection in the cargo hold is entirely reliant on the sample extraction smoke detection systems, since crew seldom go into the hold and that fire patrols do not take place in the holds. On-deck detection, it is reliant on visual identification by the crew since there is no requirement on technical system to assist and added to this it was noted that visual identification is affected by the size of the crew, the size of the vessel, time of the day and weather conditions.

The second HAZID on containment highlighted structural integrity of containers as an essential element in the containment strategy together with shutting of openings and ventilation ducts (in the cargo holds), as is active boundary cooling. Loss of containment was defined in four major categories: flame propagation, heat being transferred through materials (e.g., radiant heat through container walls, bulkheads, hatches), loss of structural integrity that could occur at different levels, and explosion and it could be identified from a container itself up to the level of hold and bay.

The third HAZID on firefighting highlighted the issue with CO2 in the cargo holds and the limited amount carried onboard. In addition to the performance of CO2 system and its dependency on the effectiveness of cargo hold air tightness and ability to penetrate the individual container units. Also, maintenance of CO2 system is challenging, and crew training is important. Local fire extinguishing in the container unit is limited and highly reliant on early detection, something that the current detection methods do not support in all scenarios. Location of the container is a critical

parameter for local fire extinguishing, as access to the unit is paramount. The prescribed equipment does not allow for fire extinguishing of units high in the stack. Local extinguishment of a unit in the cargo hold is unlikely to occur due to the hazardous environment and the added risk to crew, in addition to the accessibility to the individual units. Flooding of cargo hold with water was discussed since this can be used, on certain grounds, stability and structure needs to be considered. Flooding of cargo hold may create mixing cargo that could result in new hazards.

The fourth HAZID on prevention identified main cargo types to be responsible for a large proportion of cargo fire accidents, namely: calcium hypochlorite, charcoal, and lithium-ion batteries. There is expected to be an increase in lithium-ion batteries transport and accidents in relation to other good types. Non- or misdeclaration, were considered key to many of the faults and errors occurring in cargo preparation. Issues with inspection, such as variations in required frequency, were a concern as well as lack of screening tools and information exchange.

Task 2 – Risk-analysis

The objective of the CARGOSAFE study is to reduce the risk of fire in containerships' cargo. This risk reduction shall be based on Risk Control Options. An evaluation of each of these solutions are performed in Task 4, to assess their possible cost-effectiveness. Hence, the goal of Task 2 was the creation and quantification of a risk model, able to provide risk levels in terms of life loss, cargo loss, ship loss, environmental loss, and salvage cost for the generic ships, as well as the evaluation of risk reductions provided by the upcoming RCOs. One of the main challenges faced was the selection of the most relevant type of risk models and its quantification with the most accuracy possible, since IMO's Revised Guidelines for Formal Safety Assessment (FSA) considers the quality and the accuracy of the data used as the most important points[2].

To address these challenges, the following actions were taken:

- Review of several previous studies lead on containerships, of several types of risk models and selection of a relevant type of risk model.
- Development of the risk model structure, selection of the most relevant tiers of a fire development.
- Collection of several databases from EMSA, gathering of information about important fleet characteristics, evolution of accident frequencies, etc.
- Post-processing these databases to extract as much relevant data as possible to fill the risk model.
- Quantification of the created risk model, as well as a consequence risk model, used as a complement to the risk model.
- Computation of the different risk levels (PLL, PLC, PLS, EPL) for the generic ships.

Several studies, such as the study included in FP 54/15[3] , the project SAFEDOR[4] and a study proposed by DTU[5] were reviewed to determine the structure of the incoming risk model that would suit the CARGOSAFE study the best. The type of risk model chosen was based on an event tree (supported by fault trees and risk contribution trees), because of its simplicity to be understood, created, and potentially updated in the upcoming steps of the study. The tiers of this risk model represent the different steps encountered when a fire occurs onboard, from the ignition to the potential containment of the fire in the space of origin. The ignition tier was included using a bowtie approach. Bowtie approach is a structured approach which captures causes on its left and consequences on its right, with the unwanted event in the middle.

Based on the Prevention HAZID in Task 1, a risk model for prevention was developed in Task 2. The prevention risk model has been developed based on three categories of goods that ignite:

· Dangerous goods that are not properly declared.
· Dangerous goods that are properly declared.
· Non-dangerous goods.

[2] IMO, MSC-MEPC.2/Circ.12/Rev.2: Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process, 2018.
[3] REVIEW OF FIRE PROTECTION REQUIREMENTS FOR ON-DECK CARGO AREAS, FSA – Container fire on deck, Details of the Formal Safety Assessment, Submitted by Germany, IMO FP54 INF.2, 2009
[4] MSC 83/INF.8: FSA – container vessels - Details of the Formal Safety Assessment, IMO, 2007
[5] DTU, Container ships: fire-related risks, Journal of Marine Engineering and Technology, 2021

For each category of goods that ignite a fault tree was developed that shows the initiating events leading to ignition of the goods. Probabilities of the three categories of goods that ignite were extracted from accident statistics and fault trees for each of the three categories was qualitatively evaluated through an expert workshop.

EMSA provided extensive data, including either characteristics of the ships present in the fleet, or information about the relevant accidents that occurred onboard these ships during the period of interest, i.e., from 1997 to 2021. These data were used, in the first place, to gain an overview of the main characteristics of the fleet (i.e., number of shipyears (SY), evolution of cargo capacity, determination of a generic ship) as well as information about accidents as a whole. The main findings are the following:

- The total number of shipyears in the fleet for the period of 1997-2021 is 1.01E+05 SY.
- The total number of TEU capacity.years, which is the total capacity of the fleet, for the period 1997-2021 is 3.35E+08 TEU capacity.years.
- The frequency of cargo fires per shipyears has increased during the last years, starting around 7.50E-4 fires/SY in the early 2000s, and having doubled in the early 2020s.
- The frequency of cargo fires in fires per TEU capacity.year has remained stable for the whole studied time period, around 3.70E-7 fires/TEU capacity.years.

These data provided by EMSA were used to develop a new fire-fighting risk model and to quantify it. Each accident in the casualty database was studied and their narrative texts were post-processed. The goal was to be able to extract relevant data directly from the database for each case (i.e., if the fire had been put out with fire hoses, with CO_2, if the crew had to evacuate, etc.).

Based on the historical data, the historical PLL has been computed:

PLLhist=1.45E-4 fatalities per shipyear.

Two event trees were developed in the fire-fighting risk model: one for a cargo fire starting on deck, and one for a cargo fire starting in hold. The choice for these two event trees was guided by the differences regarding fire detection equipment and fire-fighting systems and strategies between a fire starting either on deck or in hold. The tiers of the fire-fighting risk model represent the different steps encountered when a fire occurs onboard, from the ignition to the potential containment of the fire in the space of origin, including fire-fighting operations such as manual firefighting or CO_2 release in holds.

A consequence model was developed as a complement for each of the risk scenarios. The model contains two main parts. First, it is the contribution consequence tree, which tiers were identified and accounted for as the main contributors to the final aftermath of the fire. These factors were: required and received external assistance, final damage to the cargo and ship, and evacuation or abandonment of the ship. The second part of the consequence model is built for the consequence quantification. This part accounts for the aftermath of a fire in terms of potential loss of life expressed as equivalent fatalities, and cargo loss expressed as a percentage of the total TEU capacity of the ship and ship damage stated qualitatively.

For a generic ship representing the median of world fleet characteristics the risk model in terms of cargo transported and main design features, associated to the consequence model mentioned above, returns the following values:

- PLLmedian= 3.93E-4 fatalities per shipyear.
- PLCmedian= € 14,184 euro per shipyear.
- PLSmedian= € 3,719 euro per shipyear.
- EPLmedian= € 2,325 euro per shipyear
- TPLmedian= € 29,213 euro per shipyear.

The PLLmedian values were compared to previous models “PLLhist”, extracted from the database, and were found to have the same order of magnitude. Hence, it can be assumed that the risk model developed here, which was the target of Task 2, is a pretty good approximation of the actual situation and generates more life risks that have not been observed or reported. This model shall then be used in the upcoming tasks, in particular during Task 4, to assess the potential cost-effectiveness of each selected RCO.

As part of a sensitivity analysis, other generic ships with higher TEU (18000, 7500 and 3500, representing three generic sizes used throughout the study for three groups: twin island, post-panamax and rest of the fleet) were used to calculate the approximated budget for the risk control options. It is concluded that the budget allocated for risk control options for median and lower size ships is relatively low. However, the budget to reduce fatalities and economic loss increases proportionally to the TEU number. Therefore, there is justification to propose hardware RCOs mainly on the cargo hold fires, which is the main contributor to the risk.

Task 3 – Risk control options (RCOs)

Gathering input from the HAZID workshops (Task 1), several risk control measures (RCMs) were taken into consideration for choosing the viable RCOs. The chosen RCOs were classified into fire prevention, fire detection, firefighting, and fire containment. The effectiveness of each RCO was then evaluated in terms of risk reduction potential and technology readiness level (TRL). Based on this assessment, the realistic RCOs were selected and considered for the cost-effectiveness assessment (CEA) (Task 4).

Out of 18 RCMs, 5 RCOs were chosen for fire prevention, which included container screening tools, maintaining a database of rejected cargo, planning stowage, improvement of lashing on the deck and improvement of test methods on self-heating cargo. The effective assessment for RCOs aimed at fire prevention was largely qualitative. However, container screening and the improvement of lashing were quantitatively assessed. The maximum reduction of the probability of ignition was estimated at 6.19% and 1.63% for these two RCOs respectively. These two options were chosen as the most viable RCOs for prevention due to their higher TRL and overall risk reduction potential.

Five RCOs for fire detection were further assessed in this study. They are optimization of the current system in place, temperature monitoring of individual containers, IR cameras for heat/ flame detection, AI based smoke detection and portable IR cameras distributed among the crew.

- The performance of the current detection system (based on smoke detection) was quantitively assessed using computational fluid dynamics (CFD). The long detection times was identified as a potential room for improvement. In the current system, the smoke is required to flow through a pipe from the collection point to the detector unit. This alone could add 300s to the overall detection time. Under the optimization of the existing system, the effect of having individual detector units on the cargo hold and increasing the number of smoke sampling points (sniffers) were considered. The optimized system clearly reduces the detection time although implementing such modifications in existing vessels was identified as a limitation. The most likely potential reduction of risk due to the improvement was not as significant and was below 3% for all the cases.

- As per the results of the CFD simulations, monitoring temperatures of individual containers resulted in very low detection times depending on the size of the fire. However, the system has limited use on deck and requires additional protection against damage especially during loading and unloading.

- Despite being proven to be effective in other industrial and commercial applications, using IR cameras and AI based smoke detection were not applicable in the cargo holds due to weather effects, movement of the vessel and tight stacking of containers. The risk reduction potential of IR camera-based detection for slow growing fires could be between 5.4% and 2.4% depending on the type of the vessel. The risk reduction potential for larger vessels such as twin island (generic ship 1) is lower compared to feeder (generic ship 3) and single island (generic ship 2). For fast growing fires, IR based detection proved more effective with higher risk reduction potential being around twice compared to that of for slow growing fires.

- Portable IR cameras for crew members were mostly identified as a tool for confirming a fire but not as the primary means of detection. The risk reduction potential of this RCO was estimated to be below 3% for both slow and fast-growing fires.

Optimization of the CO2 extinguishing system, introduction of novel firefighting tools, tools which increase the reach for the firefighters, unmanned firefighting techniques and water mist turbines were chosen as the RCOs for firefighting.

- There are limitations to CO2 as an extinguishing agent especially against self-oxidizing fuels such as li-ion batteries. The risk reduction potential of the CO2 extinguishing system remained constant for all the ship types, but it proved to be far more effective against slow growing fires with a risk reduction potential of 20% as opposed to 5% and 2.5% for fast-growing fires and explosions respectively.

- A handheld firefighting device which is able to drill into the container wall and inject a water mist spray inside the container was considered as an improvement over the current firefighting techniques. Manual handheld firefighting is as expected, not effective against explosions. However, the potential of such devices is promising with risk reduction potentials for slow and fast-growing fires around 12% and 6% for feeder vessel type (generic ship 3) and around 25% and 9% for both single island and twin islands vessel type (generic ship 1 and 2).

- Reaching containers at higher tiers was addressed in the next RCO where the usable tools were presented which are capable of hoisting firefighters safely to higher elevations. The risk reduction potential of these solutions was less than 7% for all ship types and fires.

- A remote-controlled water monitor has the advantage of operating from a distance that does not expose the firefighters to the conditions surrounding the fires. In addition, it would prevent crew exhaustion during firefighting operations, making them more efficient. However, such devices face several challenges with compatibility in cargo decks mainly due to the extreme geometrical features of container decks.

- The solution of water mist turbines also faces similar challenges with steep angles and reaching higher tiers. However, cooling the stack of origin has a larger effect on the risk reduction potential which leads to risk reduction potentials between 30% and 40% for slow growing fires and between 12% and 17% for fast-growing fires and explosions leading to fires.

Containing the fire to the origin focuses on minimizing flame spread to adjacent stacks through hatch covers or just via flame impingement. Active suppression systems under the hatch covers, passive fire protection on the cargo holds, stack cooling techniques for firefighting on the deck and flooding the cargo holds were considered as the RCOs for fire containment.

- Flame spread from the cargo hold into the deck can happen through the hatch covers which can be avoided by using systems such as sprinklers which create a barrier between the deck and the cargo hold.

- Passive fire protection systems such as fire insulation and intumescent coatings provide much needed thermal insulation which can contain the fire for longer times preventing flame spread between decks and cargo holds. Good housekeeping and proper maintenance are required to avoid any damage to the insulation materials used to ensure that the system is not compromised. Installing passive fire protection led to risk reduction potentials of 12.5% and 25% for slow and fast-growing fires.

- Water based containment solutions were investigated as on-deck cooling solutions. Comparatively higher maximum risk reduction potentials over 45% up to 65% for slow growing fires and over 25% for fast-growing fires were estimated for these solutions. For fires resulted by explosions, the effectiveness was estimated to be relatively low ranging between 11% and 13% for all three vessel types. However, as with many water-based systems such as water curtains and portable water monitors, these systems face challenges in ensuring that the water droplets reach all the containers which require cooling. Additionally, the operation of such devices can also be affected greatly by weather conditions as well. Flooding the cargo holds with water was considered as potential RCO.

• Flooding the cargo holds is a destructive solution which will compromise all the containers and the goods which get submerged in water. Flooding the cargo hold with a large amount of water also affects the stability of the vessel. The risk reduction potential from implementing this solution against slow growing ranged between 38% to 23% for the three vessel types. Against fast fires and explosions, the RCO was less effective but, still risk reduction potentials between 25% and 15% for fast-growing fires and, for explosions values around 13% to 8% were estimated.

Task 4 – Cost-effectiveness assessment

The Cost-effectiveness assessment was carried out for the 3 generic ship types / sizes and for both a new building and retrofit solution scenario, in total 6 vessel categories. For different metrics / values have been defined of relevance for the assessment, which are: GCAF (Gross Cost of Averting a Fatality), NCAF (Net Cost of Averting a Fatality), NPV (Net Present Value) and BCR (Benefit vs Cost ratio). The first metric is an indicator of to what degree an RCO is cost effective with respect to reducing loss of life, and the three other metrics and values are indicators of to what degree RCOs are effective from an economic perspective. Benefit and cost calculation variables have been estimated for all RCOs and vessel categories via results from task 3 and price information from various relevant vendors, industry experts etc. Calculation of costs and benefits have included the initial investment cost but also a discounting of future costs and benefits based on a chosen discount rate of 3.16% in line with US Government Treasury bonds. Benefits covered are loss of cargo, ship, salvage, and environmental costs and have been adopted in calculations based on task 3 results. To judge if an RCO is cost-efficient, a CAF assessment criterion of 8.7M € was estimated robustly using two alternative methods. Also, a NPV > 0 € and BCR of 1 and above were used as criteria to assess economic potential of the RCOs implementation for industry and society. The calculations and underlying cost and benefit assumptions are explained in the report.

Results of the RCO cost effectiveness assessment are shown per vessel category (generic ship 1, 2 and 3, as well as Retrofit and New buildings) and a ranking of the different RCOs is presented. The results show that only one RCO D5 (Portable IR cameras for manual detection) can be recommended from a GCAF / Loss of life impact perspective. For the Twin Island (generic ship 1), the CAF criterion is fulfilled since it is below 8.7M €m, and for the two other types of ships, it has if not the lowest a low GCAF compared with the other RCOs.

However multiple RCOs can be recommend from an economic perspective taking into account NCAF, NPV and BCR calculation results. F4 (Methods for unmanned firefighting) is the only RCO which has visible economic potential across all 3 vessel types, but only for the new building scenario. D5 and F3 (Manual firefighting tools that increase reach) (have visible economic potential for all 3 vessel types, though less for Feeder (generic ship 3) compared to the other vessel types. D2 (Heat Detection), F2 (Improved manual firefighting tools for individual container breaching and firefighting) and C2 (Passive protection to prevent fire spread towards the deck) also carry significant economic potential for particularly Twin and Single Island (generic ship 1 and 2). Finally, P4 (Improved control of lashings) and C1 (Active protection underneath hatch covers to protect fire spread towards the deck) have some visible economic potential for particularly the Twin Island (generic ship 1). The study thus demonstrates a pattern where RCOs in general becomes more attractive the bigger the vessel is in slot capacity, and a pattern where RCOs occasionally are more attractive for new built compared to retrofitted vessels.

A sensitivity analysis was made to validate the robustness of the results. Emphasis was made on testing to what degree RCO cost effectiveness results would change if implementation (investment and discounted annual) costs were increased or reduced with 20%. The sensitivity analysis revealed that all the RCOs considered cost effective in CARGOSAFE remains cost-effective / recommendable, even after a 20% increase in their costs. As expected, some RCOs turned out to improve mainly their economic attractiveness after a 20% cost reduction. For the Twin Island (generic ship 1) as it could be expected, the solution that can potentially become cost-effective is **P1** as the base BCR was already close to 1. For a Single Island (generic ship 2), no solutions can become more cost-efficient and, onboard a feeder, **F4** improves its impact.

Task 5 – Recommendations for decision making

Following the Cost-effectiveness assessment, several RCOs have been demonstrated to be potentially cost-effective, based on Cost-Benefit Ratio. The Benefit-Cost ratio (BCR) has been calculated for every RCO by first calculating the difference between accumulated discounted benefits versus the initial year zero investment plus accumulated discounted cost over the 25 years, see below. Strictly speaking, a RCO is cost-effective if its BCR is above 1. Although, due to uncertainties in the values used in the costs, it was decided to also keep RCOs which CBR was close to 1 to avoid disregarding potentially relevant RCOs.

Through, the calculations, it has been clearly indicated that the size of the ship has an impact on this cost-effectiveness. Thus, demonstrating that there is no such thing as "one size fits all" solution. Hence, the cost-effective RCOs presented below may be different for each generic ship.

Below are tables sorted in highest to lowest according to BCR.

Table 1: BCR-sorted RCOs for the Feeder (generic ship 3).

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
F4	10 000 €	0 €	-435 €	0.956	1.045	3.16E-06	126.4E+6	5.5E+6
F3	15 000 €	0 €	-3 812 €	0.746	1.341	2.23E-06	269.4E+6	68.5E+6
F2	15 000 €	0 €	-7 200 €	0.520	1.923	1.57E-06	382.5E+6	183.6E+6
C2	184 150 €	0 €	-95 702 €	0.480	2.082	7.38E-05	99.8E+6	51.8E+6
D2	85 440 €	2 500 €	-76 599 €	0.409	2.446	3.03E-05	170.8E+6	101.0E+6
D5	1 520 €	243 €	-3 779 €	0.349	2.862	9.96E-07	233.1E+6	151.7E+6
P4	0 €	1 680 €	-21 477 €	0.276	3.629	5.08E-06	233.5E+6	169.1E+6
P1	184 417 €	2 769 €	-202 294 €	0.133	7.528	1.93E-05	483.8E+6	419.5E+6
D1	106 038 €	0 €	-97 850 €	0.077	12.950	7.73E-06	548.5E+6	506.2E+6
C3	321 408 €	3 214 €	-355 644 €	0.059	16.819	5.74E-06	2.6E+9	2.5E+9
C1	350 000 €	25 000 €	-759 453 €	0.040	24.935	3.72E-05	850.1E+6	816.0E+6
F4R	283 916 €	0 €	-274 351 €	0.034	29.683	3.16E-06	3.6E+9	3.5E+9
F5	525 000 €	22 500 €	-904 911 €	0.019	53.755	5.67E-06	6.5E+9	6.4E+9
F1	500 000 €	22 500 €	-881 905 €	0.017	59.177	1.35E-05	2.7E+9	2.6E+9
D4	71 405 €	6 560 €	-184 489 €	0.014	69.778	5.77E-07	13.0E+9	12.8E+9
D1R	856 588 €	0 €	-848 400 €	0.010	104.611	7.73E-06	4.4E+9	4.4E+9
D3	1 800 000 €	18 000 €	-2 104 593 €	0.006	162.160	2.84E-06	29.9E+9	29.7E+9

Table 2: BCR-sorted RCOs for the Single Island (generic ship 2).

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
D5	1 520 €	243 €	33 563 €	6.778	0.148	1.81E-05	12.9E+6	-74.3E+6
F4	10 000 €	0 €	24 430 €	3.443	0.290	6.59E-06	60.7E+6	-148.3E+6
F3	15 000 €	0 €	23 930 €	2.595	0.385	4.99E-06	120.2E+6	-191.8E+6
F2	15 000 €	0 €	12 265 €	1.818	0.550	3.51E-06	170.9E+6	-139.8E+6
C2	480 000 €	0 €	294 152 €	1.613	0.620	3.28E-04	58.5E+6	-35.9E+6
D2	170 320 €	2 500 €	104 749 €	1.488	0.672	1.30E-04	65.9E+6	-32.2E+6
P4	0 €	4 987 €	-42 601 €	0.516	1.938	1.75E-05	200.7E+6	97.1E+6
P1	391 389 €	5 877 €	-322 635 €	0.348	2.871	6.66E-05	297.3E+6	193.7E+6
C1	735 000 €	52 500 €	-1 212 095 €	0.270	3.697	2.61E-04	254.7E+6	185.8E+6
D1	225 167 €	0 €	-168 625 €	0.251	3.982	3.30E-05	272.6E+6	204.2E+6
C3	687 456 €	6 875 €	-695 838 €	0.140	7.161	1.59E-05	2.0E+9	1.8E+9
F1	500 000 €	22 500 €	-797 039 €	0.112	8.968	6.22E-05	577.0E+6	512.7E+6
D4	151 624 €	6 560 €	-248 614 €	0.070	14.241	2.50E-06	4.3E+9	4.0E+9
F4R	490 535 €	0 €	-456 105 €	0.070	14.247	6.59E-06	3.0E+9	2.8E+9
F5	525 000 €	22 500 €	-859 981 €	0.067	14.852	1.19E-05	3.1E+9	2.9E+9
D1R	1 818 917 €	0 €	-1 762 375 €	0.031	32.169	3.30E-05	2.2E+9	2.1E+9
D3	3 300 000 €	33 000 €	-3 819 819 €	0.016	62.076	8.34E-06	18.6E+9	18.3E+9

For the Single Island (generic ship 2), from an economic perspective, 6 RCOs being **D5, F4** (only new building**), F3, F2, C2, D2** (in ranked order) are very attractive and should also be considered as recommendable for implementation.

Table 3: BCR-sorted RCO's for the Twin Island (generic ship 1).

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
D5	1 520 €	243 €	351 973 €	61.598	0.016	7.93E-05	2.9E+6	-177.6E+6
F3	15 000 €	0 €	257 633 €	18.176	0.055	1.62E-05	37.1E+6	-637.4E+6
F4	10 000 €	0 €	106 278 €	11.628	0.086	1.01E-05	39.7E+6	-421.7E+6
C2	711 200 €	0 €	4 690 006 €	7.594	0.132	1.02E-03	27.8E+6	-183.4E+6
F2	15 000 €	0 €	76 060 €	6.071	0.165	5.43E-06	110.5E+6	-560.5E+6
D2	458 240 €	2 500 €	1 326 521 €	3.641	0.275	3.95E-04	50.8E+6	-134.2E+6
C1	805 000 €	57 500 €	4 023 921 €	3.211	0.311	1.34E-03	54.2E+6	-119.8E+6
P4	0 €	7 360 €	154 273 €	2.188	0.457	5.18E-05	100.3E+6	-119.2E+6
P1	938 967 €	14 099 €	-108 591 €	0.909	1.101	1.97E-04	241.6E+6	22.1E+6
F1	500 000 €	22 500 €	-180 760 €	0.798	1.252	2.20E-04	163.0E+6	32.8E+6
D1	540 400 €	0 €	-136 153 €	0.748	1.337	1.10E-04	196.6E+6	49.5E+6
F5	525 000 €	22 500 €	-477 776 €	0.482	2.075	3.82E-05	964.4E+6	499.7E+6
C3	1 116 000 €	11 160 €	-893 062 €	0.320	3.127	2.62E-05	2.0E+9	1.4E+9
D4	363 899 €	6 560 €	-403 588 €	0.159	6.305	4.68E-06	4.1E+9	3.4E+9
F4R	1 037 284 €	0 €	-921 006 €	0.112	8.921	1.01E-05	4.1E+9	3.7E+9
D1R	4 365 400 €	0 €	-3 961 153 €	0.093	10.799	1.10E-04	1.6E+9	1.4E+9
D3	3 600 000 €	36 000 €	-3 981 711 €	0.060	16.701	1.56E-05	10.9E+9	10.2E+9

Table 4 summarizes the cost-effectiveness of all assessed solution for the three generic ships, based on BCR.

Table 4: Summary of cost-effectiveness of all RCOs for the 3 generic ships.

RCO ID	Description	Twin Island	Single Island	Feeder
P1	Container screening tool	Maybe	No	No
P4	Improved control of lashing	Yes	No	No
D1	Optimizing current smoke detection system	No	No	No
D1R	Optimizing current smoke detection system (retrofitting)	No	No	No
D2	Heat detection looking at individual container temperature rise	Yes	Yes	No
D3	Fixed IR cameras. Coupled to a software solution to automate detection	No	No	No
D4	CCTV - AI - smoke detection	No	No	No
D5	Portable IR cameras for crew to enhance manual detection	Yes	Yes	No
F1	Increasing effectiveness of current CO2 system	No	No	No
F2	Improved manual firefighting tools for individual container breaching and firefighting	Yes	Yes	No
F3	Manual firefighting tools that increase reach	Yes	Yes	No
F4	Methods for unmanned fire fighting	Yes	Yes	Maybe
F4R	Methods for unmanned firefighting (retrofitting)	No	No	No
F5	Watermist canon	No	No	No
C1	Active protection underneath hatch covers to protect from fire spread towards the deck	Yes	No	No
C2	Passive protection to protect from fire spread towards the deck	Yes	Yes	No
C3	Fixed external container stack cooling system to stop spread between stacks	No	No	No

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List of Abbreviations

ABS	American Bureau of Shipping
ALARP	As Low as Reasonably Practicable
ATEX	Atmosphères Explosible
BCR	Benefit Cost Ratio
BD	Below Deck
BIMCO	Baltic and International Maritime Council
BM	Breadth Moulded
BND	Boundary
BV	Bureau Veritas Marine & Offshore SA
CAF	Cost of Averting a Fatality
CCTV	Closed-Circuit Television
CEA	Cost-Effectiveness Assessment
CFD	Computational Fluid Dynamics
CINS	Cargo Incident Notification System
Circ.	IMO Circular
CO	Carbon monoxide
CO_2	Carbon dioxide
COO	Container Of Origin
CSAP	Cargo Safe Access Plan
CSC	Convention for Safe Containers
CSM	Cargo Securing Manual
CSZ	Container Spacing Zone
CT	Consequence Tree
CTU	Cargo Transport Unit Code
DB	Double-Bottom Ballast Tanks

DBI	Danish Institute of Fire and Security Technology
DG	Dangerous Goods
DNV GL	Det Norske Veritas and Germanischer Lloyd
DRI	Direct Reduced Iron
DTU	Danmarks Tekniske Universitet (Technical University of Denmark)
DVB	Divinylbenzene
ECFP	Enhanced Cargo Fire Protection
EMCIP	European Marine Casualty Information Platform
EMSA	European Maritime Safety Agency
EPL	Environmental Potential Loss
ET	Event Tree
FDS	Fire Dynamics Simulator
FEU	Forty-foot Equivalent Unit
FF	Firefighting
FI	Frequency Index
FMEA	Failure Mode and Effects Analysis
FOV	Field Of View
FSA	Formal Safety Assessment
FSS Code	International Code for Fire Safety Systems
FT	Fault Tree
GCAF	Gross Cost of Averting a Fatality
GDPR	General Data Protection Regulation
GT	Gross Tonnage
HAZID	Hazard Identification
HOO	Hold Of Origin
HRR	Heat Release Rate
HRRPUA	Heat Release Rate Per Unit Area
IACS	International Association of Classification Societies
IHS	Information Handling Services
IMDG Code	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
IMSBC Code	International Maritime Solid Bulk Cargoes Code
IR	Individual Risk
ISO	International Organization for Standardization
IUMI	International Union of Marine Insurance
LBZ	Large Bunkering Zone
LEL	Lower Explosion Limit
LMIU	Lloyds Maritime Intelligence Unit
LOA	Length Over All
LOF	Lloyd's Open Form
MEKP	Methyl Ethyl Ketone Peroxide
MEPC	Maritime Environment Protection Committee
MFF	Manual firefighting

MSC	Maritime Safety Committee
MSRI	Mariner Safety Research Initiative
NCAF	Net Cost of Averting a Fatality
NPV	Net Present Value
OD	On Deck
OMT	Odense Maritime Technology
P&S	Port and Starboard
PA system	Public Address System
PLC	Potential Loss of Cargo
PLL	Potential Loss of Life
PLS	Potential Loss of Ship
POB	Persons On Board
PPE	Personal Protective Equipment
RCM	Risk Control Measure
RCO	Risk Control Option
RCT	Risk Contribution Tree
RISE	Research Institutes of Sweden
RZ	Dangerous Goods Risk Zones, as per CINS guidelines on Safety Considerations for Ship Operators Related to Risk-Based Stowage of Dangerous Goods on Containerships
SDU	University of Southern Denmark
SI	Severity Index
SOLAS	International Convention for the Safety of Life At Sea
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
SY	Shipyear
TEG	Technical Expert Group
TEU	Twenty-Foot Equivalent Units
TF	Total Flooding
TPL	Total Potential Loss
TRL	Technology Readiness Level
TRS	Turbine Response System
UHE	Unwanted Hazardous Event
ULCS	Ultra Large Containerships
VLCS	Very Large Containerships

1. Introduction

The CARGOSAFE study is being carried out for the European Maritime Safety Agency (EMSA) by a consortium with The Danish Institute of Fire and Security (DBI) as leader, together with the Research Institutes of Sweden (RISE), University of Southern Denmark (SDU), Odense Maritime Technology (OMT), and the classification society Bureau Veritas Marine & Offshore (BV) as partners (subcontractors).

The study is aimed at investigating cost-effective measures for reducing the risk from cargo fires on containerships. The study encompasses both newbuilds and existing containerships and has been done per the instructions in the Tender Specifications (EMSA/OP/17/2021) and in dialogue with EMSA during the work.

1.1 Definition of the problem

Fires on containerships, in particular originating in containers, have gained increasing visibility in the last 5 years, even though cargo fires are already a known characteristic accident occurrence for such ship types. The increased visibility of cargo fire accidents comes well aligned with an increase in the size of these ships, with a fleet which has seen a close to 30% capacity increase in the VLCS and ULCS categories over the last 2 years.

1.1.1 Objective

The objective of the study is to identify cost-effective Risk Control Options (RCOs) for cargo fires onboard containerships. The study has encompassed both newbuilds and existing containerships.

1.1.2 Boundaries

The CARGOSAFE study focusses on three generic vessel types: ULCS/VLCS twin island vessel, a single island vessel (post-panamax and ULCS/VLCS), and the rest of the fleet (most consisting of feeder like vessels). The accidents taken into account occurred from 1997 to 2021.

1.2 Generic model

The fleet referred to as the “CARGOSAFE fleet” is represented by the following characteristics:

- Ships designated as “container ships”.
- Gross Tonnage above 500GT.
- Built after 1980.
- No requirement on the classification by an IACS society.

These four criteria are detailed below.

1. **Ships designated as “container ships”**

This category includes the three following StatCodes: A33A2CC (Container Ship (Fully Cellular)); A33B2CP (Container Ship (Fully Cellular/Passenger ship) and A33A2CR (Container Ship (Fully Cellular/Ro-Ro Facility)).

2. **Gross Tonnage above 500GT**

All the vessels from the fleet are above 500 GT.

3. **Built after 1980**

Based on data from BV internal sources, at the date of the study, less than 0.5% of ships built in or before 1980 were still in activity. 1980 was thus arbitrarily decided as a cut-off date for this study.

4. **No requirement on the classification by an IACS society**

Some of the previous EMSA studies (such as FIRESAFE I and II) decided to exclude ships that have never been classed by a Classification Society member of the International Association of Classification Societies (IACS). The point was to minimize the effects of under-reporting of accidents.

In the case of the CARGOSAFE study, based on the data provided by EMSA, approximately 85% of the ships in the CARGOSAFE fleet were classed by an IACS member at the date of the study or when the ship got retired. Amongst the relevant accidents, approximately 88% of them happened to ships classed by an IACS member at the date of the study or when they got retired.

Since these two values are very close, the impact of under-reporting was deemed negligible. Thus, the study shall not make any distinction based on IACS classification.

For a detailed review and description of the fleet cf. section 3.2.

1.2.1 Technical/engineering subsystem

The following summary of the regulation review provides the basis on which the analysis is carried out (cf. Annex B for more information). The analysis is limited to only focusing on the minimum requirements as stated in SOLAS.

Fire protection standards for containerships are set by IMO SOLAS Chapter II-2, which applies to seagoing containerships engaged in international voyages. Since most containerships are intended to carry dangerous goods, it may be considered that the requirements for container cargo holds carrying dangerous goods are also applicable.

Then, it can be noted that several fire safety measures are mandatory for enclosed container cargo holds, including:

- Container cargo holds are provided with a fixed gas (usually CO2) fire-extinguishing system.
- When intended to carry explosives, container cargo holds are provided with a fixed water-spray system intended for boundary cooling purposes. Such system is not provided in all cargo container holds.
- Fixed fire detection is installed in container cargo holds. As a note, there is no specification on the type of detectors to be installed (fire, smoke or heat in line with FSS Code or smoke extraction system).
- Container cargo holds are ventilated through a dedicated ventilation system capable of providing 6 air changes per hour and electrical equipment installed in the holds is certified safe type with respect to the risk of explosive atmosphere.
- A60 fire integrity is required between the container cargo hold and the engine room.

For cargo area on weather decks however, limited fire safety measures are included in SOLAS, such as A60 fire integrity is required between the container area and the engine room. Additional requirements for water-based portable fire-fighting material have been introduced by resolution MSC.365(93) and are applicable only to containerships built on or after 01/01/2016 such as:

- Ships shall carry, in addition to the equipment, at least one water mist lance.
- The water mist lance shall consist of a tube with a piercing nozzle which is capable of penetrating a container wall and producing water mist inside a confined space (container, etc.) when connected to the fire main.
- Ships designed to carry five or more tiers of containers on or above the weather deck shall carry, in addition to the water mist lance, mobile water monitors as follows:
  - ships with breadth less than 30 m: at least two mobile water monitors; or
  - ships with breadth of 30 m or more: at least four mobile water monitors
- The mobile water monitors, all necessary hoses, fittings and required fixing hardware shall be kept ready for use in a location outside the cargo space area not likely to be cut-off in the event of a fire in the cargo spaces.
- As a result of the adding water monitors, additional requirements to hydrants were also included such as:

  - Sufficient number of fire hydrants shall be provided such that all provided mobile water monitors can be operated simultaneously for creating effective water barriers forward and aft of each container bay and, that two jets of water as required can be supplied at the pressure generally required. Furthermore, each of the required mobile water monitors can be supplied by separate hydrants at the pressure necessary to reach the top tier of containers on deck.

The mobile water monitors may be supplied by the fire main, provided the capacity of fire pumps and fire main diameter are adequate to simultaneously operate the mobile water monitors and two jets of water from fire hoses at the required pressure values. If carrying dangerous goods, the capacity of fire pumps and fire main diameter shall also comply with regulation 19 carriage and dangerous goods in SOLAS chapter II-2, as far as applicable to on-deck cargo areas.

- The operational performance of each mobile water monitor shall be tested during the initial survey on board the ship to the satisfaction of the Administration. The test shall verify that:
  - the mobile water monitor can be securely fixed to the ship structure ensuring safe and effective operation; and
  - that the mobile water monitor jet reaches the top tier of containers with all required monitors and water jets from fire hoses operated simultaneously.

1.3 Related documents

MSC 83/25/5 — International Maritime Organization (IMO): "*Work programme, Fire protection on cargo ships - proposed review of SOLAS chapter II-2 with regard to fire protection of cargos carried on deck",* 28 June 2007.

FP 53/17 — International Maritime Organization (IMO): "*Review of fire protection requirements for on-deck cargo areas, Fire risk for on-deck cargoes and suggested steps to improve related protection*", 12 November 2008.

MSC 83/28 — International Maritime Organization (IMO): "*Report of the maritime safety committee on its eighty-third session*", 26 October 2008.

FP 53/INF.2 — International Maritime Organization (IMO): "*Review of fire protection requirements for on-deck cargo areas, Formal Safety Assessment – Container fire on deck: Step 1: Details of the current risk level and the hazard identification*", FP 53/INF.2, 12 November 2008.

MSC 83/21/2 — International Maritime Organization (IMO): *"Formal Safety Assessment, FSA – container vesselS"*, 3 July 2007.

MSC 83/INF.8 — International Maritime Organization (IMO): "*Formal Safety Assessment, FSA – container vessels, Details of the FSA*", 3 July 2007.

MSC/Circ.1023 — International Maritime Organization (IMO): *"Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process"*, IMO MSC/Circ.1023, 5 April 2002.

MSC 83/INF.2 — International Maritime Organization (IMO): "*Consolidated text of the Guidelines for Formal Safety Assessment (FSA) for Use in the IMO rule-making process*", MSC/Circ.1023-MEPC/Circ.392, 14. May 2007.

MSC 72/16 — International Maritime Organization (IMO): "*Formal Safety Assessment – Decision parameters including risk acceptance criteria*", 14. February 2000.

FP 51/3/2/Rev.1	International Maritime Organization (IMO): "*Performance testing and approval standards for fire safety systems, Assessment of the fire behaviour of cargo loaded on ro-ro vehicle deck in relation to the design standards for fire extinguishing systems*", FP 51/3/2/Rev.1, 27 November 2006.
Resolution MSC.99(73)	International Maritime Organization (IMO): Adoption of Amendments to the International Convention for the safety of life at sea, 1974, as amended. SOLAS chapter II-2: "*Construction – Fire protection, fire detection and fire extinction*", 2002

1.4 Method of work

The CARGOSAFE FSA follows the structure and instructions as described in IMO's Formal Safety Assessment Consolidated Guidelines (MSC-MEPC.2/Circ.12/Rev.2).

The FSA procedure is an IMO tool used to help the decision-making process in the evaluation of new maritime safety regulations. It allows to make comparisons between existing and possibly improved regulations, with a view to achieve a balance between the various technical and operational issues, and between maritime safety and costs. The study was divided into 5 tasks, as is the FSA method:

- TASK 1 – Hazard Identification
- TASK 2 – Risk-Analysis
- TASK 3 – Risk Control Options
- TASK 4 – Cost-Effectiveness Assessment
- TASK 5 – Recommendations for decision-making

1.5 Composition and expertise of the FSA team

The following section describes the primary FSA team composition and the individual areas of expertise. Several other individuals have partaken and supported in various tasks during the study.

1. Anders V. Kristensen (DBI), (+45) 50807809, AVK@dbigroup.dk, Master Mariner, Coordinator of CARGOSAFE
2. Konrad Wilkens (DBI), Fire safety engineering & risk analysis
3. Aqqalu Ruge (DBI), Human, societal, and organizational factors & risk analysis
4. Lorena Cifuentes (DBI), Fire safety engineering & risk analysis
5. Thushadh Wijesekere (DBI), Fire safety engineering, simulations, and modelling
6. Antoine Breuillard (BV), Maritime fire safety & risk analysis
7. Leon Lewandowski (BV), Maritime fire safety & risk analysis
8. Antoine Cassez (BV (former)), Maritime fire safety & risk analysis
9. Anna Olofsson (RISE), Fire safety engineering
10. Roshni Pramanik (RISE), Risk analysis
11. Stina Andersson (RISE), Fire safety engineering & risk analysis
12. Franz Evegren (RISE), Fire safety engineering & risk analysis
13. Joanne Ellis (RISE), Senior maritime researcher & risk analysis
14. Björn Forsman (RISE), Senior maritime consultant & risk analysis
15. Niels Gorm Maly Rytter (SDU), Cost effectiveness analysis
16. Nicolai Emil Hinge (SDU), Cost effectiveness analysis
17. Claus-Bo H. Henriksen (OMT), Naval architect.

For a more detailed description of the FSA team's backgrounds- and experience cf. Annex R.

1.6 FSA organization

The following section describes the organization around the FSA process and the tasks. The CARGOSAFE group consists of members from the organizations DBI, BV, RISE, SDU, and OMT. This core-team has been involved in all tasks throughout the entire FSA process.

- TASK 1 – Hazard identification. This task and workshops were led by DBI, apart from the 'prevention' workshop which was led by RISE. BV and OMT supported at the workshops.
- TASK 2 – Risk-analysis. This task was led by BV with support by DBI and RISE (for prevention), and OMT.
- TASK 3 – Risk control options. This task was led by DBI, with support by BV and RISE (for prevention), OMT and SDU.
- TASK 4 – Cost effectiveness assessment. This task was led by SDU, with support from DBI, BV, RISE (for prevention) and OMT.
- TASK 5 – Recommendations for decision-making. This task was done by all partners.

2. HAZARD IDENTIFICATION

The objective of Task 1: Hazard Identification (HAZID) was to identify and rank different scenarios where the unwanted hazardous event (UHE) is possible.

Four HAZID workshops were designed according with the first step of the International Maritime Organization (IMO) guidelines on Formal Safety Assessment (FSA) MSC-MEPC.2/Circ.12/Rev2. They were held online (via Microsoft Teams) in combination with the internet whiteboard tool MIRO, to facilitate interactivity and discussions centred on the four identified fire protection layers and subsequent fire scenarios.

The objective of the HAZID workshops was to identify a series of fire scenarios within the following fire protection layers: detection, containment, firefighting, and prevention.

2.1 Background information

The HAZID workshops were supported by relevant background information, which served the purpose to ensure alignment of knowledge of the relevant ships, technological systems, statistical data, accident categories, dangerous goods reference documents, dangerous goods classes, safety considerations, type of fires, as well as applicable regulations and codes. Additionally, the tender specifications, container fire dimensions, FSA steps, conditioning variables, ignition sources, and description of the HAZID was provided on the online MIRO board, to ensure that the participants could access them easily throughout the workshops.

The information was gathered and presented in collaboration between experts from DBI, BV, RISE, and OMT.

2.1.1 Definition of terms

The Hazard and the UHE were defined as the starting point of the study and defined by the tender as follows, see Table 5.

Table 5:Initial definitions of Hazard and Unwanted Hazardous Event.

Hazard	Transport of containerized cargo onboard container vessels
Unwanted Hazardous Event (UHE)	Fire inside a containerized unit onboard a container vessel

In addition, a general list of terminology to be used in the risk assessment and HAZID workshops was created before the first workshop. The list was based on the FSA Guidelines MSC-MEPC.2/Circ.12/Rev.2, Section 2 "BASIC TERMINOLOGY". Before each workshop, the list was expanded with new terms relevant for the given fire protection layer (theme) in focus for the specific HAZID. A selection of the relevant principal definitions was presented before each workshop. For a full list of definitions used in HAZIDs, cf. Annex C.

2.1.2 General assumptions

Before the first HAZID workshop, a preliminary list of general assumptions was drafted. The list served as a basis, of agreement for the limitations of scope. The preliminary list was presented at the first HAZID workshop focused on detection. Following a discussion of the preliminary defined assumptions, changes were proposed and ultimately agreed upon by the second HAZID workshop focused on containment.

The final list of general assumptions which delimit the scope of the HAZID workshops, and the subsequent analysis read as follows:

1. The vessel is fully crewed and the crew STCW trained.
2. No crew is impaired at fire event initiation.
3. No additional notations are followed, and no additional equipment is onboard.
4. The vessel is fully compliant with SOLAS.
5. No extreme weather (bad weather situations which occur at high frequency on most journeys can be considered such as fog and rain).
6. Different loading configurations can be considered, however when in doubt assume the vessel is fully loaded (i.e., that the maximum number of containers are onboard, and they are full to the capacity of the given vessel) as this is the scenario which poses most challenges in terms of delayed detection and potential for maximum fire spread.
7. The vessel is fully operational at the time of the initiating event i.e., not experiencing issues with propulsion, navigation, or listing.
8. The incident can happen at any time of day.
9. Cargo lashing and stacking is done according to procedure for the given vessel.
10. If properly declared, dangerous cargo is stowed according to IMDG Code. CINS risk locations are to be considered.
11. The seat of fire is in a container.

The original list did not include port scenarios, which means that port scenarios were not initially considered in the detection workshop. The additional scenarios and one extra detection method was subsequently added to the Failure Mode and Effects Analysis (FMEA) sheet by the CARGOSAFE consortium.

2.2 Methods

The methods used in task 1 is described in the following sections.

2.2.1 Workshops

The HAZID workshops were executed as a systemic brainstorming session, including a group of multidisciplinary experts, and served the purpose of identifying fire scenarios associated to each of the four fire protection layers. The HAZID workshops were developed and executed according to the Failure Mode and Effects Analysis (FMEA) procedure. The following areas were under investigation: Detection, Containment, Firefighting, and Prevention.

The workshops on Detection, Containment, and Firefighting were led, facilitated, and coordinated by DBI, in collaboration with Furstenberg Maritime Advisory on February 1st, 3rd, and 8th, 2022, respectively.

The workshop on Prevention was led by RISE on February 10th, 2022, and coordinated and facilitated by RISE and DBI, in collaboration with Furstenberg Maritime Advisory.

The facilitators from DBI, BV, and RISE who were involved in the HAZID workshops, all have extensive experience with fire risk assessments and facilitating this type of workshop. The workshops were supplemented with detailed background information provided by BV, OMT, RISE, and DBI.

2.2.1.1 Participants

The participants in the HAZID workshops included experts with a wide range of backgrounds to ensure the relevant expertise was available for the given themes. The experts assisted in the hazard identification process and subsequent discussions. The HAZID workshops had between 40 and 45 participants ranging the entire container shipping industry and subsequent stakeholders. The Table 6 below demonstrates the wide range of expertise present at the workshops. Note that specific names of participants have been left out due to privacy and General Data Protection Regulation (GDPR) concerns.

Table 6:Field of expertise with corresponding organizations from the HAZID workshops.

Field of expertise	Organization
Ship design	OMT
Shipping operations	Maersk, Evergreen, CMA-CGM, MSC
Shipping management	Maersk, Evergreen, CMA-CGM, MSC
Fire safety	DBI, RISE, BV
Human factors	DBI, RISE
Fire risk assessment	DBI, RISE, BV
Dangerous goods	Existec, RISE
Flag Administration	Denmark, France, Germany
Equipment manufacturer	Danfoss, VIKING,
Insurance	SKULD, Codan, IUMI
Training	SIMAC, Maersk, Evergreen, CMA-CGM, MSC
Port operations	Maersk, Evergreen, CMA-CGM, MSC
Regulations & Class rules	BV
Trade and employer organization	Danish Shipping, International Chamber of Shipping, World Shipping Council, BIMCO
University	University of Southern Denmark

2.2.2 Failure Mode and Effects Analysis (FMEA) procedure

The HAZID workshops were developed and executed according to the Failure Mode and Effects Analysis (FMEA) procedure, a method approved for this type of work in the IMO FSA Guideline. Before each workshop was initiated, a spreadsheet was developed to guide the procedure for the brainstorming session and served the purpose of ensuring documentation of the results. The spreadsheets were developed by DBI and follow the structure of the FMEA methodology. For the final FMEA spreadsheets cf. Annex A.

The FMEA methodology facilitates analysis of functions of hardware or humans of the subject in question - and encourages individual analysis of all items in the system. Following this method, a list of failure modes was identified, followed by an analysis of the effects of the failure. This method allows analysis of how single failures may cause system failure.

Prior to the respective workshops, a selection of functional methods was pre-identified for each respective fire protection layer. The identified methods for each layer were based on the prescribed SOLAS requirements (and for Prevention the IMDG Code), and therefore did not include additional notations or optional/voluntary added equipment. The methods were discussed, altered, and developed collectively on the individual workshops, serving the objective of ensuring alignment on the methods subject to analysis. For each method, a list of desired functions was identified collectively by the participants, using the MIRO online whiteboard where everyone could put sticky notes. The same procedure was applied to the identification of affecting conditions, i.e., a list of conditions that may influence the performance of the desired functions was identified for each method. Figure 1 shows one example of the excel sheet for Method of detection with Desired function and Affecting conditions.

Method of detection	Desired function	Affecting conditions
Smoke detection system (sampling)	*Quick *Precise *Reliable *Robust *No added complexity *High detection rate & low false positives *Low maintenance required *Ability to monitor real time sampling levels *Identify fire location *Redundency *Easily understandable information in fire panel	*Type of detector *Type of fire (e.g. liquid/solid, high smoke producing, high energy content etc.) *Ventilation *Weather conditions *Location of sampling points *Amount of cargo (number of containers) *Maintenance and state of system *Cargo hatch open *Hold size and location *Alarm panel design *Capacity of sampling fan *Location of fire *Cargo packing * Early detection * Detection of incipient phase

Figure 1: Example from the detection spreadsheet showing the Desired functions and Affecting conditions identified for the smoke detection system.

Following the identification of desired functions and affecting conditions, the participants collectively brainstormed a list of failure modes and effects for each method in question. A failure mode was here defined as something that may, through the affecting conditions, inhibit one or more of the desired functions of the method being addressed. See Figure 2 for example.

Failure mode	Effect
Faulty wiring to alarm system	*False alarms leading to deactivation *No detection alarm because it is not connected *Fault in alarm signal leading to wrong detection location
Sampling pipe leak	*Delay of detection and alarm signal *No detection due to high dilution of sample air *False detection location *False alarm
Clogging of sampling pipe	*Delay of detection and alarm signal *No detection due to lack of sample air from reduced or stopped air sampling *False detection location *False alarm
Failure to reactivate detection zones	*Delay of detection and alarm signal *No detection *False detection location
Sampling pipes too large dilute smoke	*Delay of detection and alarm signal *No detection due to high dilution of sample air
Smoke ventilated away from sampling points due to weather conditions (e.g. high wind, pressure)	*Delay of detection and alarm signal *No detection due to smoke not entering sampling points *False detection location *False alarm

Figure 2: Extract of the failure modes and effects from the detection spreadsheet (note, the figure does not show the full list, for this see Annex A).

The final session in each workshop focused on the conditioning variables as stated in the tender. Subsequently, the participants partook in open discussions on each of the themes of the day and provided inputs on potential safety measures or RCOs. The conditioning variables considered (as specified by the tender):

- Containership Type/Size.
- Twin Island ULCS/VLCS.
- Standard Single Island Post-Panamax.
- Feeder with aft bay.
- Feeder with no aft bay and an open cargo hold.

- DG Declaration.
- Declared.
- Undeclared.
- Misdeclared (*was specifically added by the CARGOSAFE consortium in addition to the variables stated in the original tender, due to a lack of nuance in original choice. See Annex C for definitions).

- Location of initiating event.
- Above/below deck.
- CINS Risk location (RZ0 to RZ5).
- Proximity to superstructure/island/accommodation.
- Reefer bay (electrical fire).
- Proximity to machinery space/fuels tanks.

- Construction.
- Before 1JAN2016.
- After 1JAN2016.

These variables and comments were documented in columns F to M (cf. Annex A) and in notes which is carried over to Task 2.

2.2.3 Facilitation of the workshop online

To facilitate the workshops online, the internet tool MIRO was used as an online whiteboard. The MIRO board was prepared in advance of every workshop and included a range of information available to the participants Figure 3.

Information available on the board included:

- Information on relevant regulations and codes, vessel types (including examples of general arrangements), technical background information, background slides and videos, the tender specifications required by EMSA, as well as a background information specific to the respective workshop themes.
- An agenda for the individual workshops, list of participants, ground rules and guidelines for the workshop.
- Process tools.
- A series of whiteboards prepared for the listed desired functions, affecting conditions, failure modes and effects, respectively.

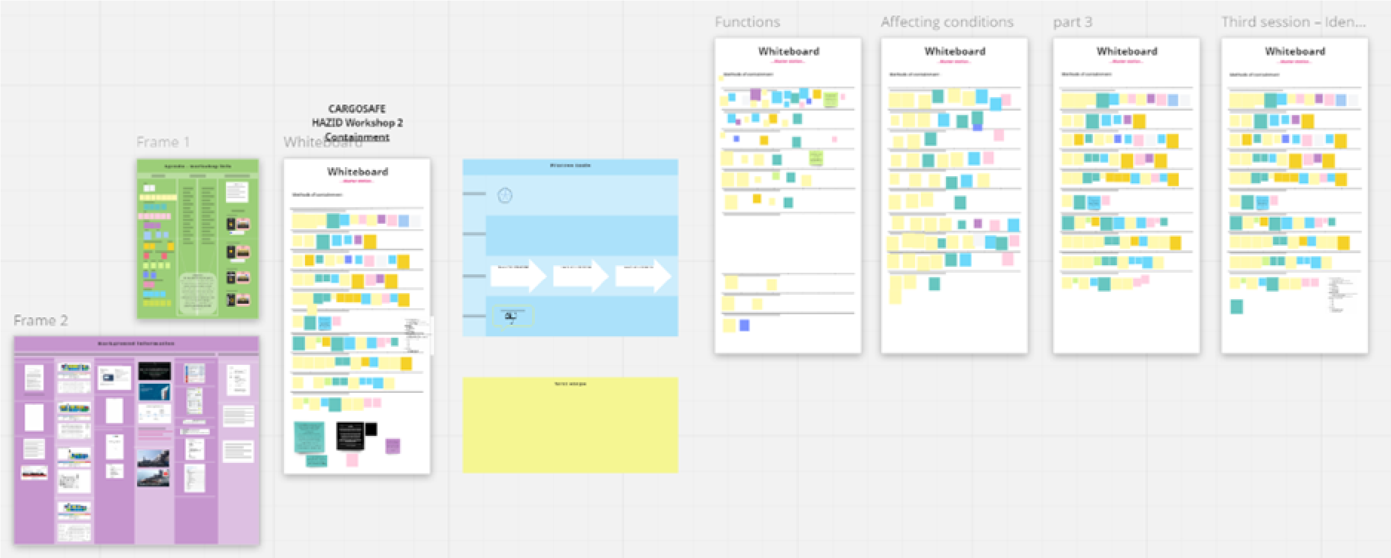


Figure 3:The MIRO board from an out zoomed perspective showing the filled whiteboards (with different colour sticky notes), the purple background information, the green participation information (agenda, house rules etc.), the blue for notes to upcoming workshops and the yellow with general comments.

The whiteboards were listed with the pre-identified functional methods in question. These were agreed upon by the participants and then carried over to all subsequent whiteboard and discussions in the given workshop.

The participants were given time to reflect and respond to every theme on the whiteboard. The opinions and reflections were noted on a virtual sticky note and added to the board. After each session, the sticky notes were reviewed by the moderators and DBI, to ensure that no clarifications were needed to explore the expertise of the participants. This process was used for identifying desired functions, affecting conditions, and failure modes and effects for each functional method respectively.

At the end of the respective workshops, the MIRO boards were subsequently imported into the premade FMEA spreadsheets. When the data import to the spreadsheet was completed, the responsible party for the workshop reviewed the data again, with the objective to sort, formalize and clean up the data. When the initial raw data had been processed, the responsible party applied their expert knowledge to supplement the data with additional expertise to ensure sufficient quality. Subsequently, the CARGOSAFE consortium reviewed all the sheets and information herein, to ensure lists were exhaustive and that the details provided were correct.

2.3 Hazards

The following section addresses the theme and results from each of the four HAZID workshops. In addition, any relevant or particular developments, or decisions made for/at the given workshop is described.

2.3.1 Detection

2.3.1.1 Workshop description

The workshop exploring the theme Detection served to explore the subject of detection with the purpose to improve the understanding of different detection systems and manual methods of detection, as well as to create an understanding of how and why current detection systems and methods fail.

For the CARGOSAFE study and the workshop, detection was defined as “the action or process of identifying indicators of a fire event.” Consequently, technical systems and detection by crew and officers were both included.

Besides, a review of the existing methods of detection, procedures and technology associated with detection, human elements were also discussed to improve the understanding of how the smoke detection system can fit or disrupt work practices and emergency response on board. This included delays in the decisions and response process. In addition, four manual methods of detection were explored and analyzed. This is highly relevant since manual detection is an essential detection method e.g., for the weather deck, manual detection is the only method currently available.

The positioning of the detection systems' sampling points was discussed, as the placement of the detectors can influence the success of the detection system. Additional factors influencing the detection system, such as wind, ventilation, air circulation, cargo hold airtightness, geometry, stacking, were likewise discussed.

During the Detection workshop it was suggested to add heat detection in cargo holds as an additional method to consider and analyze. However, during the workshop no input was given to this method of detection. Upon subsequent review, it was decided to exclude this method of detection from the final FMEA spreadsheet. The main solution to detect a fire on board containerships (in the cargo hold) is the smoke extraction sampling system. However, alternative systems such as linear heat detection through the hold holds is currently under investigation by different stakeholders. This should not be considered in the initial HAZID, but rather be investigated at a later stage as a potential RCO.

The detection timeline as used in the workshop is illustrated in Figure 4

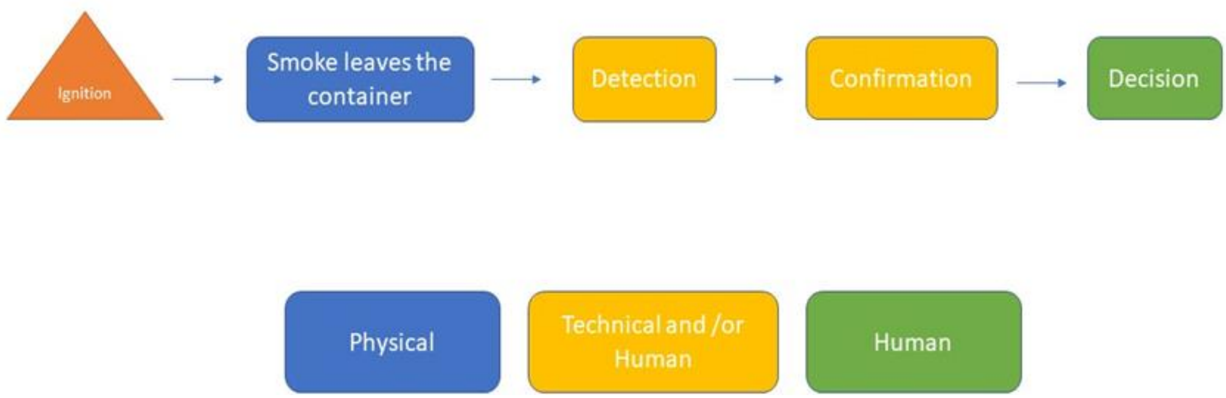


Figure 4: The detection timeline as used in the workshop.

2.3.1.2 Workshop results

- Detection in the cargo hold (below deck) is fully reliant on the technical system (sample extraction smoke detection systems). Crew seldom go into the cargo hold and fire patrols do not take place below deck.
- The failure modes identified can be separated into three main categories:
  - Failures of the sampling system itself.
  - Failures due to the design of the ship (e.g., size of vessel, ventilation location) or the external environment (e.g., weather, time of day).
  - Failures due to unknown cargo, creating hazards that are unaccounted for.
- The size of the ship will have a significant impact on the detection time via the smoke sampling system. The system relies on smoke leaving the container, reaching the sampling point, and travelling through the pipe.
- The human-machine interface of the detection and alarm panel can cause delays in the critical decision response phase.
- Identification of the seat of fire is imprecise with the smoke sampling system. Precision is limited to hold level at best.
- Detection on the weather deck is reliant on visual identification by crew since there is no technical system to assist.
- Visual identification is affected by the size of crew, the crew's workload, the vessel size, the time of day, and weather conditions.
- Fire patrols are highlighted as being unreliable as a detection method.
- Detection from port should not be depended upon as a reliable method of detection.
- Results from the firefighting workshop demonstrate that the firefighting methods are highly reliant of quick detection times - which the current detection methods do not support.

2.3.2 Containment

2.3.2.1 Workshop description

The workshop exploring the theme Containment served to explore the subject with the purpose to improve the understanding of different methods of containment, as well as to create an understanding of how and why current containment procedures and methods fail. Furthermore, it aimed to explore the on the current fire containment requirements and the containment options that the respective ship design practices offer.

For the CARGOSAFE project and the workshop, containment was defined as “the action and methods for limiting the products of combustion’s (e.g., flame, heat, and smoke) propagation and the subsequent damages to the area of origin.” Consequently, both including physical boundaries and active measures aimed at containment.

The workshop investigated containment on unit level spanning containment between holds and bays, as well as between cargo holds/bays and spaces e.g., engine space, super structure etc.

The primary focus of the workshop was the exploration and analysis of the physical boundaries (e.g., steel walls of container, bulkheads, hatches, distances between bays) containing the fire, and secondarily, active boundary cooling measures. Thus, the workshop included active firefighting methods, but were limited to boundary cooling efforts, i.e., containment, and therefore excluded active measures aimed at fire extinguishing. These were covered in the relevant workshop titled firefighting.

2.3.2.2 Workshop results

- Weak points in containment were identified on all scales ranging from the container itself to the hold/bay level.
- Containment is not a design parameter and relies solely on inherent performance of the materials used. The main design parameter on both unit and vessel level is effective logistics operation.
- Loss of containment was defined in four major categories:
  - Flame propagation.
  - Heat being transferred through materials (e.g., radiant heat through container walls, bulkheads, hatches).
  - Loss of structural integrity at different levels.
  - Explosion.
- Active boundary cooling was considered as part of the containment strategy.
- Active boundary cooling is reliant on crew availability (size), availability of equipment, quality of the available equipment.
- Smoke containment has contrasting impacts. It is desirable to contain smoke to avoid intoxication of crew and contamination of the accommodation. However, all current methods of detection are reliant on smoke not being contained.
- Shutting of openings and ventilation in the cargo hold was highlighted as a critical means of containment (and firefighting).
- Structural integrity of containers was highlighted as an essential element in the containment strategy - due to its failure leading to fire spread, mechanical damage to other systems including the vessel, wide scale collapse of stacks, increased risk to crew, and significantly hampering firefighting efforts.

2.3.3 Firefighting

2.3.3.1 Workshop description

The workshop exploring the theme Firefighting served to explore the subject with the purpose to improve the understanding of different methods of firefighting, as well as to create an understanding of how and why current firefighting procedures and methods fail.

For the CARGOSAFE project and the workshop, several definitions were highlighted. Firefighting was defined as “active means of attacking a fire in an attempt to get it under control”, thus, including both means of suppression and extinguishment. Fire suppression was defined as “active means of controlling the fire, but not necessarily extinguish the fire completely.” And lastly, fire extinguishment was defined as “active means of stopping the fire completely, i.e., no risk of re-ignition.

The workshop explored firefighting procedures and equipment above deck and within the cargo hold separately (cf. Figure 5). The firefighting systems and methods above and below deck were investigated, including an exploration of when and why the systems fail. Both technical systems as well as manual firefighting was explored.

The effectiveness of firefighting was investigated with the aim to explore whether there are critical points within a fire scenario that would deem any of the current required firefighting equipment insufficient, or where there are situations within scenarios were the crew cannot fight the fire due to safety concerns. This serves the purpose to highlight the requirements on fast action and decision making, to investigate the effectiveness of current systems and methods, and to include considerations regarding crew safety, and finally, to explore when and how safety of the crew has an impact on the strategy to fight the fire.

During the initial review of the pre-defined functional methods, it was proposed to add flooding of the hold. This was agreed upon, and the method was explored and analyzed equally to the pre-defined methods, cf. Annex A for the full details.

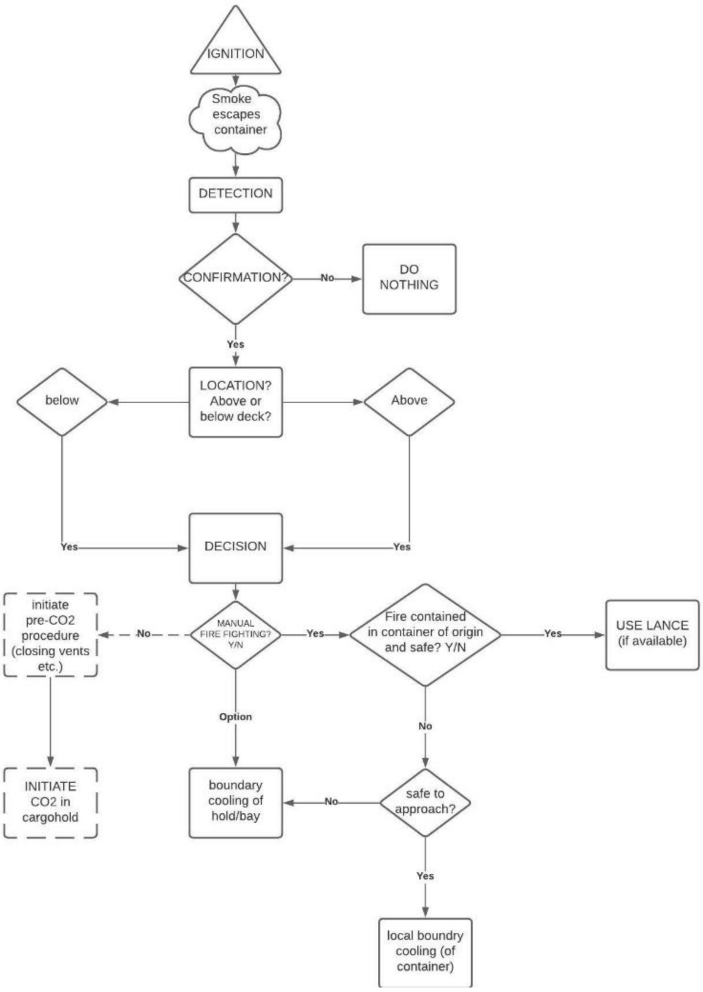


Figure 5:The firefighting timeline as used in the workshop.

2.3.3.2 Results

- Local fire extinguishing in the container unit is limited and highly reliant on early detection, something that the current detection methods do not support in all scenarios.
- Location of the container is a critical parameter for local fire extinguishing, as access to the unit is paramount.
- The prescribed equipment does not allow for fire extinguishing of units high in the stack.
- Local extinguishment of a unit in the cargo hold is unlikely to occur due to the hazardous environment and the added risk to crew, in addition to the accessibility to the individual units.

- Crew accessing the hold during a fire is often discouraged or forbidden by the operator.
- Performance of equipment to penetrate containers can be varied (depending on type of equipment and quality).
- Undeclared dangerous goods were highlighted as the primary risk due to unknown behavior of content in the unit.
- Effectiveness of boundary cooling is dependent on location of seat of fire.
- Inability to locate seat of fire will reduce the effectiveness of boundary cooling e.g., due to hostile conditions (toxic smoke, visibility, radiant heat).
- PPE of crew may inhibit extended firefighting capabilities.
- Inadequate firefighting equipment (insufficient number of hoses, hydrants etc.) will reduce the effectiveness of local firefighting and boundary cooling possibilities.
- Performance of CO_2 system is highly dependent on the effectiveness of cargo hold air tightness and ability to penetrate the individual container units.
- The limited time frame CO_2 remains in the hold and the inability to extinguish the fire inside the individual container units – results in the system being used as means of temporary suppression rather than extinguishment.
- Design failures can occur throughout the system which may impact performance significantly.
- Scaling of CO_2 system is based on design principles for smaller vessels and may not apply to new larger vessels.
- Hesitation of the use of CO_2 (due to only having one-shot systems) leads to a delayed decision (needs approval from onshore support) which may significantly affect its ability to suppress a fire.
- Limited amount of CO_2 is a significant issue.
- Maintenance of CO_2 system is challenging. Crew training is important.
- Structure of the vessel cannot necessarily sustain the full flooding of one cargo hold (stability and structure effects are to be taken into account).
- Water level detection is not available in the cargo holds in order to be able to flood the cargo hold and have the information of the water level. If the fire is too high, flooding water may not reach the fire seat.
- Flooding a cargo hold may create mixing cargo that could result in creating other hazards or make other cargo to react with sea water.

Decision to flood a cargo hold can take time (time of the Class analysis, availability of information needed such as cargo weight for decision making and analysis, etc.). Flooding is also seen as a last resort.

2.3.4 Prevention

2.3.4.1 Workshop description

The workshop exploring the theme Prevention served to increase the understanding of activities carried out to prevent the ignition of cargo on board and to deepen the understanding of how and why these activities may fail. Scenarios resulting from these failures were also discussed.

For the CARGOSAFE project and the workshop, Prevention was defined as any activities and/or conditions to prevent the ignition of containerized cargo on a containership.

The scope of the prevention workshop included the identification of hazards along the supply chain that could lead to the ignition of goods within a container on board a container ship. The scope considered the full chain from the preparation of the goods for transport to the time when they are ready to be unloaded from the containership. The IMDG Code, developed to ensure the safe carriage of dangerous goods by sea, has provisions that apply to many of the steps along the chain, including packing, declaration, and stowage. These provisions can be considered as a key preventive measure applied to many of the activities. SOLAS regulations considered relevant to prevention of ignition on board the vessel includes those related to cargo holds, such as mechanical ventilation air changes per hour, and electrical equipment certification requirements.

For the purposes of discussion and analysis at the workshop, eight functional areas were considered (or methods of prevention), represented by boxes on the timeline shown in the Figure 6 Although the cargo preparation step, shown in the grey box, is outside of the control of the ship operator, it was considered that faults that occur at this step, such as misdeclaration/non-declaration of goods or poor packing, often are a contributing factor to accidental fires on board containerships. Thus, this functional area was included in the HAZID workshop.

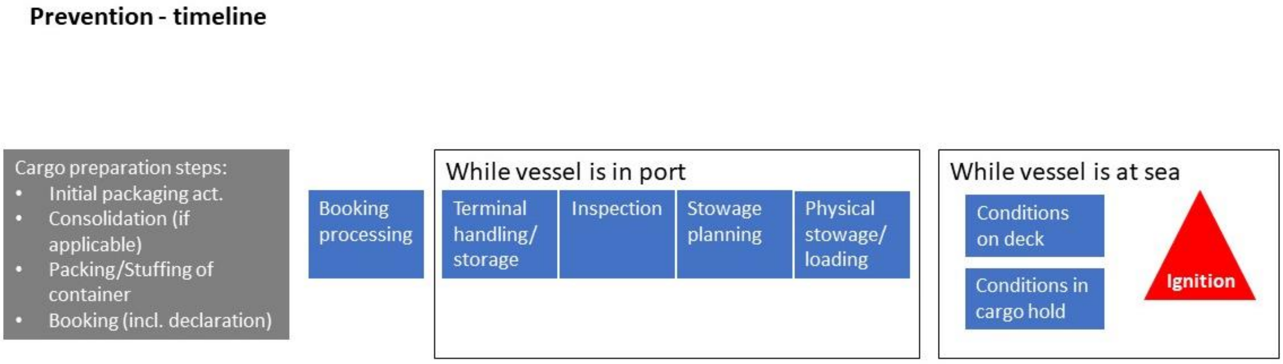


Figure 6: The prevention timeline as used in the workshop.

Blue boxes along the timeline represent activities occurring within the transport chain. The ship operator controls the booking acceptance and processing, stowage planning, and conditions while the vessel is at sea. Handling and storage of the goods at port are carried out by the terminal operator, and inspection at the port is carried out by national regulatory authorities. Physical loading and stowage are done by port personnel but is overseen by ship personnel. During the workshop desired functions, affecting conditions, and failure modes, and effects for each of the functional areas were brainstormed by the group of experts attending.

2.3.4.2 Results

- Prevention of faults and errors that occur during the cargo preparation steps, such as non- or misdeclaration, as well as packaging inside the cargo unit, were considered key to many of those present. One participant stated that all major fire activities on their ships that had occurred the previous year involved goods that had either not been declared or were misdeclared.
- Testing procedures for self-heating goods was also raised as an important issue – the need for revising procedures was discussed.
- IMDG Code: the special provisions and limited quantities exemptions were considered to be problematic in that in some cases they were used for advantage by some less responsible shippers to transport goods without having to declare dangerous goods.
- Main cargo types identified to be responsible for a large share of cargo fire accidents included calcium hypochlorite, charcoal, and lithium-ion batteries. This was shown from the preliminary statistics presented and from comments from experts present at the workshop.
- There is expected to be an increase in lithium batteries transport and accidents in relation to other goods' types. Transport of recycled batteries and transport of batteries in products such as laptops are issues to be followed.
- Technology and changes in products transported are considered to be faster than what the regulations can keep pace with.
- Lack of efficient screening tools and consistent procedures were identified as problem areas. Common screening tools, information exchange, and machine learning were raised as promising risk reduction measures that could be implemented to improve the situation. "Know your client" was also considered important – along with blacklisting problematic shippers and exchanging information between carriers. Framework for information sharing even with inspection authorities (possible RCO).
- Issues with inspection were a concern and included national variations in the frequency of inspections, time requirements to carry it out, and how they were targeted. A framework for information sharing with those responsible for screening bookings and other agencies was raised as a possibility for improvement.

2.3.5 Technical Expert Group (TEG) Workshops and updates to the FMEA sheets

After completion of the initial task 1 draft report, DBI hosted 5 workshop meetings with the Technical Expert Group (TEG) to review the initial findings. The function of the Technical Expert Group (TEG) is to include the broad and various aspects of fire safety in container shipping by virtue of the group' s respective expertise in their fields, as well as peer review of results achieved in the safety study. The group consists of the participants who attended the online hazard identification workshops as well as additional parties from the maritime industry, such as manufactures of firefighting equipment and other related equipment, technical universities, and maritime stakeholders.

Each of the workshops focused on the findings from each of the HAZID sessions. Although, interest and the level of participation was so intense for the Firefighting session that this had to be extended to a subsequent follow-up meeting. The TEG did not have any particular criticism to the findings or the FMEA sheets submitted for review. Therefore, the discussions primarily centered around RCOs for the various failure modes. These have subsequently been added to the FMEA sheets and can be seen in Annex A (lines in yellow highlight).

2.4 Ranking

The prioritization by risk level was done quantitatively at the end of Task 2. It was plotted using the frequency of a fire per shipyear, obtained from the data base. The consequence of the incidents is reported as Euro Loss. It is presented in cf. section 3.9.2 Scenario plot for ranking (dots in frequency/severity plan).

3. RISK-ANALYSIS

The objective of Task 2: Risk Analysis was to develop a detailed investigation of the causes, initiating events and consequences of the more important accident scenarios identified in Task 1. Hence, a quantification of risk for the selected hazardous scenarios derived from Task 1 was carried out.

3.1 Background material for risk analysis – Source of information

Information sources used in this risk analysis were data provided by EMSA, a database owned by BV (IHS2019), accident reports and websites. This part summarizes the sources of information used in the study. The database used for the study is presented on Annex 1 (Database Accident List), however, it is not publicly available.

3.1.1 Data provided by EMSA

To perform the statistical analysis requested for the FSA study, EMSA provided data, describing the fleet as well as the accidents.

For the fleet, a database from IHS MARINFO has been used, describing the container ships fleet built on or after 1981. For the casualties, only fires or explosions originating from the cargo were considered as per EMSA tender specifications:

- A database from IHS MARINFO, describing casualties that happened on or after 2009 for container ships.
- A database from LMIU ex-MARINFO, describing casualties that happened between 1997 and 2016 for containerships.
- A database from EMCIP, describing casualties that happened on or after 2011 for containerships.

The distribution of the 124 relevant accidents amongst these three databases is displayed in, and the time periods

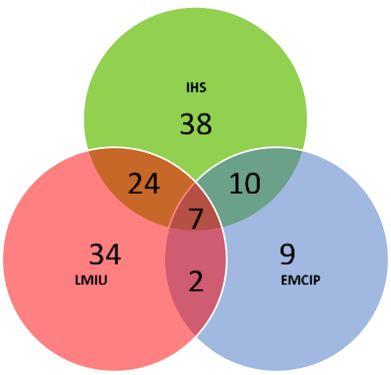


Figure 7: Distribution of the relevant accidents amongst the three casualty databases.

covered by each of them is presented in Figure 8.

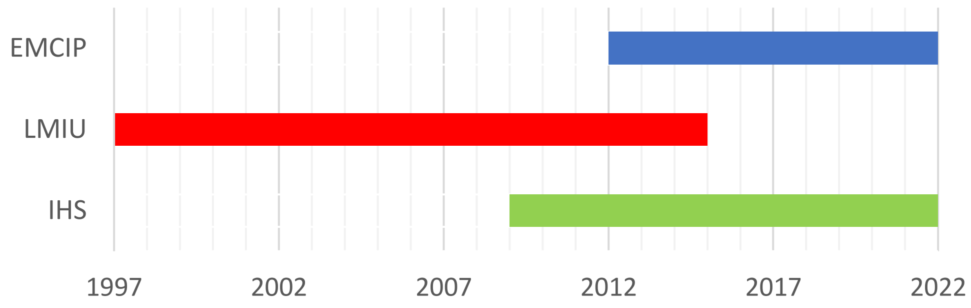


Figure 8:Time periods covered by the databases.

Regarding the completeness of the casualty database, it was discussed with the Technical Expert Group that these databases merely contain fires which have been sufficiently severe to be reported there. Less severe fires may have occurred in higher numbers, with events such as self-extinguishing fires or sufficiently slow to be noticed during unloading potentially fires managed by crew but not reported, etc. For example, insurance companies may have much more occurrence of container fires as identified in recent IUMI presentation[6] . Nevertheless, in terms of FSA these accidents should not count in terms of consequences (presumably one container lost or partly lost) and can be excluded from the study. In addition, as mentioned in several FSAs, if RCOs are cost-beneficial for a lower count of historical data than the benefit should be even higher than the one demonstrated by the study.

3.1.2 Additional data from other sources

To obtain a sufficient amount of data to be exploited later in a historical analysis the quantity of information on casualties presents in the databases provided had to be expanded. This was done using several ways. First, the description of the accident provided in the database (named "Precise Text") was post-treated to display it in a useable form (i.e., the origin of the fire, the mean of firefighting used, etc. were displayed each in a separate column). Then, investigation reports were gathered and used when they were available. Websites of maritime information were browsed, and finally, internal database (IHS database owned by BV) was used.

IMO GISIS database was also analysed to check potential missing data. Two things were present in the GISIS database that had not been treated previously: a non-serious accident from 2007, not present in any of the other databases checked and an additional investigation report for an accident considered. The report was short and did not provide any new information. Thus, it was decided to only use the three databases mentioned above, for the sake of consistency.

3.2 Containerships fleet analysis

This part summarizes the gathering and analysis of data describing the ships falling within the scope of interest of the CARGOSAFE study. The characteristics of these ships are described below. This step is required in the IMO's Formal Safety Assessment guidelines (MSC-MEPC.2/Circ.12/Rev.2), section 4.

3.2.1 Characteristics of the fleet

The fleet referred to below as the "CARGOSAFE fleet" is represented by the following characteristics:

1. Ships designated as "container ships".
2. Gross Tonnage above 500GT.
3. Built after 1980.
4. No requirement on the classification by an IACS society.

These four criteria are detailed below.

[6] Fire in Container vessels -The right questions. Mikkel Andersen, Codan Marine Insurance, 3 March 2022, Presentation at IMO-SSE8

1. Ships designated as "container ships"

This category includes the three following StatCodes: A33A2CC (Container Ship (Fully Cellular)); A33B2CP (Container Ship (Fully Cellular/Passenger ship) and A33A2CR (Container Ship (Fully Cellular/Ro-Ro Facility)).

2. Gross Tonnage above 500GT

All the vessels from the fleet are above 500 GT.

3. Built after 1980

Based on data from BV internal sources, at the date of the study, less than 0.5% of ships built in or before 1980 were still in activity. 1980 was thus arbitrarily decided as a cut-off date for this study.

4. No requirement on the classification by an IACS society

Some of the previous EMSA studies (such as FIRESAFE I and II7) decided to exclude ships that have never been classed by a Classification Society member of the International Association of Classification Societies (IACS). The point was to minimize the effects of under-reporting of accidents.
In the case of the CARGOSAFE study, based on the data provided by EMSA, approximately 85% of the ships in the CARGOSAFE fleet were classed by an IACS member at the date of the study or when the ship got retired. Amongst the relevant accidents, approximately 88% of them happened to ships classed by an IACS member at the date of the study or when they got retired.
Since these two values are very close, the impact of under-reporting was deemed negligible. Thus, the study shall not make any distinction based on IACS classification.

3.2.2 Analysis of the fleet

Based on the IHS database provided by EMSA, 7677 ships were considered relevant for the study.

3.2.2.1 Evolution of the CARGOSAFE fleet

Figure 9 displays the evolution of shipyears amongst the CARGOSAFE fleet along the years, from 1997 to 2018[8]. This number is growing constantly, with two noticeable rates of increase, one from 1997 to 2010 and another, weaker, from 2010 to 2018.

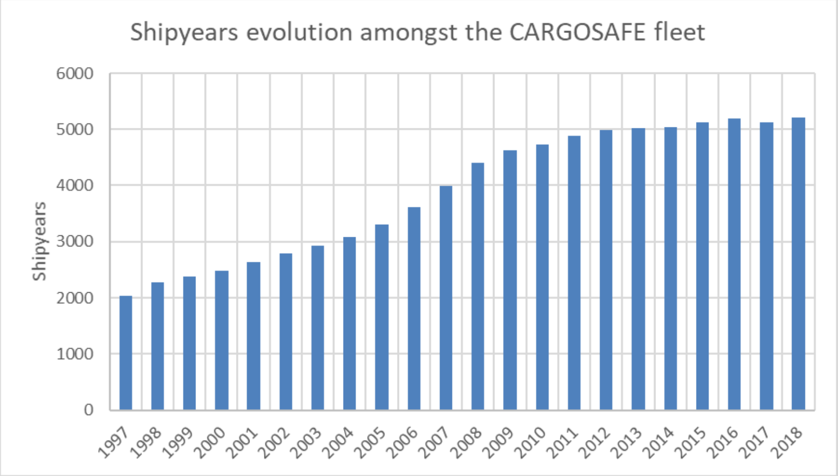


Figure 9:Evolution of shipyears amongst the CARGOSAFE fleet along the years

[7] EMSA | Firesafe (europa.eu)
[8] The ship database provided by EMSA including only ships built after 1980. This historic cut-off point introduced a bias in the evolution of the shipyears and capacity of the fleet. Hence, both Figures 9 and 10 are based on another set of IHS 2019 database to mitigate it.

Figure 10 depicts the evolution of the total cargo capacity of the CARGOSAFE fleet (in TEUyears) along the years, from 1997 to 2018. As for the previous graph displaying the evolution of shipyears, the number of TEUyears capacity is increasing each year. However, in this case, the rate of increase is still strong in the 2010-2018 period since ships joining the fleet are bigger every year.

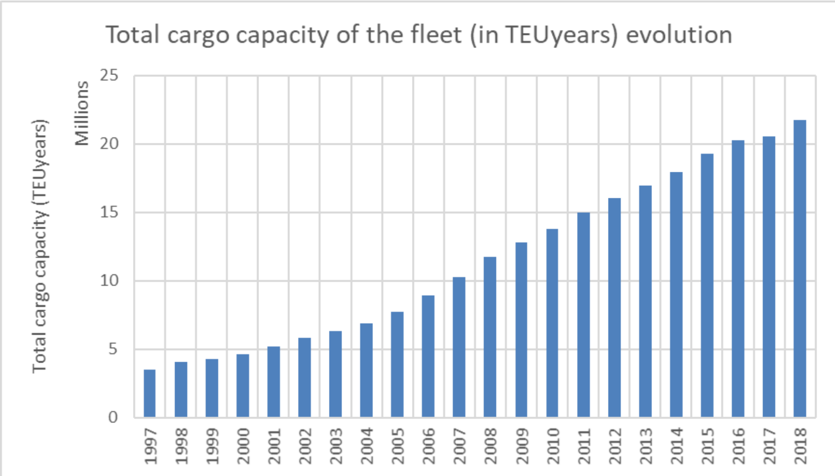


Figure 10:Evolution of cargo capacity (in TEUyears) amongst the CARGOSAFE fleet along the years.

3.2.2.2 Median ship

Table 7 provides the important values of different characteristics (Gross Tonnage, Length Overall, capacity in Twenty-foot Equivalent Units and Breadth Moulded) for the CARGOSAFE fleet. A more precise distribution of these characteristics is displayed in Figure 11. These median characteristics are used to define the Median Ship, which is the conceptual ship supposed to represent the fleet with the most accuracy. It has been decided to consider the median over the average, because the median is supposed to be a better representative of a large non-symmetrical population, since it is not affected by outliers.

Table 7:Important values of principal characteristics for the CARGOSAFE fleet.

	Average	Median
Capacity (GT)	47785	28616
LOA (m)	224	208
Capacity (TEU)	4475	2600
BM (m)	32.4	32.2
Count	7677	
ShipYears	96586	

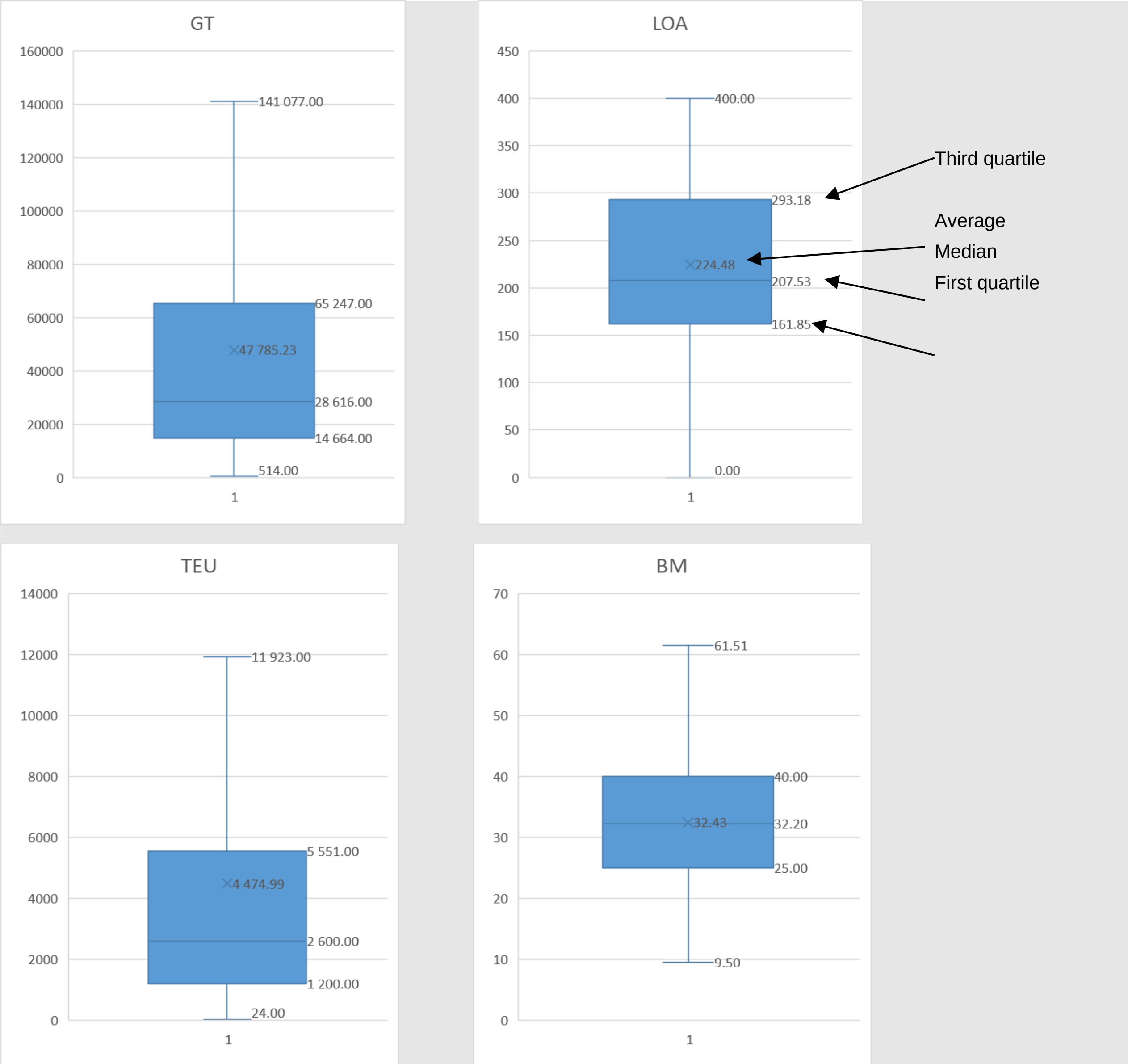


Figure 11:Distribution of the CARGOSAFE fleet by GT, LOA, TEU, BM.

This Median Ship is used as the basis for the calculations of the current risk quantifications.

3.2.2.3 Ship categories

Originally, the CARGOSAFE FSA had defined four categories to be investigated, amongst the fleet described above:

- Twin Island ULCS/VLCS.
- Standard Single Island Post-Panamax.
- Feeder with aft bay.
- Feeder with no aft bay and open cargo hold.

Unfortunately, none of the databases provided by EMSA did include the sub-categories of container ships (i.e., “ULCS”, “Post-Panamax”, etc.). Thus, a polynomial relation between each containership's sub-category and her characteristics (such as gross tonnage, length, cargo capacity) was developed based on an IHS 2019 database, which included these sub-categories. This formula was then applied to ships present in the CARGOSAFE fleet.

a. Twin Island ULCS/VLCS

Thanks to the method described above, the ULCS/VLCS category was made available in the CARGOSAFE database. To split the "Twin Island" from the "Single Island", a simple criterion based on the length was found. After having analysed a large number of pictures of ships, it would seem that ULCS with a length overall (LOA) between 334m and 364m are single island ships, whether out of these bounds they are twin island ships.

b. Standard single Island Post-Panamax

"Post-Panamax" is a sub-category defined in the CARGOSAFE database. All of these are single island ships. It was decided to add the single island ULCS/VLCS to this category, to have a better uniformity in the categories characteristics than if they had been studied amongst the smaller ships.

c. Feeder with aft bay / **4.** Feeder with no aft bay and open cargo hold

Even though the category "feeder" was defined in the database, no way was found to differentiate ships that did or did not have an aft bay. Moreover, feeder with open cargo hold only accounted for less than 1% of the fleet. Thus, categories c. and d. will be included in a last category, which includes ships not belonging to the categories a. and b.

3.2.3 Categories to be considered for the study and selection of the generic ships

The three final categories that are studied in CARGOSAFE are as follows:

a. Generic Ship 1, representing Twin Island ULCS/VLCS (782 ships).
b. Generic Ship 2, representing Standard Single Island Post-Panamax and Single Island ULCS/VLCS (1184 ships).
c. Generic Ship 3, representing the rest of the fleet (5711 ships).

The ships and their respective safety systems are described in the following section. In Figure 12 to Figure 14, the characteristics of the generic ships described are indicated by a red dot.

3.2.3.1 Generic Ship 1

a. General description and design of vessel

The vessel to be designed and constructed as an environmentally friendly, all welded steel, single screw, diesel engine driven cellular containership with transom stern, bulbous bow, and semi-spade rudder. The hull structure primarily to be of a double hull construction. Water ballast tanks to be arranged in side-tanks, deep-tanks, and double-bottom. Three side ballast tanks each side to be arranged as heeling tanks. All oil tanks to be arranged in inboard protected locations. Engine room and accommodation arranged as "twin-island" configuration and located between hatch 19/20 and 8/9 respectively.

Containers to be carried in 23 cellular hold bays with 21 positions across. On deck 24 bays, up to 10 tiers high with 23 positions across. In general, structural arrangement for containers in holds to be based on high-cube-types. In total about 1000 of 40 ft reefer containers to be carried, about 2/3 on deck and 1/3 in holds. All reefers to be air cooled.

Height in holds amidship to be arranged for 11 ISO containers (8½' high) or 10 high cubes (9½' high). 45 ft long containers can be carried on deck only at bay in front of casing and on 4ft tier and above on other bays. 20ft long containers on deck to be stowed three high. No 20ft containers on aftermost bay.

b. *Safety systems*

An addressable fire detection system is installed. The system consists of a combination of detectors and manually operated call-points. Detector types: heat, smoke, or other products of combustion, flame, or any combination of these factors, depending on the location.

A brief operating instruction is fitted close to the control panel on the navigating bridge. A smoke detection system is installed for detecting the presence of smoke in cargo holds. The smoke detector panel is placed in the ship's control centre. Detected smoke and loss of power initiates a signal in the wheelhouse and in the Engine Control Room. The general alarm and fire detection alarm system is connected to the public address system, the system is in compliance with the requirements in SOLAS. In the engine room, machinery and cargo areas, an alarm and sounder system (pictograms, sounders, and beacons) in compliance with International Regulations is installed. As required at each location, the system includes (not limited to) fire alarm, general alarm, engine alarm, telephone call and fire extinguish release.

Arrangements for stopping accommodation, engine room and cargo hold ventilation is provided in the wheelhouse and fire station.

Fire hydrants are located on upper deck to facilitate firefighting in case of container fire on deck. A low-pressure CO_2-system is installed as a fixed fire extinguishing system suitable for cargo holds, engine room and engine control room, including switchboard room. When releasing the system to the designated space, the system starts alarm, closes fans and fire dampers automatically. Manually closing of the dampers in the cargo area, except for the forward 4 holds, which are fitted with remote operated dampers. For cargo holds, a smoke detecting system based on air sampling is installed. The system is designed to allow extraction of air samples when the cargo fans are in operation.

c. *Distribution of the characteristics amongst the categories*

Table 8 provides the important values of different characteristics (Gross Tonnage, Length Overall, capacity in Twenty-foot Equivalent Units and Breadth Moulded) for the Generic Ship 1. A more precise distribution of these characteristics is displayed in Figure 12.

Table 8:Important values of principal characteristics for the Generic Ship 1.

	Average	Median	Gen Ship
Gross Tonnage (GT)	161283	153000	
Length Overall (m)	369	366	399
Cargo capacity (TEU)	15873	14993	18000
Breadth Moulded (m)	52.3	51.0	59.5
Count	782		
ShipYears	3346		

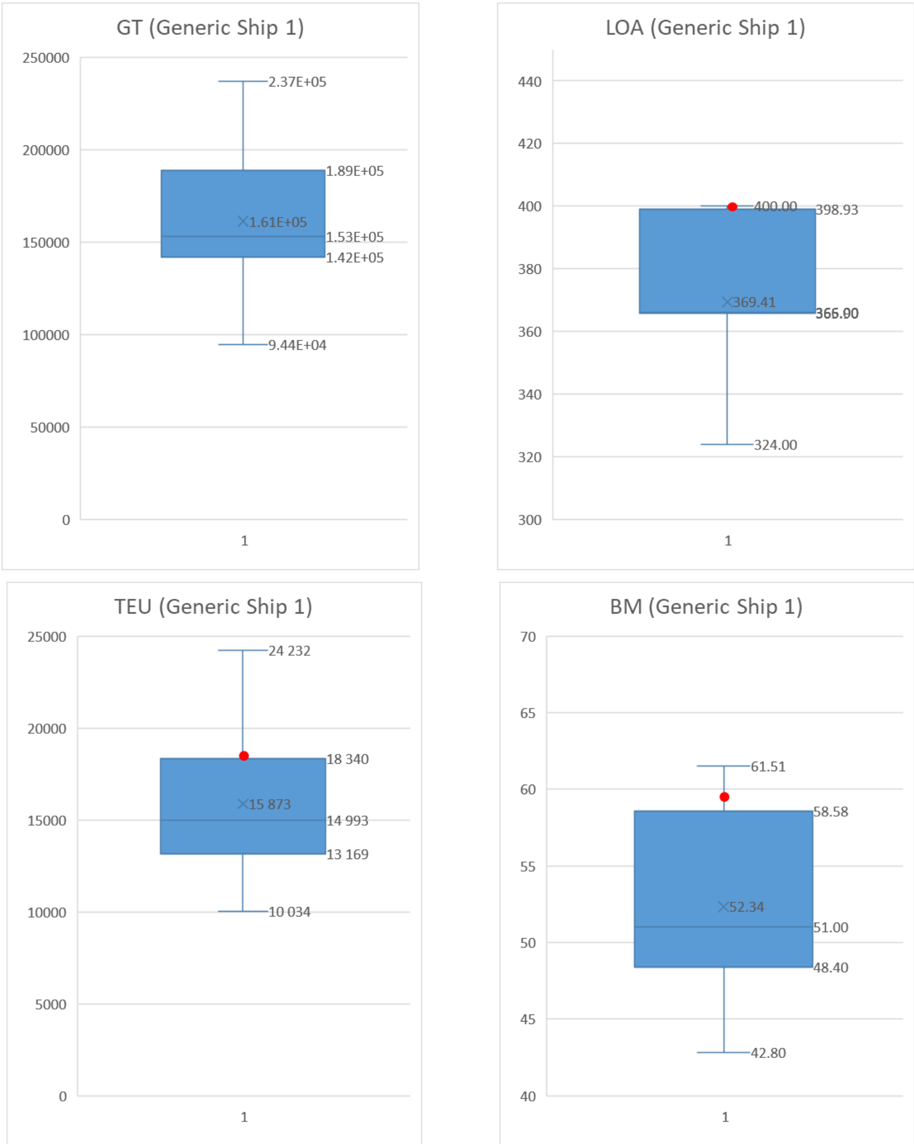


Figure 12:Distribution of the Generic Ship 1 fleet by GT, LOA, TEU, BM

3.2.3.2 Generic Ship 2

a. General description and design of vessel

The Vessel is designed and constructed as a single screw, diesel engine driven containership with fully cellular holds, with bulbous bow, bow- and stern thrusters, forecastle, transom stern, semi- spade rudder and flush upper deck without camber. The vessel is designed for the carriage of containers exclusively and dangerous cargo in hold numbers 1, 2, 3 and 4 and on open deck except over engine room.

The hull below the upper deck is divided by bulkheads, decks, and flats to form:
Fore peak, stores room and chain lockers, cargo holds numbers 1-16 and 17-21.
Wing and double bottom ballast and fuel tanks (port and starboard).

Machinery space with double bottom, fuel oil tanks (port and starboard), diesel oil tanks, low sulfur service tank etc.

Aft peak, steering gear room, miscellaneous rooms, and mooring deck (below upper deck).

All cargo holds are of double skin construction.

b. *Safety systems*

An addressable fire detection system is installed. The system consists of a combination of detectors and manually operated call-points. Detector types: heat, smoke, or other products of combustion, flame, or any combination of these factors, depending on the location.

A brief operating instruction is fitted close to the control panel on the navigating bridge. A smoke detection system based on air sampling is installed for detecting the presence of smoke in cargo holds.

The smoke detector panel is placed in the ship's control centre. Detected smoke and loss of power initiates a signal in the wheelhouse and in the Engine Control Room. General alarm and fire detection alarm system is connected to PA system. In engine room, machinery and cargo areas, an alarm and sounder system (pictograms, sounders, and beacons) in compliance with International Regulations is installed. As required at each location, the system includes (not limited to) fire alarm, general alarm, engine alarm, telephone call, fire extinguish release, etc.

Arrangements for stopping cargo hold ventilation is provided in the wheelhouse and fire station.

Fire hydrants are located on upper deck to facilitate firefighting in case of container fire on deck. A low-pressure CO_2-system is installed as a fixed fire extinguishing system suitable for cargo holds. When releasing the system to the designated space, the system starts alarm and stops fans. The fire dampers in the cargo area are closed manually.

c. *Distribution of the characteristics amongst the categories*

Table 9 provides the important values of different characteristics (Gross Tonnage, Length Overall, capacity in Twenty-foot Equivalent Units and Breadth Moulded) for the Generic Ship 2. A more precise distribution of these characteristics is displayed in Figure 13.

Table 9: Important values of principal characteristics for the Generic Ship 2

	Average	Median	Gen Ship
Gross Tonnage (GT)	88990	89174	
Length Overall (m)	306	302	367
Cargo capacity (TEU)	8114	8102	7500
Breadth Moulded (m)	43.0	42.8	42.8
Count	1184		
ShipYears	14082		

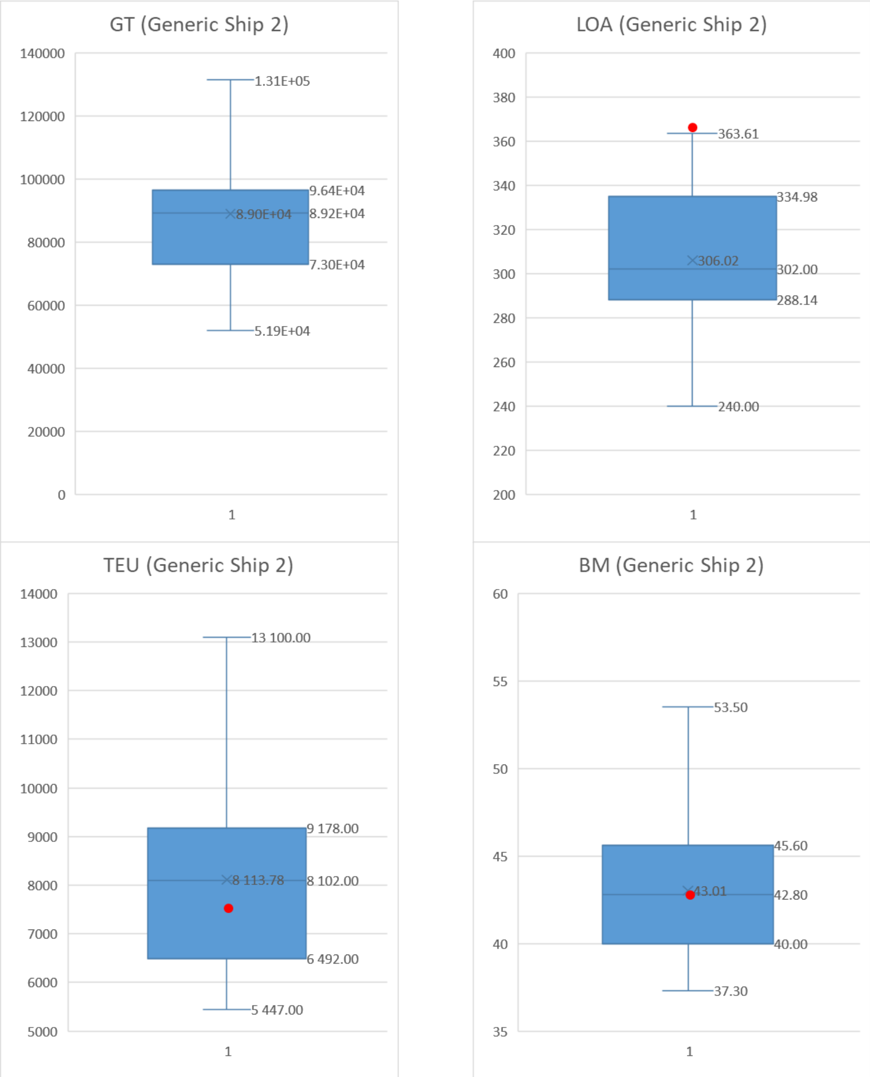


Figure 13:Distribution of the Generic Ship 2 fleet by GT, LOA, TEU, BM.

3.2.3.3 Generic Ship 3

I. General description and design of vessel

The vessel is designed for unrestricted ocean-going (except polar area and special water area) service, constructed of steel, all welded, with efficient hull form for stability and seakeeping. The vessel is a single screw diesel engine driven fully cellular container carrier, suitable for carrying dry cargo containers and reefer containers. The vessel has a bulbous bow, an open-type stern, full spade rudder and a continuous upper deck with forecastle. Engine room and accommodation block including navigation bridge is located semi-aft.

The vessel has a fore peak void, five container holds, water ballast tanks, fuel oil tanks, freshwater tanks, bow thruster room, steering gear room and engine room.
Double hull construction is provided from No.1 to No.5 cargo holds. The double hull and double bottom space are arranged as water ballast tanks. Protected fuel oil storage tanks are provided as transverse deep tanks between cargo holds. Each cargo hold has two 40ft bays. In cargo holds the container arrangement includes 12 rows across in six tiers of High Cube containers.

On deck the vessel has twelve 40ft bays, with two (2) bays aft of the superstructure. Deck containers are generally stowed in 14 rows across and up to seven tiers high. All reefers to be air cooled. Reefer containers are arranged without considering the IMDG cargoes. Dangerous goods in closed containers in accordance with SOLAS Regulation 19 of Chapter II-2. The longitudinal under deck passageway shall be arranged above 2nd deck.

II. Safety systems

An addressable fire detection system is installed. The system shall consist of a combination of detectors and manually operated call points. Detector types: heat, smoke, or other products of combustion, flame- or any combination of these factors, depending on the location.

An operating instruction is fitted close to the control panel on the navigating bridge. A smoke detection system is installed for detecting the presence of smoke in cargo holds. The smoke detector panel is placed in the ship's control centre. Detected smoke and loss of power initiates a signal in the wheelhouse and in the Engine Control Room. Arrangements for stopping accommodation, engine room and cargo hold ventilation is provided in the wheelhouse and fire station.

Fixed Seawater firefighting systems is provided for cargo holds. Sea water spraying water system: Number 1, 2 and 3 Cargo holds, Paint store. CO_2 fixed system: Engine room, Cargo holds.

The fire main line and branch line is led along the under-deck passage and connected to fire hydrants on open deck. The fire main line is loop type with isolating valve according to SOLAS requirement.

III. Distribution of the characteristics amongst the category

Table 10 provides the important values of different characteristics (Gross Tonnage, Length Overall, capacity in Twenty-foot Equivalent Units and Breadth Moulded) for the Generic Ship 3 fleet. A more precise distribution of these characteristics is displayed in Figure 14.

Table 10:Important values of principal characteristics for the Generic Ship 3.

	Average	Median	Gen Ship
Gross Tonnage (GT)	23702	18872	
Length Overall (m)	188	180	219
Cargo capacity (TEU)	2153	1800	3532
Breadth Moulded (m)	27.5	27.9	35.6
Count	5711		
ShipYears	79158		

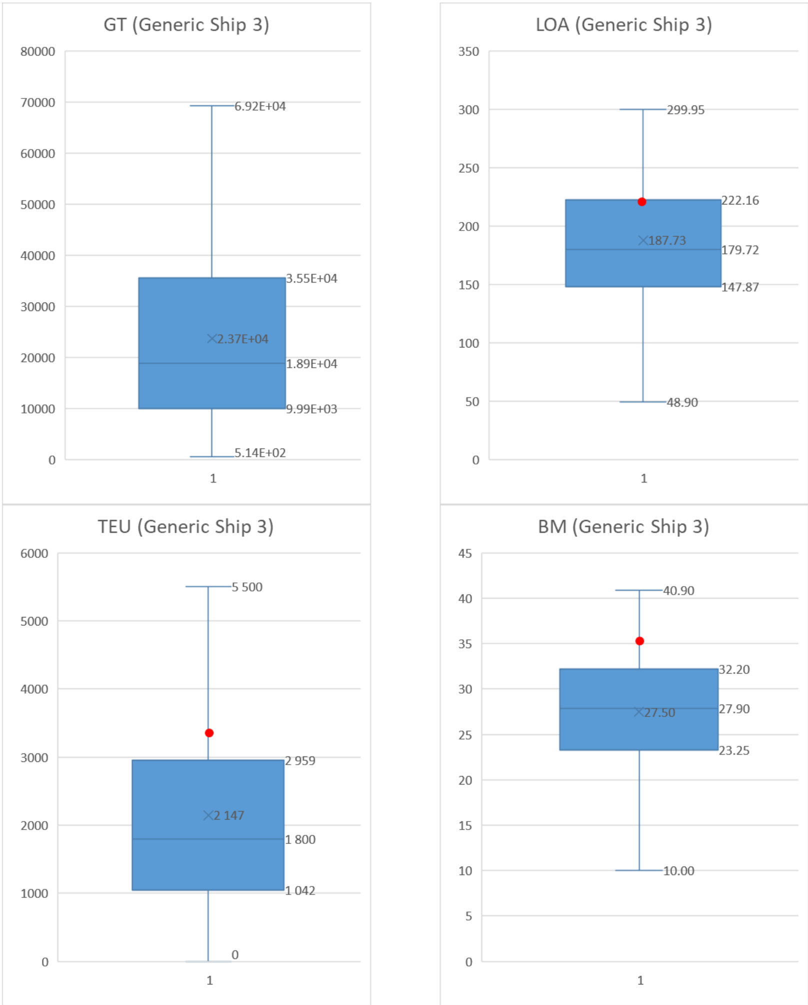


Figure 14:Distribution of the rest of the Generic Ship 3 fleet by GT, LOA, TEU, BM.

3.3 Casualty database analysis

This part details the main results obtained from the CARGOSAFE casualty database.

3.3.1 Study of the frequencies

Figure 15 shows the evolution of the accident count (total 124) along the years (totalizing 101 758 shipyears). There is an obvious increase in this number since 1997[9].

[9] The count increase after 2011 is slightly biased by the inclusion of EMCIP database which starts in 2011 and reports +9 additional events after 2011 which were not reported in MARINFO database.

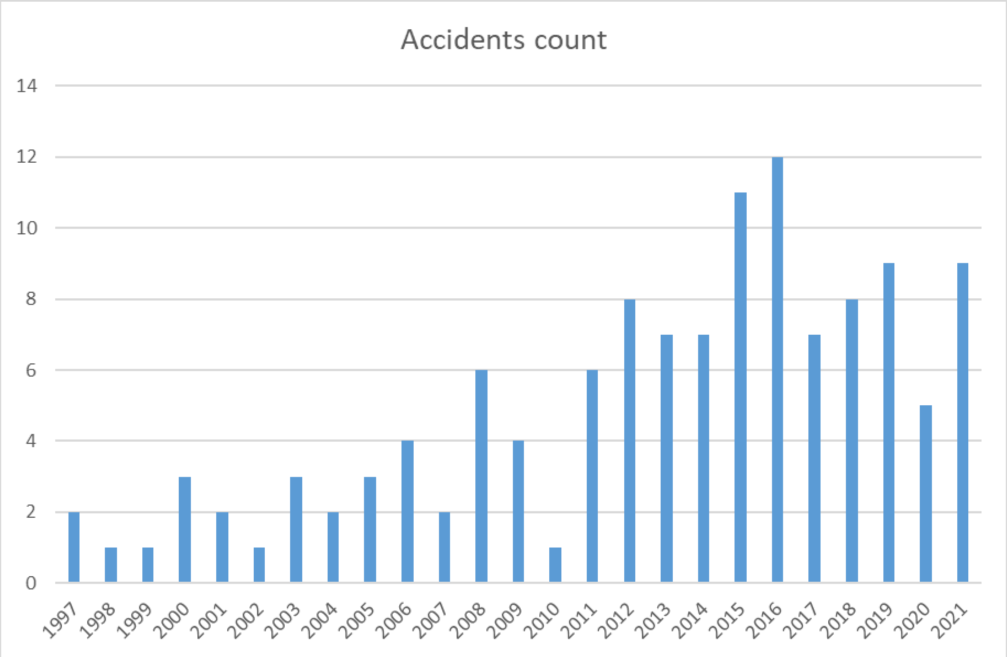


Figure 15:Number of fires in hold or on deck per year for the CARGOSAFE fleet.

The historical fire frequency can be calculated as 1.22E-3 fire per shipyear.

The trend of Figure 15 needs to be looked at having in mind the increase of shipyears and ship capacities. Figure 16 displays the frequency of fire in hold or on deck each year, per shipyear. There is still a slight increase since the beginning of the studied period (approximatively by a factor of 2).

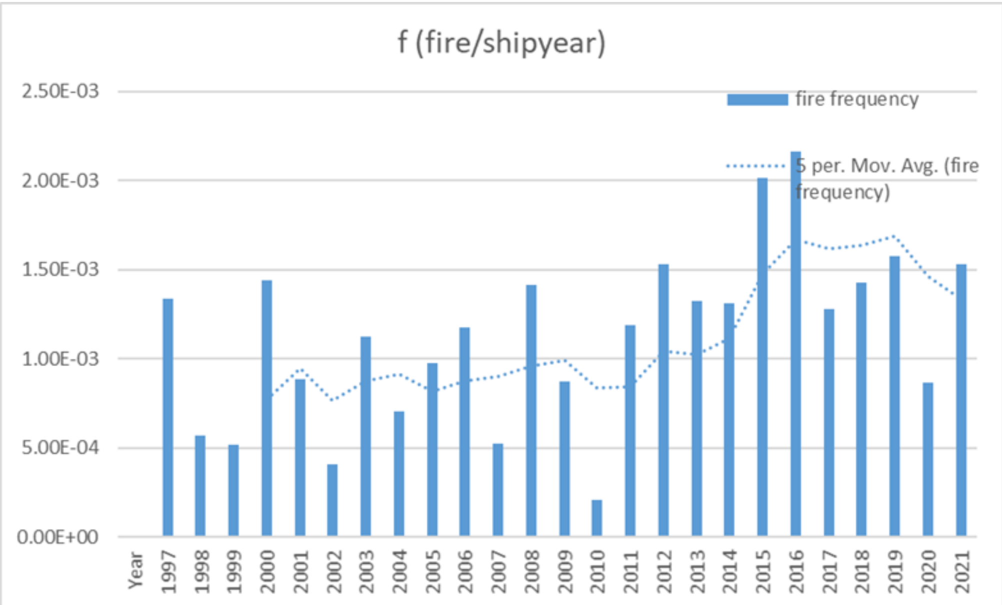


Figure 16:Fire frequency in hold or on deck per shipyear.

Finally, Figure 17 depicts the frequency of fires each year, per TEU capacity.year. This metric shows a more constant characteristic of the fire ignitions over the years and is convenient to scale the frequency with the ship capacity. The later will be noted TEUyear and refers to the ship capacity. This should not to be confused with a frequency per TEU transported.year which should include the filling ratio of the ship capacity (not known). Using this graph as well as Figure 10, since there is no increase in the frequency of ships per TEUyear but a strong increase in the number of TEUyears, it can be assumed that the ignition probability for one container remains the same (in average), and that the ignition frequency per ship is directly linked to ship capacity. The use of such a metric is pertinent with high number of containers randomly transported on board containerships.

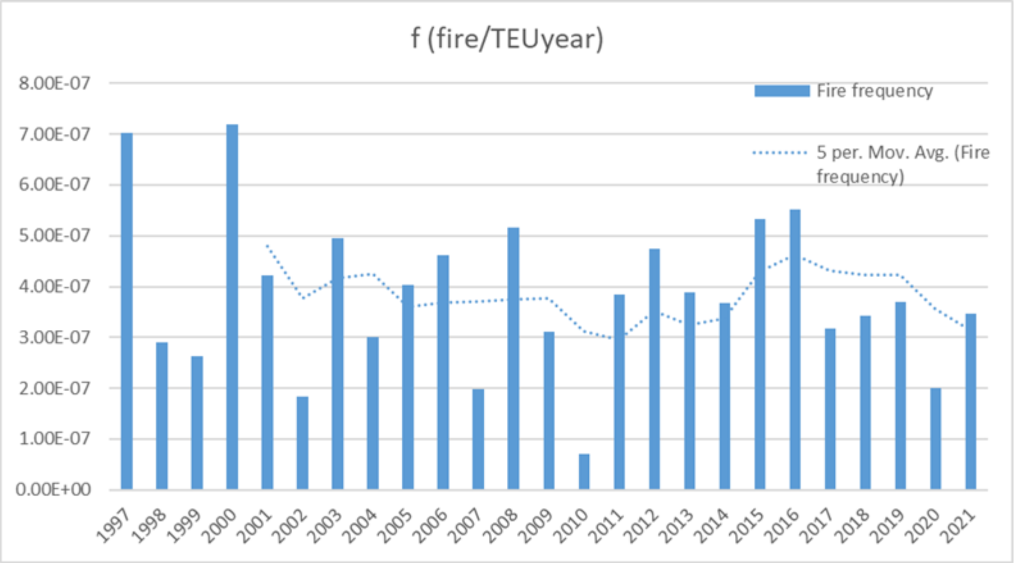


Figure 17: Fire frequency in hold or on deck per TEUyear.

The following equation can be written:

$$f_{ignition}(fires\ per\ SY) = f_{ignition}(fires\ per\ TEUyear) * CargoCapacity(TEU)$$

The above approach can then be verified. The average and the median of the TEUs of the fleet (4475 and 2600 TEUs) provide respectively 1.66E-3 and 9.63E-4 fire per shipyear and compare well to historical frequency of the fleet 1.22E-3 fire per shipyear.

In order to compute a fire frequency in fires per shipyear for each Generic Ship category, two approaches can be performed:

- The fire frequencies f_1 were computed using the upper equation, considering a constant fire frequency per TEU, whatever the size of the ship. These fire frequencies are then directly proportional to the cargo capacity of the Generic Ships and are used in the CARGOSAFE study.
- The fire frequencies f2 were computed using the number of fires that occurred for each of the three categories, then dividing this number by the number of shipyears of each category.

For each type of the Generic Ship categories, f_1 and f_2 are of the same order of magnitude. The biggest gap is for the Generic Ship 1, where the ratio f_1/f_2 is worth 1.69. This number is to be interpreted carefully, since the ships included in this category are very recent (built in 2015 in average) and therefore the sample is much smaller (see shipyears per category). Also, the severity and therefore related likely hood of under/over- reporting may differ from one ship category to the other.

Table 11:Comparison between the two ways of computing the fire frequency in fires per shipyear.

	Fire Frequency (fires/TEUyear)	Median TEU	Fire Frequency f1 (fire/TEUyear * TEU)
Generic Ship 1	3.70E-07	14993	5.55E-3
Generic Ship 2		8102	3.00E-3
Generic Ship 3		1800	6.66E-4

	N(fires)	ShipYears	Fire Frequency f2 (fire/Shipyear)	f1/f2
Generic Ship 1	11	3.35E+3	3.29E-3	1.69
Generic Ship 2	42	1.41E+4	2.98E-3	1.01
Generic Ship 3	71	7.92E+4	8.97E-4	0.74

3.3.2 Analysis of the fires from the CARGOSAFE casualty database

This part provides details about the accidents compiled into the CARGOSAFE casualty database, details that shall be used later to quantify the incoming risk model.

3.3.2.1 Ignition

Figure 18 displays the distribution of the ignition spaces for the 124 fires aggregated in the CARGOSAFE casualty database. It is found from casualty description and reports that 39% of the fires occurred on deck, whereas 55% of the relevant fires occurred in the hold and 6% are unknown. In terms of capacity, the generic ships provide between 60% and 68% of TEU capacity on deck. Therefore, the higher fire occurrence in cargo hold goes against the TEU capacity distribution. However, heavier containers presumably contain more fire sources. On-deck capacity is not fully used and carry empty or lighter containers. On the other hand, the operators will tend to have holds filled as much as possible and still with the heaviest containers. This could explain that the majority of fires occur in holds. It is also possible that small fires occurring on deck are less severe and less prone to be included in the CARGOSAFE database. This combination of arguments helped to support the distribution found from the database.

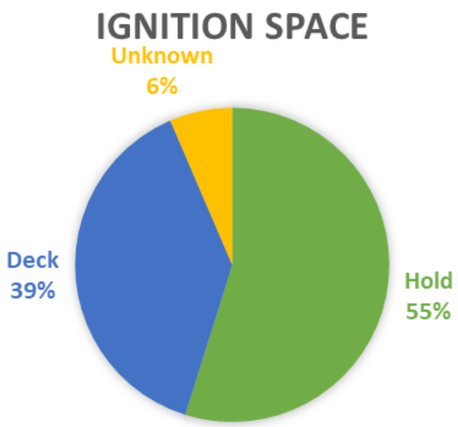


Figure 18:Ignition space distribution amongst the relevant accidents.

Considering all the “unknown” cases are distributed the same way as the other ones, it will be assumed that 41% of the fires occur on deck, whereas 59% of the fires occur in the hold.
Figure 19 displays the proportion of fire having for origin dangerous goods (whether they were properly declared or not) or non-dangerous goods. The identification of dangerous goods is based on the IMDG Code.

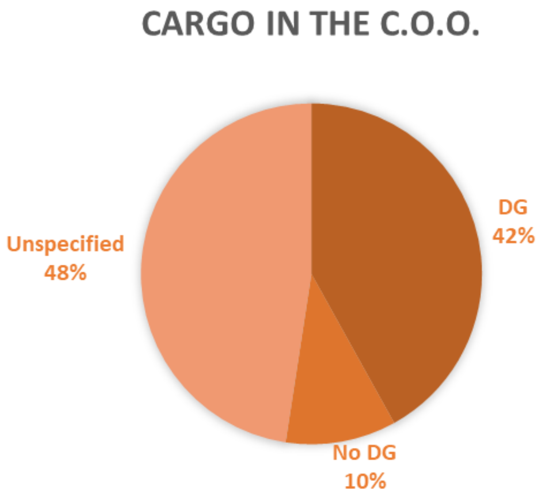


Figure 19:Source of the ignition, dangerous good (DG) or not.

This graph is obviously open to discussion since the “unspecified” part occupies almost half of the fires in the database (48%). Two approaches can be considered: first, it can be assumed that the unknown cases are distributed the same way as the “known” cases. This would lead to 81% of fires caused by dangerous goods. The other way to consider it is to assume that if the ignition source is not specified, it was not a dangerous good. This second approach leads to 42% of fires caused by dangerous goods.

Figure 20 displays the proportion of misdeclared (or undeclared, no difference has been made in this study) amongst all dangerous goods that caused a fire. As for the previous figure, more than half of the accidents records involving “unspecified”, a dangerous good did not precise whether it was declared or not. Once again, it can be first assumed that if the “unspecified” cases did not include a mention of proper declaration or misdeclaration, then the good was probably declared. This would lead to 27% of the dangerous goods causing a fire being misdeclared. It can also be assumed that declaration or misdeclaration of a cargo is not a piece of information which is amongst the few things displayed in data searches, and then consider that the “unspecified” declaration are distributed the same way as the other ones. This would lead to 63% of dangerous goods causing a fire being misdeclared.

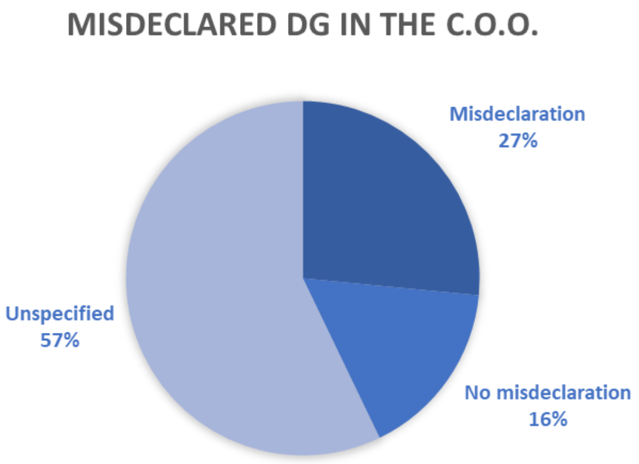


Figure 20: Distribution of the possible declaration of DG at the origin of the fire.

3.3.2.2 Firefighting – first attempt

This part summarizes data regarding the first firefighting attempt and proportion of success. Figure 22 and Figure 21display the rate of success (“yes”) and failure (“no”) of the first firefighting attempt by the crew (i.e., attacking the fire by hand with hoses, not with CO_2 or water monitors) against fire that originated on deck and in hold, respectively.

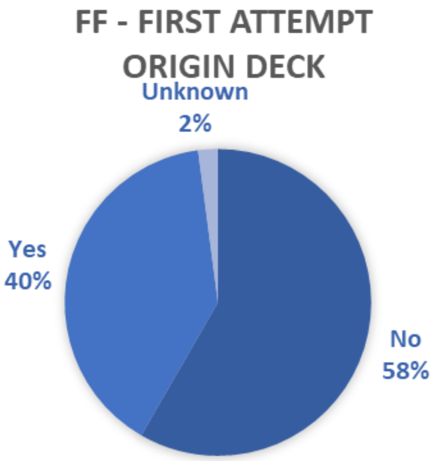


Figure 22: Proportion of success of manual firefighting for fire originating from deck.

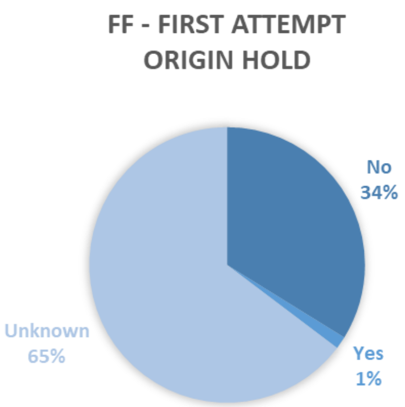


Figure 21: Proportion of success of manual firefighting for fire originating from hold.

It seems that the first attempt is most of the time unsuccessful (between 58% and 60% of the time) when the fire occurs on a deck.

In the case of a fire starting in a hold, as only one successful first attempt was spotted amongst all the accidents of the database, it is safe to assume that it is very unlikely for a manual firefighting to be successful.

3.3.2.3 Firefighting – other means than first attempt

This part summarizes data regarding the firefighting led with other means than the first attempt, obtained by key word searches. Percentages of use of each firefighting method is reported in Figure 23, for fire originating in holds. These percentages are based on all accidents with at least one mean of firefighting reported (which represent 34 cases over 68). In almost 90% of the cases, CO_2 was used. Use of water hoses may include connecting to drencher systems or firefighting below hatch[10].

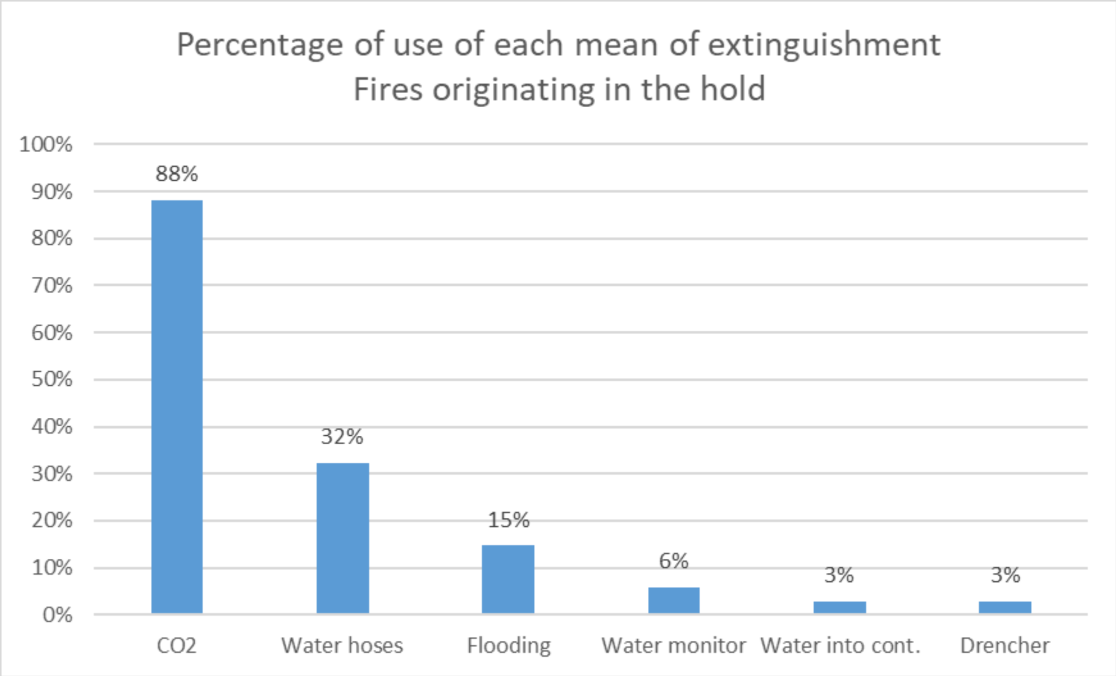


Figure 23: Percentage of use of different means of extinguishment, for fire originating in the hold.

Figure 24 displays the rates of the different outcomes of releasing CO_2 into the hold.

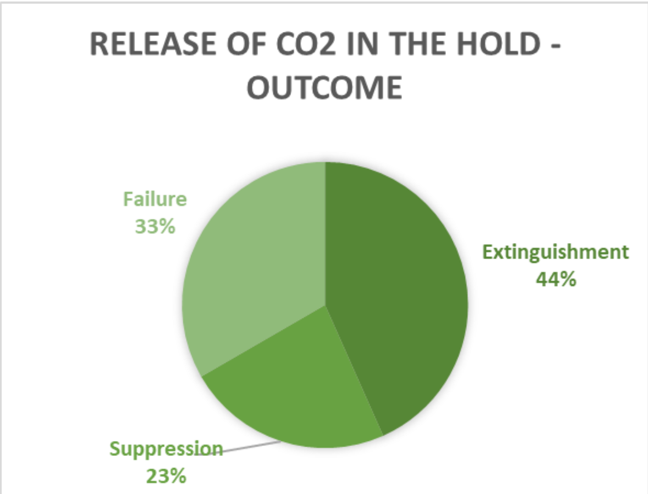


Figure 24: Proportion of Extinguishment/Suppression/Failure of fire extinguishment or suppression after the decision to release of CO2 in the hold.

3.3.2.4 Propagation

In this study, “propagation” has been defined as the spread of the fire to other spaces than the space of origin (i.e., Hold-hold, hold-deck, deck-accommodation). Regarding open deck, propagation has been defined also for fire

[10] Analysis of fires and firefighting operations on fully cellular container vessels over the period 2000 – 2015, Helge Rath, HSB/CMS, Sept 2016 https://iumi.com/opinions/position-papers

propagation between 2 bays[11]. If a fire only broke out of its container of origin, that was not considered as a propagation in the following graphs.

The five different outcomes of the propagation are defined as such:

- **Yes**: the propagation is clearly indicated in the available data.
- **Probably yes**: the propagation is not explicitly mentioned in the data, but is probable given the consequences, the narrative of the event, etc.
- **Probably no**: the absence of propagation is not explicitly mentioned in the data, but is probable given the consequences, the narrative of the event, etc.
- **No**: the absence of propagation is clearly indicated in the available data.
- **Unknown**: there is insufficient data to conclude.

Figure 25 displays the frequency of these different scenarios amongst the accidents from the casualty database

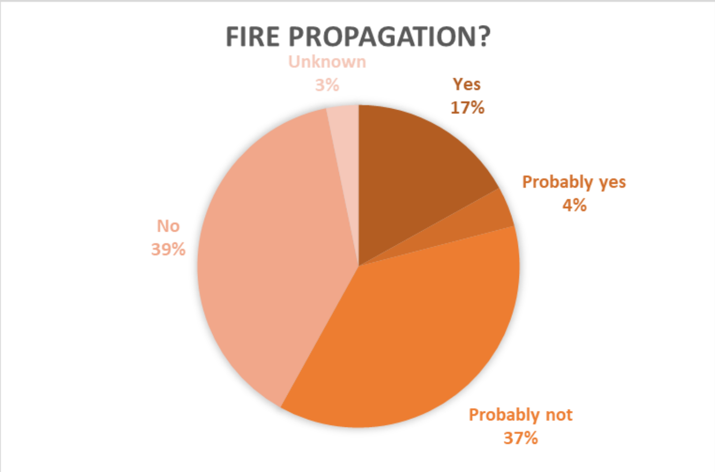


Figure 25: Possible propagation of the fire.

Even with the uncertainty on the "probably …" cases as well as the unknown ones, it is clear by looking at Figure 26 that there is, as it could be expected, a correlation between the severity of the accident and the possible propagation of the fire. For non-serious fires, the propagation probably occurred in 2% to 6% of the cases, whereas for serious fires, it probably occurred in 28% to 39% of the cases. The choice of serious/non-serious for the accidents was already made by the authors of the original databases provided by EMSA.

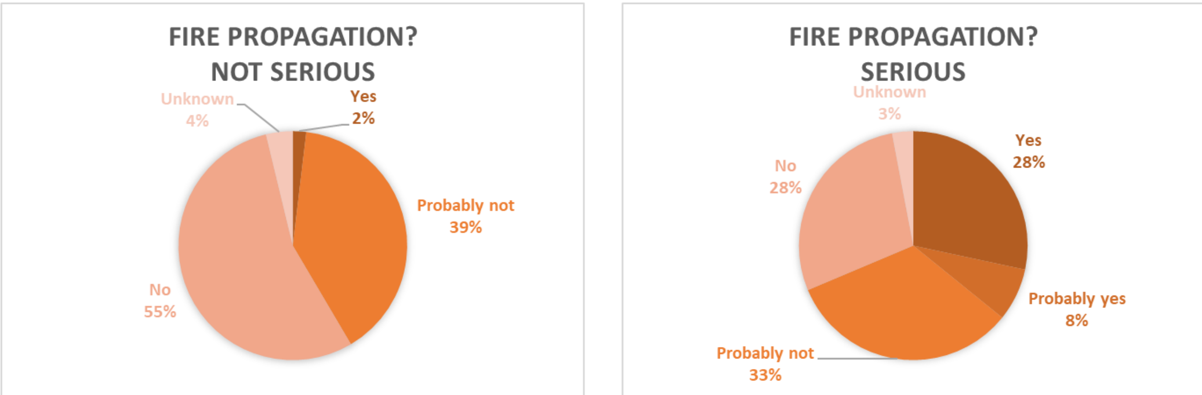


Figure 26: Possible propagation of the fire for non-serious and serious cases.

[11] In holds propagation between bays is very weakly reported

Based on Figure 27, it can be assumed that the location of origin plays a part in the possible propagation of the fire. Indeed, fires that originate on a deck did spread approximately twice as much as the fires that originated from the hold.

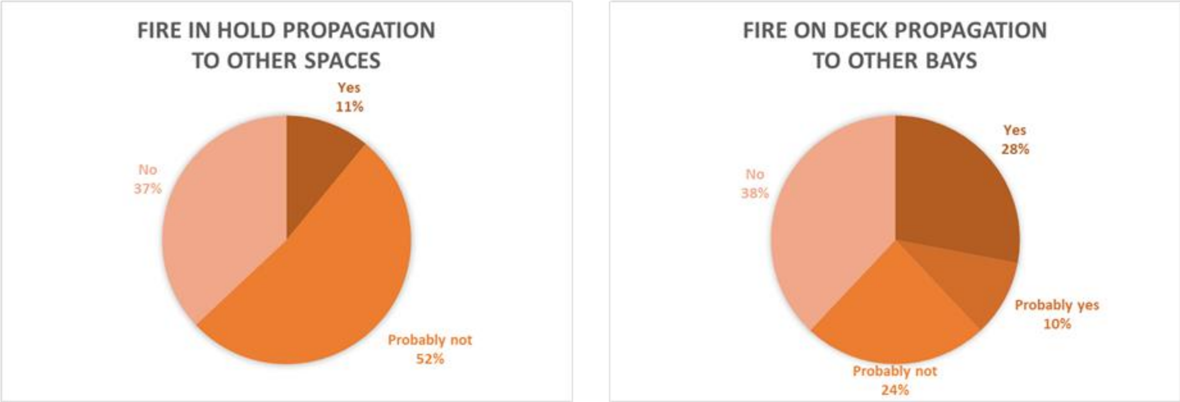


Figure 27: Possible propagation of the fire for fire starting in hold and on deck.

3.4 Classification container fires for CARGOSAFE study

The aim of this part is to depict general behaviour of container fires. Previous research showed that fires can be hard to sustain within a container due to e.g., lack of oxygen within a container, and limited ventilation. However, history shows that container fire does occur, and for the purposes of this study the characteristics of such a container fire has been simplified and classified into 3 categories:

- ***Slow fire*** – slow fire growth in container of origin (COO), leading to slow spread rates to neighboring containers, with greater possibility of detection before becoming unmanageable.
- ***Fast fire*** – higher growth rate of fire in COO, may be due to fuel self-oxidation (i.e., supplying its own oxygen) or other fuel instabilities. Higher heat output, spreads to neighboring containers much faster, with reduced chances of early detection or early intervention by crew.
- ***Explosion*** – explosive growth and direct spread/impact to neighboring containers, very little possibility of early detection and early intervention by crew.

3.4.1 Causes of fire

The following section provides the background information for the choice of the 3 fire scenario categories given above.

The causes of cargo/container fires can be simplified into two main forms:
- Self-heating/propagating fires.
- Ignition via external source of sensitive cargo or flammable gases/vapours.

Many marine cargo fires and explosions are due to self-heating in some form. In general, self-heating occurs when an exothermic (heat-producing) chemical or biochemical reaction happens within a body of cargo. The heat produced can only escape to the direct surroundings, i.e., cargo, packaging, dunnage, containers. Due to restricted heat loss, the temperature within the cargo tends to increase, which can ultimately lead to a fire in the cargo and surrounding materials.

The most common and most hazardous types of cargoes prone to self-heating are: Bulk coal self-heating, bulk coal self-heating and emitting methane, bulk direct reduced iron, charcoal, metal powder or metal turnings, seed cake, reactive solids, calcium hypochlorite, biomass in bulk, fertilizers, batteries, and reactive liquid cargo.

A brief summary of each of the hazards is given here:

- Bulk coal self-heating

Self-heating of coal depends on the reactivity of the particular coal (oxidation), starting temperature of the coal, and availability of oxygen. Coal that can self-heat produces carbon monoxide gas (CO); if coal oxidation develops to the point of problematic self-heating or burning, then some of the coal will decompose to produce flammable/explosive gas or vapor.

- Bulk coal self-heating and emitting methane
  In rare cases, coal cargoes can self-heat and emit methane at the same time. Methane is a flammable/explosive gas and so it can present an explosion risk in cargo holds. Methane-emitting coal therefore needs ventilation, and the International Maritime Solid Bulk Cargoes (IMSBC) Code advises adequate surface ventilation of holds if methane exceeds 20% Lower Explosion Limit (LEL), as 100% LEL is 5% by volume this corresponds to roughly 1% by volume in air. LEL is the lowest concentration of flammables that will burn in air. Bulk coal self-heating and emitting methane is especially problematic since the remedial actions for each occurrence are conflicting (excluding air/oxygen to tackle self-heating, vs. ventilation to reduce methane concentration).

- Bulk direct reduced iron
  Direct reduced iron (DRI) is made from iron ore through direct contact with a hot reducing gas. The resulting iron pellets are porous and can therefore be highly reactive with water, or oxygen in air, due to the large surface area present within the pores. Water ingress to holds and containers, e.g., in heavy weather, can start problematic self-heating. Seawater tends to be more reactive than fresh water. When reacting with water, direct reduced iron releases hydrogen, which is a highly flammable/explosive gas that is colorless, odorless, easily ignited, and presents a serious explosion risk.

- Charcoal
  Charcoal is shipped for various uses, including shisha pipes (water pipes) and for barbecues. Charcoal is porous and so it provides a large surface area for reaction with air/oxygen. Self-heating is therefore possible in charcoal. Some charcoal tablets for shisha pipes are not pure charcoal but contain impurities e.g., metal filings and hydrocarbon liquid, which may make them more likely to self-heat. It is prone to self-ignition if kept in large densely packed quantities at elevated ambient temperatures. This may produce a situation in which a form of thermal runaway occurs. Thermal runaway is a condition in which more heat is generated inside the system than lost to the surroundings, causing elevated temperature inside the system and may lead to self-ignition of the charcoal. These tends to be a slow process, and may happen over days or weeks, slowly building up heat in the container until potential spread to other containers is possible.

- Metal powder or metal turnings
  Finely divided metals have a large surface area. If the surfaces have not previously oxidized, then they may react with oxygen in air or water, in a similar way to direct reduced iron. Oxidation with water can produce hydrogen and consequently a serious explosion risk. Other examples of this problem involve oxidation of metal by oxygen in air, which can lead to self-heating and sometimes ignition of the metal.

- Seed cake
  Seed cake is a residue left after extracting oil from plant seeds and coconuts. Residual plant oil in seed cake can oxidize with oxygen in the air and the oxidation reaction evolves heat. Therefore, seed cake may self-heat, depending on factors such as the concentration of oil and the type of seed/oil involved. In addition, some plant oils are extracted using volatile, flammable/explosive solvents and residues of these solvents may remain in the seed cake. This can lead to the presence of solvent vapors in or around containers, and consequently add to a risk of explosion.

- Reactive solids
  Cargoes that fall into this category include calcium hypochlorite ($Ca(ClO)_2$) and other oxidizing solids. They are often used for swimming pool sterilization and fabric treatment (bleaching or washing). These materials do not oxidize but they can be relatively unstable chemicals that decompose slowly over time, evolving oxygen. This self-decomposition can evolve heat, in turn leading to ‘thermal runaway’ increasing the speed of self-decomposition, and evolving heat and gases, sometimes including further oxygen. In a cargo hold, this sequence of events leads to effects similar to an explosion. The heat and oxygen produced can lead to fire spreading. Contaminants, higher than normal ambient temperatures, packaging sizes and moisture can all influence the stability of these products.

- Biomass in bulk
  Biomass is shipped in bulk to provide fuel for ‘green’ power stations. Examples of biomass include wood chips and husks of oil seeds. These types of biomasses do not contain significant amounts of oil, limiting the risk of self-heating from oxidation of the oil. Nevertheless, biomass can naturally evolve carbon monoxide, even if it is not self-heating. This can lead to incorrect assumptions about whether there is a fire or self-heating in the biomass. Recent experience has shown that biomass can undergo a rotting process in which microbes (bacteria and mold) break it down. This can produce some heat, but the heating is not usually severe enough to cause fire. However, microbial action can continue where oxygen concentrations are low, and that type of ‘anaerobic’ rotting can produce dangerous concentrations of methane.

- Fertilizers
  Fertilizers, which are often shipped in bulk, may have some of the same characteristics as the aforementioned reactive solids and biomasses. If some fertilizers become hot enough, they may be able to decompose rapidly with evolution of heat and, often, toxic gases.

- Batteries
  There are several possible causes of rechargeable battery fire incidents including incorrect packaging, damage in transit (e.g., puncturing batteries), water ingress, and manufacturing defects. All these issues can lead to short circuits, thermal runaway, and fire. The causes of such event vary, but essentially, it occurs when the anode and cathode come in direct physical contact with each other. External heat sources also need to be considered. Lithium-ion batteries may vent with flame if heated and may require less external oxygen. Moreover, many rechargeable batteries naturally lose their charge slowly over time (‘self-discharge’). This means that self-heating can occur as the natural slow discharge releases electrical energy as heat. If that heat cannot dissipate fast enough, then batteries may become so hot that faults occur, such as failure of internal insulation. This can then spread rapidly to other batteries, leading to ignition and fast fire growth rates.

- Reactive liquid cargo
  Some chemicals are shipped as liquid monomers that tend to polymerize. Polymerization is the act of individual monomer molecules linking together to make larger molecules. Polymerization often evolves heat. Inhibitors may be added to monomers, to stop or slow down polymerization. However, if the concentration of inhibitor is too low, the rate of polymerization may increase to a point at which heat is produced very quickly and the temperature becomes very high. This can cause boiling and release of flammable monomers and polymers, which gives rise to an explosion risk.

- Ignition via external source of sensitive cargo or flammable gases/vapors
  Self-heating is one of the main common causes for fires on board containerships. It is however not the only one. The following list details other important causes:
  - Cargo hold lights
    Many bulk carrier / general cargo holds have fixed cargo lights. These can easily ignite combustible cargoes such as grain, animal feed, wood chips, pulp and paper if they are too close to the light. Self-decomposition of fertilizer has been initiated in this manner.
  - Smoking and hot works
    Cigarettes and/or hot work can ignite many cargoes, including a wide range of bulk and general cargoes. Smoking and hot work therefore need to be properly controlled. Control of smoking can be difficult where stevedores are working. Hot work permits need to be properly considered, not just a ‘tick box’ exercise. Previous research by BMT showed that in fact containers do not protect against sparks from hot works entering the container itself.
  - Vehicles and vehicles parts
    Cars, other vehicles, and their parts carried on board ships present some risk of fire. There are several risks:
    - Cargo shifting in heavy weather can lead to ignition e.g., by rupturing gasoline tanks, damaging electrical cables and causing friction.
    - Electrical faults. Many vehicles have electrical circuits that remain energized even when the ignition is switched off. Electrical faults do not commonly cause fires in cars that are not being driven, but large numbers of cars are transported by ship and occasionally a fault can develop to cause ignition during shipment.

- Shipment of car parts has also been shown to cause fire or explosion incidents due to the presence of oils and greases and fuel forming flammable vapors.

- Fumigation
  Agricultural products in bulk may be fumigated to prevent insect infestation. Solid aluminum phosphide (or similar) is often used for fumigation. Aluminum phosphide reacts with water vapor (humidity) in air to produce phosphine, a toxic and flammable/explosive gas, which kills insects. The reaction also produces heat. If there is an excessive amount of fumigant in one place, or if the fumigant is contacted by liquid water e.g., from sweating or condensation, then the fumigant can react quickly. This can evolve excessive heat and lead to ignition of cargo and/or packaging such as bags or paper placed over the top of the cargo. Under certain conditions, the fumigant gas itself may ignite, producing an explosion.

- Flammable liquid cargo
  Flammable liquid cargoes present risks of explosions in cargo tanks and other compartments. These explosions are often followed by fire.

3.4.2 Fire spread from the container of origin

Once a fire has been initiated in the COO, the potential methods of spread to the neighbouring containers are as follows[12]:

- The plywood floor of the container above the COO. This is a weakness in the container design with regards to fire, and it has been shown that it can ignite only from the heated steel roof of the COO. Once ignited, burn through not only exposed the cargo contained in this container but also allows for much higher oxygen flow into that container which can accelerate the fire spread. Floors in newer containers that have substituted the original plywood for a lighter bamboo plywood, and if the plywood floor had a water proofing layer (normally bitumen) on the underside, tests performed in CONTAIN[13] showed the risk of spread was increased.
- Ignition of the rubber seals around the door can also induce spread via flame impingement on the container above and through flaming droplets of melted rubber.
- Heat transfer via radiation and convection. Due to the closeness of container stacked both on deck and in the hold of ships, heat can easily transfer over these gaps and impact the neighboring containers with high enough heat fluxes that the cargo contained within them can auto-ignite.
- Explosion can breach the COO and allow the pressure wave, flames, and heat to impact neighboring containers leading to spread.
- Structural collapse of COO due to excessive heating can also be a highly dangerous spread mechanism. A Study by DBI[14] showed that if the structural columns of a container reached 500-600 ^{o}C that failure could occur leading to potential container stack collapse.

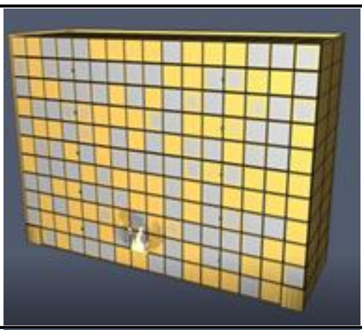
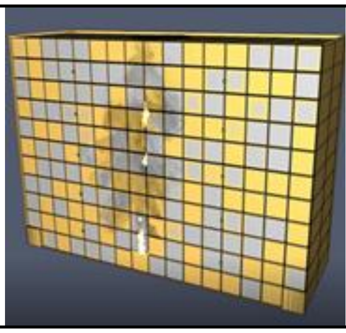
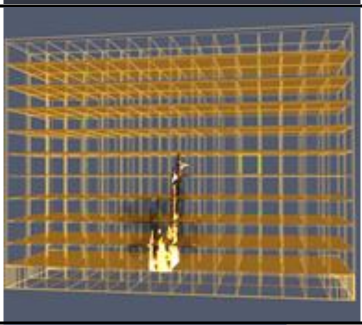
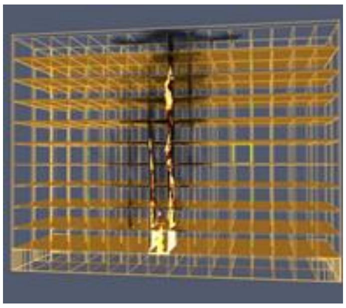
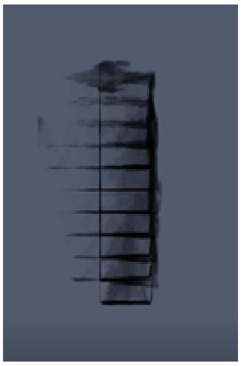
In a “real” scenario, with a multitude of containers, within a cargo hold, the mechanisms described above will work together, and will likely feed, and/or feed on each other. Fire is generally a non-linear process, thus simply “adding” these mechanisms together will not be sufficient, chain reactions can occur, where one process feeds another, which then gives more back to the first, accelerating this, and so on. This interaction between mechanisms can have a significant impact e.g., how quickly fire can spread through a cargo hold, as spread between containers is likely to be an accelerating process, not a constant one.

It should also be noted, that spread rates will differ horizontally vs vertically. With vertical spread i.e., from bottom of stack to top being much higher than horizontal spreading of both the fire and smoke. This is clearly illustrated in Table 12: Initial simulation of fire in cargo hold exploring potential spread pathways.Table 12 below which shows some initial simulations of a fire in cargo hold, and the travel of smoke and fire. Additionally, as can also be observed a fire

[12] CONTAIN – Exploring the challenges of containership fires, Danish institute of fire and security technology, 2020, https://brandogsikring.dk/en/research-and-development/maritime/contain/
[13] CONTAIN – Exploring the challenges of containership fires, Danish institute of fire and security technology, 2020, https://brandogsikring.dk/en/research-and-development/maritime/contain/
[14] Thermo mechanical modelling of a shipping container – Report, DBI, 2022.

breaks out of the COO, due to the small gaps between containers, large flame extension can be seen, thus direct flame impingement is likely to be not only on the first container above but could be several containers that feel the direct heat from the fire, helping to accelerate fire spreading to those containers as well.

Table 12: Initial simulation of fire in cargo hold exploring potential spread pathways.

Observation/ comments		Observation/ comments	
Fire starts in the middle container of the bottom row		Fire quickly ascends vertically	
Same as above, with containers made to be see-through		Here the fire spread vertically is much more easily seen, note the strong vertical movement compared to the little horizontal movement	
Same as above, with containers completely hidden so that only fire a smoke is observed		Different view of the same time period as image to the left. Most interesting here is how the smoke is also very restricted to vertical movement	
side view of same time period as above, showing only the smoke, note the high proportion of smoke collecting between the container row next to the bulkhead, rather than travelling in between containers		Front view	

3.5 Methods and tools for risk analysis

The project CARGOSAFE uses Formal Safety Assessment (FSA) as a procedure to achieve project outcomes. FSA Guidelines[15] refer to both fault trees (FTs) and event trees (ETs) as Risk Analysis techniques and combine them in a so-called risk contribution tree (RCT). In FSA guidelines, all risks should be looked at, and contribute to ship total risk level (collisions, groundings, propulsion failures, fire, etc.). CARGOSAFE only looks at one fraction of fire events on board container ships, i.e., fire originating from cargo, and targets reductions on potential life and monetary loss. For these events, CARGOSAFE Task 2 Risk Analysis is the 'bowtie' approach that is similar to FSA RCTs.

A fault tree is a logic diagram showing the casual relationship between events which singly or in combination occur to cause the occurrence of a higher-level events. An event tree is a logic diagram used to analyse the effects of an accident, a failure, or an unintended event, see[16]. Thus, when combining all the three methods, namely, the bowtie approach, fault tree, and event tree, it results in the structure of the global risk model for CARGOSAFE. Figure 28 captures the structure of the global risk model which combines the abovementioned methods.

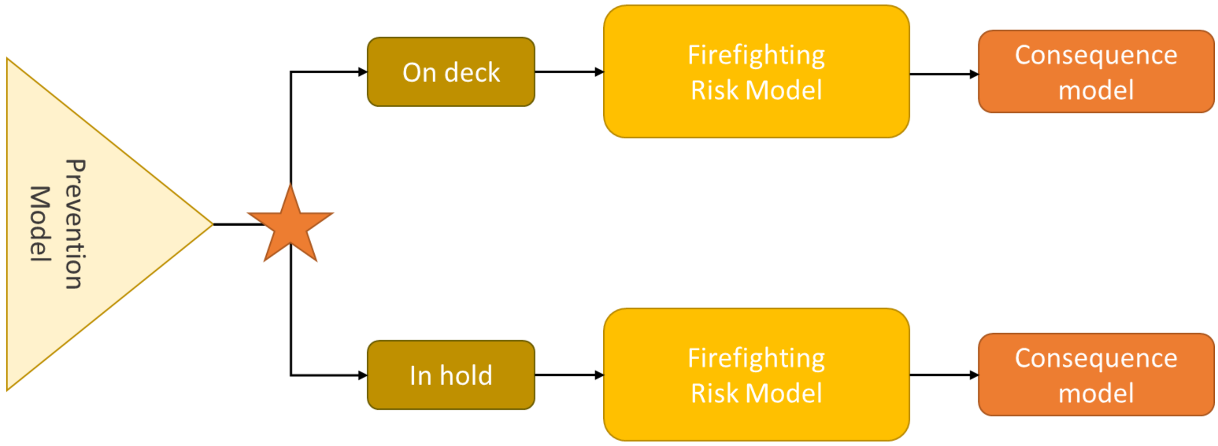


Figure 28: Basic structure of the global risk model in Project CARGOSAFE Task 2 Risk Analysis.

The prevention side of the risk model lies towards the left, which captures the causal relationships using the fault trees. In the middle is the unwanted hazardous event (UHE) and towards the right is the onboard fire-fighting event tree (detection, containment, and firefighting) and the consequence model (assistance, evacuation, severities for life, cargo, ship, and environment). The subsequent sections explain each of these in more details.

It is to be noted that FTs are used only within the Prevention Risk Model in Task 2 Risk Analysis in project CARGOSAFE. FTs are developed for nodes in the event trees on the right side of the bow tie for Task 3 to examine RCO influence.

3.6 General description of Risk Model for a cargo fire

3.6.1 Prevention

3.6.1.1 Use of Bow Tie and Fault Trees as Prevention Risk Model

In the project CARGOSAFE, Task 2 Risk Analysis chooses the bow tie approach as the basis of the global risk model. This means, prevention belongs to the left side of the bow tie which captures causes leading to an "unwanted hazardous event" (UHE) which in CARGOSAFE is interpreted as ignition inside containerized unit. In other words, ignition prevention is addressed on the left side of the bow tie, while fire timeline, severity and consequences are captured on the right side.

[15] MSC-MEPC.2/Circ.12/Rev.2
[16] FSA, MSC-MEPC.2/Circ.12/Rev.2, Annex, Page 37.

Furthermore, prevention risk model, consists of fault trees that have been developed based on the outcome of the hazard identification (HAZID) workshop dedicated to prevention. The fault trees are developed to capture the various failure pathways that can cause the UHE. Thus, the bottom nodes in fault trees are used as tracing techniques to show how certain failures might occur leading to the top event.

3.6.1.2 General Assumptions & Limitations

It is to be noted that in project CARGOSAFE the focus is on containership fires onboard. More precisely, in Task 2 Risk Analysis, for Prevention the focus is clearly on conditions above deck and conditions in cargo hold. This means, should there be any failure pathways arising from terminal handling, inspection, stowage planning, physical stowage or loading etc., while the vessel is at port or even earlier such as when the booking processes are conducted, those are out of scope for this task. The fault tree has been created using exclusive OR-gates, meaning that only one of the events considered in the bottom nodes needs to occur for the top event to occur. The usage of mutually exclusive OR-gates is made under the assumption that only one fire incident occurs at a time. This means, the prevention fault tree does not consider two or more fires occurring simultaneously onboard.

3.6.1.3 General Description of Prevention Fault Tree

As mentioned earlier, the top event of the fault trees for ignition prevention is the unwanted hazardous event (UHE), i.e., “ignition inside a containerized unit”.

The fault trees consist of five levels. These levels are further described below.

Level 1:

The first level of the prevention fault tree offers three categories of goods that ignite, listed below.

- *Ignition of dangerous goods that is not properly declared*. This category includes ignition of goods that are identified as dangerous goods according the IMDG Code and that has not been properly declared. “Not properly declared” covers both types of mis-declaration. One, where the misdeclaration arises from human error, which is unintentional and the other, where the misdeclaration is carried out with a malicious intention. “Not properly declared” category also includes dangerous goods that are undeclared.
- *Ignition of dangerous goods that is properly declared*. This category includes ignition of goods that are identified as dangerous goods according to the IMDG Code and that has been properly declared. In this category, it is assumed that handling and stowage of the dangerous goods has been made using correct procedures, complying with the IMDG.
- *Ignition of non-dangerous goods*. This category covers ignition of goods that are not identified as dangerous goods according the IMDG code. This category also includes small packages of high fire risk cargo packed together that are not identified as dangerous goods according to the IMDG Code.

Each category of goods that ignite is followed by a fault tree of its own, showing the mechanism of various failure modes. This means, each fault tree is applicable for respective category. It also means that each fault tree captures how the applicable bottom nodes lead to ignition at the top. Figure 29 shows the three categories of goods that ignite captured in Level 1.

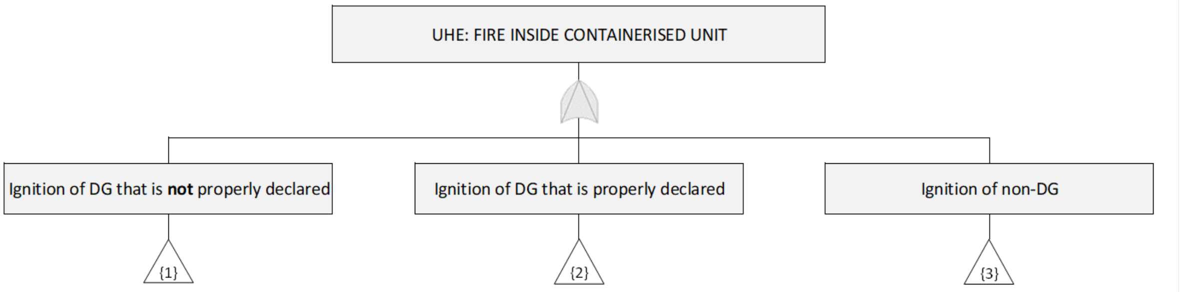


Figure 29: Level 1: The three categories of goods that ignite.

Level 2:

Ignition in Level 2 can occur due to either one of the two main ignition categories listed below:

- *External ignition source.* This category covers all ignition sources that do not stem from the goods or the cargo itself.
- *Self-ignition.* This category covers self-ignition of goods. Self-ignition is the process of autoignition arising from exothermicity of the material itself. Quintiere[17] describes this process as spontaneous ignition. Moving forward, the term self-ignition will be used instead of spontaneous ignition. Self-heating describes the exothermic process leading to spontaneous ignition. Only self-ignitable goods are covered in this category which means that other ignition sources are not considered here. This category also considers that self-heating of the goods of some sorts are followed by self-ignition.

Figure 30 below shows the two main ignition categories captured in Level 2.

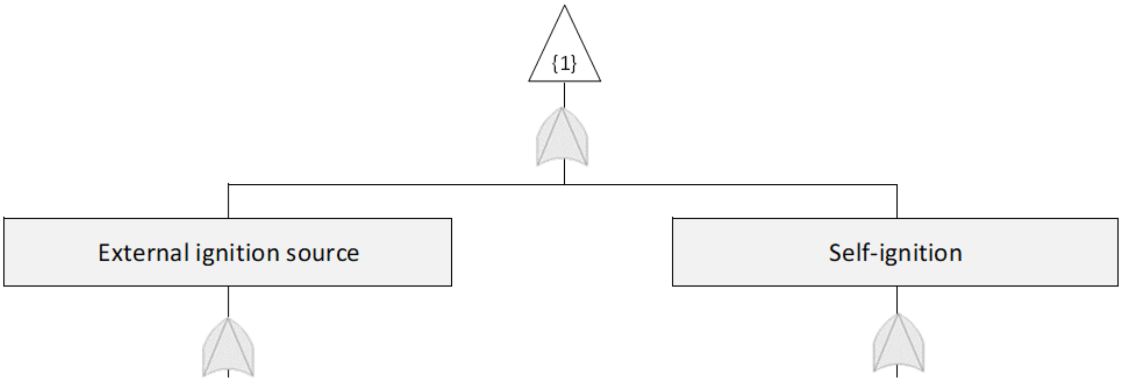


Figure 30: Level 2: The two main ignition categories.

Level 3:

The main ignition category called S*elf-ignition* has been divided into two sub-categories:

- *Self-heating following external prolonged heating.* This category covers self-heating (leading to self-ignition) that occurs following an increased ambient temperature.
- *Self-heating without external prolonged heating.* This category covers self-heating (leading to self-ignition) that occurs without any increase in the ambient temperature.

[17] Quintiere G. J. (2006), Fundamentals of Fire Phenomena, John Wiley & Sons Ltd, Chichester, West Sussex, England. P. 117.

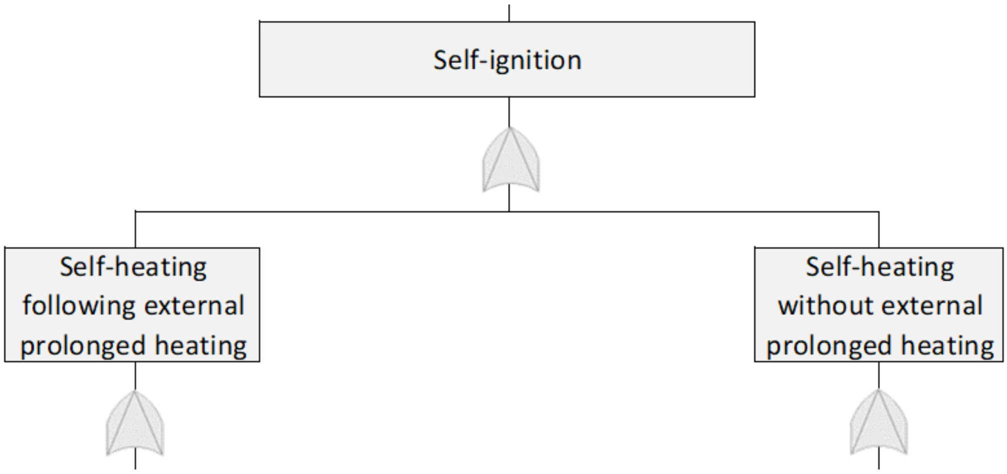


Figure 31 below shows the two sub-categories for self-ignition captured in Level 3.

Level 4:

For *Ignition of dangerous goods that is not properly declared* and *Ignition of dangerous goods that is properly declared*, the sub-category *Self-heating without external prolonged heating* has been further divided into two sub-categories:

- *Self-heating without release* covers events that causes the goods to self-heat without the goods having been released from its packaging.
- *Self-heating following release* covers events where there is a release of the goods, leading to self-heating of the goods. This category also covers events where either there is a release of one self-ignitable substance or there is a release of two incompatible substances that may lead to self-heating of goods and finally leading to self-ignition.

Figure 31: Level 3: The two sub-categories for Self-ignition.

For *Ignition of non-dangerous goods* this sub-categorization of *Self-heating without external prolonged heating*, namely, *Self-heating without release and Self-heating following release* is not applicable. Figure 32 below shows the two sub-categories captured in Level 4.

Figure 32: Level 4: Sub-categories for Ignition of dangerous goods that is not properly declared and Ignition of dangerous goods that is properly declared.

Level 5:
The last level of the prevention fault tree are the bottom nodes that constitute the initiating events. As indicated by the mutually exclusive OR-gates, each of the initiating events can by themselves cause the top event (*Fire inside containerized unit*). The bottom nodes are further described below.

For *External ignition source* there are five bottom nodes:
- *Fire in reefer component.* This node covers events where there is a fire in a reefer component which spreads from the reefer component to the goods causing ignition. This node should also consider other potential external fires in the cargo.
- *Fire in ship adjacent to containerized unit.* This node covers events where a fire adjacent to a containerized unit causes goods inside to ignite. For example, fires in engine room, accommodation, and workshops.
- *Spark/flames.* This node covers events where sparks, flames, or splinters due to hot works, sparks from the funnel, smoking, or failure of -explosion proof equipment etc., can cause ignition. It should be noted that ignition sources that are covered by *sparks* have, in general, relatively low energy. Therefore, these ignition sources are mostly relevant when there is presence of goods that require relatively low ignition energy. For example, it could be accumulation of flammable gases due to failure of ventilation.
- *Lightning.* This node covers events where a lightning bolt causes ignition of goods.
- *Other*. This node covers all other ignition sources such as friction between goods.

Figure 33 below captures Level 5 which shows the five bottom nodes which are initiating events for *External ignition sources.*

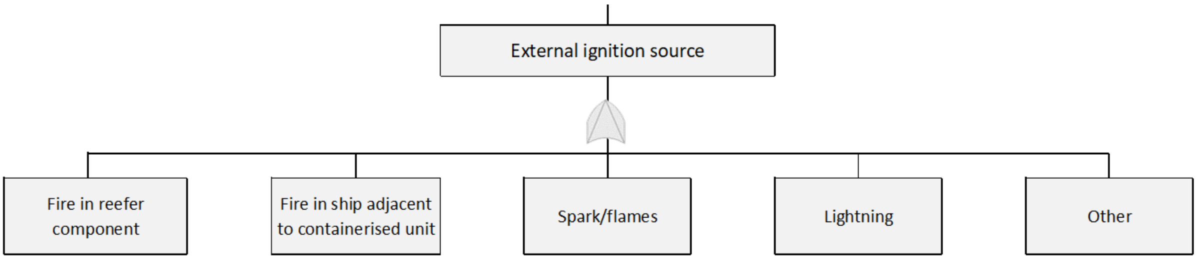
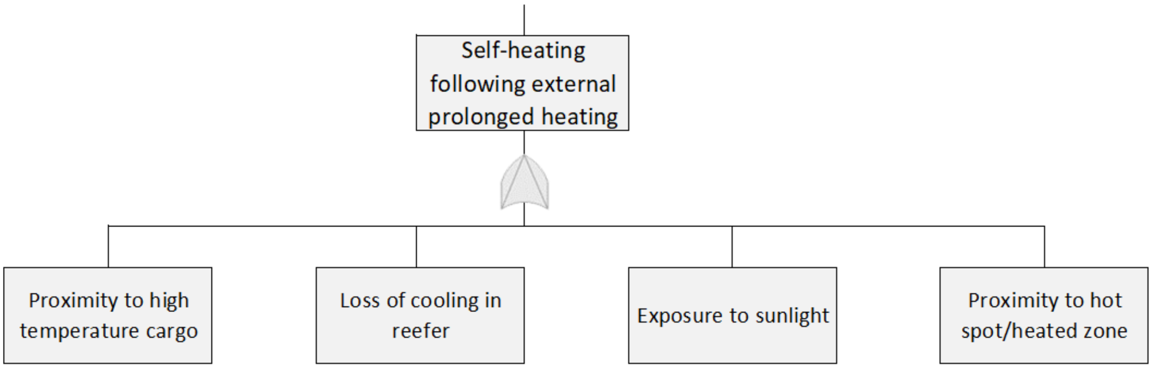


Figure 33: Level 5: The five bottom nodes for External ignition sources.

For *Self-ignition\Self-heating following external prolonged heating* there are four bottom nodes:

- *Proximity to high temperature cargo.* This node covers events where goods can self-ignite due to self-heating from proximity to a high temperature cargo.
- *Loss of cooling in reefer.* This node covers events where there is a power loss or damage in a reefer. This may lead to higher temperatures inside the container than intended, causing the goods stored inside to ignite.
- *Exposure to sunlight.* This node covers events where a container is exposed to sunlight, causing high enough temperatures inside the container to initiate a self-heating process that leads to self-ignition of the goods inside. This node is not applicable for *Ignition of dangerous goods that are properly declared* because it is then assumed that the dangerous goods that are properly declared are in compliance with the IMDG Code for Dangerous Goods. This means if they are packed, stowed, and placed according to the IMDG Code, then, they are not expected to be exposed to sunlight.
- *Proximity to hot spot/heated zone.* This node covers events where heat from proximity to a hot spot/heated zone/heated space causes containerized goods to self-heat leading to ignition. This node is not applicable for *Ignition of dangerous goods that is properly declared,* because it is then assumed that the dangerous goods that are properly declared are in compliance with the IMDG Code for Dangerous Goods. This means, if they are packed, stowed, and placed according to the IMDG Code, then, they are not expected to be placed in proximity to hot spot/ heated zone/ heated space.

Figure 34 below captures Level 5 which shows the four bottom nodes which are initiating events for *Self-ignition\Self-heating following external prolonged heating.*



There is one bottom node linked directly to *Self-ignition\Self-heating without external prolonged heating as listed below*:

- *Water ingress*. This node covers events where water gets inside a container and reacts with goods inside or enables self-heating of the goods inside which finally leads to their ignition. While in some cases, when water gets inside a container, it may react with the goods, in others, the water inside causes self-heating of the containerized goods by heat of adsorption, or it may enable other reactions, or cause microbial growth/activity. An example of goods that may react with water is DRI. Water ingress can happen due to for example crushing while onboard, too heavy loading on top (e.g., due to misdeclaration or mistake in cargo handling), damaged or non-sealed container, previously attained damage, or damage during container handling. The condition of the container is an affecting condition for this event. Condition of the container is of high relevance for this node because events covered under this node does not require any release of the goods. Instead, damage to the container which can cause water to get inside the container meaning water ingress is considered here.

Figure 34: Level 5: The four bottom nodes for Self-ignition\Self-heating following external prolonged heating.

For the sub-category *Self-ignition\Self-heating without release,* there are three bottom nodes:

- *Insulation effect.* This node covers events where there is an insulation effect inside the container, causing self-heating of the goods. For example, insulation effect can occur due to poor packaging when the packaging is not in compliance with the IMDG Code. Thus, insulation effect is caused when heat is trapped inside a container leading to self-heating which finally leads to self-ignition. However, this node does not cover heating between containers since that is included under a separate node namely, *External ignition source\Proximity to self-heating cargo*. This node is not applicable for *Ignition of dangerous goods that is properly declared,* because it is then assumed that the dangerous goods that are properly declared are in compliance with the IMDG Code for Dangerous Goods. This means, if they are packed, stowed, and placed according to the IMDG Code, then, they are not expected to be packed poorly, or placed or stowed poorly which can cause an insulation effect.
- *Goods not sufficiently cooled before packing.* This node covers events where when if goods are packed before they are sufficiently cooled, it can lead to their self-heating finally leading to their self-ignition.
- *Degradation/ Other.* This node covers events where there is a degradation of the goods, causing self-heating of the goods finally leading to their self-ignition. Typical examples of degradation and/or ageing include when the goods are forgotten or left behind for a long time under poor conditions. When they are stored longer than their shelf-life, it causes formation of radicals/consumed stabilizers/ antioxidants which further lead to self-heating of the goods that finally leads to their self-ignition. It also covers ageing or flaws in lithium-ion batteries causing thermal runaway of the batteries leading to self-ignition.

For the sub-category *Self-ignition\Self-heating following release,* there are three bottom nodes:

- *Poor quality of packaging.* This node covers events where the quality of the packaging material and/or the procedure (manner) of packaging does not comply with the IMDG code of DG regulation even though there may be sufficient dunnage of the goods inside a container. Thus, this node covers events where the packaging quality is poor, or the packaging material is poor which causes a release of self-ignitable goods that leads to ignition. Events such as air ingress due to poor quality of packaging of self-ignitable goods leading to self-ignition are also included here.
- *Extreme mechanical stress.* This node covers events where a release of self-ignitable goods can occur due to mechanical stress exceeding what can be expected during normal operations. For example, this could be due to crushing, poor container handling, or that a container shifts due to poor lashing or bad weather.
- *Insufficient dunnage of goods.* This node covers events where release of self-ignitable goods can occur during normal operation due to insufficient dunnage of the goods inside a container.

Figure 35 below captures Level 5 which shows all seven bottom nodes which are initiating events for *Self-ignition\Self-heating without external prolonged heating.*

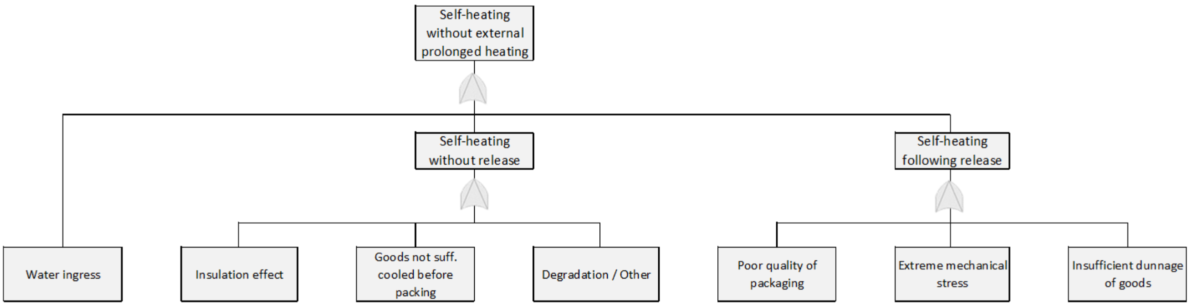


Figure 35: Level 5: All seven bottom nodes under Self-ignition\Self-heating without external prolonged heating.

Ignition of non-dangerous goods:
For *Ignition of non-dangerous goods*, the main ignition category *Self-ignition* is reduced. This is because many of the failure modes relating to self-ignition are not applicable if the goods are non-dangerous according to the IMDG Code. Although, there are instances when self-heating of non-dangerous goods classified according to the IMDG Code may lead to self-ignition. The test methods currently in use for self-heating substances was originally developed for charcoal and is therefore not applicable to all materials. This is currently an operational, scientific as well as a knowledge gap which needs to be addressed. Furthermore, there is a quantity aspect related to dangerous goods in the IMDG Code. If packed in smaller quantities, certain goods such as Li-ion batteries does not need to be declared as dangerous goods. Based on this, the *Self-ignition* category stops at Level 2 for *Ignition of non-dangerous goods.*

Prevention fault tree: Overview of bottom nodes

Table 1Table 13 below gives an overview of the bottom nodes of the prevention fault tree and where they are applicable.

Table 13: An overview of bottom nodes in prevention fault tree and where they are applicable.

Nodes	Ignition of DG that is not properly declared	Ignition of DG that is properly declared	Ignition of non-DG	Above deck	Below deck
External ignition source\Fire in reefer component	X	X	X	X	X
External ignition source\ Fire in ship adjacent to containerized unit	X	X	X	X	X
External ignition source\ Spark/flames	X	X	X	X	X
External ignition source\Lightning	X	N/A	X	X	N/A
External ignition source\Other	X	X	X	X	X
Self-ignition	N/A	N/A	X	X	X
Self-ignition\ Self-heating following external prolonged heating\ Proximity to high temperature cargo	X	X	N/A	X	X
Self-ignition\ Self-heating following external prolonged heating\ Loss of cooling in reefer	X	X	N/A	X	X
Self-ignition\ Self-heating following external prolonged heating\ Exposure to sunlight	X	N/A	N/A	X	N/A
Self-ignition\ Self-heating following external prolonged heating\ Proximity to hot spot/heated zone	X	N/A	N/A	X	X
Self-ignition\Self-heating without external prolonged heating\Water ingress	X	X	N/A	X	X
Self-ignition\Self-heating without external prolonged heating\ Self-heating without release\insulation effect	X	N/A	N/A	X	X
Self-ignition\Self-heating without external prolonged heating\ Self-heating without release\goods not suff. Cooled before packing	X	N/A	N/A	X	X
Self-ignition\Self-heating without external prolonged heating\ Self-heating without release\degradation/other	X	X	N/A	X	X
Self-ignition\Self-heating without external prolonged heating\ Self-heating following release\ Poor quality of packaging	X	N/A	N/A	X	X
Self-ignition\Self-heating without external prolonged heating\ Self-heating following release\ Extreme mechanical stress	X	X	N/A	X	X
Self-ignition\Self-heating without external prolonged heating\ Self-heating following release\ Insufficient dunnage of goods	X	N/A	N/A	X	X

3.6.1.4 Qualitative assessment of the prevention fault tree(s)

Level 1 of the prevention fault tree is quantified using containership accident statistics. The lower levels (Level 2-Level 5) have not been quantified, but rather qualitatively assessed. The purpose of this assessment is to map the failure pathways in the fault tree with respect to the three most common initial fuels causing fire hazards onboard containerships, according to the statistics identified in CARGOSAFE. These initial fuels are lithium-ion batteries, charcoal, and calcium hypochlorite. For a more in-depth assessment, another type of high fire risk goods is also considered, namely Divinylbenzene (DVB). Divinylbenzene (DVB) and has been identified as a potential cause of the fire onboard MSC Flaminia in 2012 (See accident report [18]). In addition, there are other fuels that have cause fires onboard containerships according to accident reports. Table 14 below shows some of these initial fuels and the accidents onboard containerships that they have been involved in.

Table 14: Containership fire accidents and causing initial fuels. The location on deck (OD) or below deck (BD) is included.

Name of vessel (year of incident)	OD/BD	Initial fuels
CMA CGM Rossini (2016)	BD	Lithium-ion batteries
Caroline Maersk (2015)	BD	Charcoal
MSC Katrina (2015)	BD	Charcoal
Ludwigshafen Express (2016)	OD	Charcoal
Kitano (2001)	OD	Activated carbon pellets
Charlotte Maersk (2010)	OD	Methyl ethyl ketone peroxide (MEKP)
Zim Rio Grande (2012)	OD	Thiourea dioxide
MSC Flaminia (2012)	BD	Uncertain
Yantian Express (2019)	OD	Coconut charcoal

The qualitative assessment is performed in two steps. The first step is performed by conducting a workshop with experts within the CARGOSAFE consortia held on 28th of March 2022. The participating experts covered the areas of operational aspects of containerships, self-heating, containership accidents, and fire safety. In addition to the workshop, further inputs on lithium-ion batteries were sought through discussions with battery fire safety experts. In the second step, in addition to the expert workshop on failure pathways, references are made to accident literature and the IMDG Code when applicable, especially in absence of any expert input to failure pathways or initial fuels leading to fire hazard onboard containerships. The result of the assessment is presented in Table 15 below called Summary of qualitative assessment for the prevention fault tree(s).

[18] BSU. (2014). Investigation Report 255/12 Fire and explosion on board the MSC FLAMINIA on 14 July 2012 in the Atlantic the ensuing events.

Table 15: Summary of qualitative assessment for the prevention fault tree(s).

Initiating fuel	Mapped out during expert workshop	Supporting literature
External ignition source\Fire in reefer component		
Not relevant for any of the initial fuels		
External ignition source\ Fire in ship adjacent to containerized unit		
Li-ion	X	
Charcoal	X	
$Ca(ClO)_2$	X	
DVB	N/A	
External ignition source\ Spark/flames		
Li-ion	X	
Charcoal	X	
$Ca(ClO)_2$	X	According to the IMDG Code, calcium hypochlorite and similar substances shall "be placed in adequately ventilated areas" (Source: [19]). Failure of ventilation leading to accumulation and ignition of flammable gases are included in this node.
DVB		DVB is prone to polymerization which can generate heat and flammable gases. In the presence of an ignition source, the generated gas can explode (Source: [20]).
External ignition source\Lightning		
Li-ion	X	
Charcoal	X	
$Ca(ClO)_2$	X	
DVB		See note under *External ignition source\ Spark/flames*
External ignition source\Other		
Li-ion	X	
Charcoal	X	
$Ca(ClO)_2$	X	
DVB		See note under *External ignition source\ Spark/flames*
Self-ignition\ Self-heating following external prolonged heating\ Proximity to high temperature cargo		
Li-ion		See note under *Self-ignition\ Self-heating following external prolonged heating\ Exposure to sunlight*
Charcoal	X	
$Ca(ClO)_2$	X	According to the IMDG Code, calcium hypochlorite and similar substances shall be "shaded from direct sunlight and all sources of heat" (Source: [21]). This makes calcium hypochlorite relevant for failure modes involving increased ambient temperatures.
DVB		When chemical inhibitors are used to stabilize substances such as DVB, the effectiveness relies on the temperatures not being too high and that the journey time is no longer than the time that the chemical inhibitor remains effective (Source: [22]). This makes DVB relevant for failure modes involving increased ambient temperatures.

[19] IMO. (2020) International Maritime Dangerous Goods Code 2020 Edition (inc. Amendment 40-20) P. 207-208, chapter 3.3, 314.
[20] CINS, International Group of P&I Clubs, and TT Club. (2019). Guidelines for the Carriage of Divinylbenzene in Containers. P. 4.
[21] IMDG Code, chapter 3.3, 314; IMO. (2020) International Maritime Dangerous Goods Code 2020 Edition (inc. Amendment 40-20). P. 207-208.
[22] IMDG Code; IMO. (2020) International Maritime Dangerous Goods Code 2020 Edition (inc. Amendment 40-20). P. 218.

Self-ignition\ Self-heating following external prolonged heating\ Loss of cooling in reefer		
Li-ion	N/A	
Charcoal	N/A	
$Ca(ClO)_2$		Calcium hypochlorite may be transported in reefers at 10 °C. If so, then loss of cooling in the reefer can lead to accumulation of heat produced by calcium hypochlorite decomposition. Loss of cooling for longer periods of time increases the risk of calcium hypochlorite heating up faster.
DVB		DVB may be stabilized using temperature control (Source: [23] [24]). When temperature control is used to stabilize substances such as DVB, loss of cooling may lead to instability of the substance.
Self-ignition\ Self-heating following external prolonged heating\ Exposure to sunlight		
Li-ion	X	The onset temperature of abnormal heat generation for lithium-ion batteries has been observed to be around 70-150°C. However, observations of exothermic reaction at temperatures around 50 °C are also reported (Source: [25]). In an investigation report for the accident onboard Zim Rio Grande in 2012, it was hypothesized that containers on deck had reached a temperature of around 50°C (Source: [26]). In an investigation report for the accident onboard X-Press Godavari in 2020, it is hypothesized that exposure to sunlight was a contributing factor to a fire starting in a container carrying lithium-ion batteries (Source: [27]). It is unlikely that the temperatures onboard would be high enough to create exothermic reactions leading to a fire in transported lithium-ion batteries, but not unthinkable, especially when considering prolonged heating.
Charcoal	X	
$Ca(ClO)_2$	X	See note under *Self-ignition\ Self-heating following external prolonged heating\ Proximity to high temperature cargo*
DVB		See note under *Self-ignition\ Self-heating following external prolonged heating\ Proximity to high temperature cargo*
Self-ignition\ Self-heating following external prolonged heating\ Proximity to hot spot/heated zone		
Li-ion	N/A	See note under *Self-ignition\ Self-heating following external prolonged heating\ Exposure to sunlight*
Charcoal	Not available	
$Ca(ClO)_2$	X	See note under *Self-ignition\ Self-heating following external prolonged heating\ Proximity to high temperature cargo*
DVB		When chemical inhibitors are used to stabilize substances such as DVB, the effectiveness relies on the temperatures not being too high and that the journey time is no longer than the time that the chemical inhibitor remains effective (Source: [28]).
Self-ignition\Self-heating without external prolonged heating\Water ingress		
Li-ion	X	According to discussions with battery fire safety experts, if the lithium-ion battery cells get in contact with salt water, they can be damaged, causing unwanted reactions.
Charcoal	N/A	
$Ca(ClO)_2$	X	
DVB	N/A	
Self-ignition\Self-heating without external prolonged heating\ Self-heating without release\insulation effect		

[23] CINS, International Group of P&I Clubs, and TT Club. (2019). Guidelines for the Carriage of Divinylbenzene in Containers. P. 5.
[24] IMO. (2020) International Maritime Dangerous Goods Code 2020 Edition (inc. Amendment 40-20). P.218.
[25] X. Feng, S. Zheng, D. Ren, X. He, L. Wang, H. Cui, X. Liu, C. Jin, F. Zhang, C. Xu, H. Hsu, S. Gao, T. Chen, Y. Li, T. Wang, H. Wang, M. Li, and M. Quyang, (2019). "Investigating the thermal runaway mechanisms of lithium-ion batteries based on thermal analysis database," Applied Energy, vol. 246, pp. 53-64.
[26] Marine Safety Investigation Unit, and Transport Malta. (2013). Report No.: 11/2013 MV ZIM RIO GRANDE. P. 3.
[27] Marine Safety Investigation Unit, and Transport Malta. (2021). Report No.: 21/2021 MV X-PRESS GODAVARI. P. 6-8.
[28] IMO. (2020) International Maritime Dangerous Goods Code 2020 Edition (inc. Amendment 40-20). P. 21.

Li-ion	X	
Charcoal	X	The self-heating properties of charcoal in combination with charcoal being a relatively good thermal insulator may cause a cycle of heating leading to self-ignition (Source: [29]).
$Ca(ClO)_2$	X	Calcium hypochlorite decomposes and releases heat at different rates depending on temperature. At higher temperatures, the rate of decomposition increases. If the released heat is not able to escape from within the material, it can create a cycle of increased decomposition and temperature (Source: [30]).
DVB		When chemical inhibitors are used to stabilize substances such as DVB, the effectiveness relies on the temperatures not being too high and that the journey time is no longer than the time that the chemical inhibitor remains effective (Source: [31]).
Self-ignition\Self-heating without external prolonged heating\ Self-heating without release\goods not suff. Cooled before packing		
Li-ion	Not available	
Charcoal	X	According to the IMDG code, charcoal should be cooled down to ambient temperature before packing (Source: [32]).
$Ca(ClO)_2$	N/A	
DVB	N/A	
Self-ignition\Self-heating without external prolonged heating\ Self-heating without release\degradation/other		
Li-ion	X	This node covers ageing or flaws in lithium-ion batteries causing thermal runaway.
Charcoal	N/A	
$Ca(ClO)_2$	N/A	
DVB		If chemical inhibitors are used to stabilise substances such as DVB, aging of the goods (for example due to the goods having been left in port for a long time under poor conditions) increases the risk of exceeding the time that the chemical inhibitor remain effective.
Self-ignition\Self-heating without external prolonged heating\ Self-heating following release\ Poor quality of packaging		
Li-ion	X	The IMDG Code has requirements regarding the packaging of lithium-ion batteries (IMDG Code, Dangerous goods list). If these requirements are not met, especially for damaged batteries, it can increase the fire risk.
Charcoal	Not available	
$Ca(ClO)_2$	X	
DVB		DVB is prone to polymerization which can generate heat. The polymerisation can be initiated if DVB comes into contact with air (Source: [33] [34]). Events causing release of DVB so that it gets in contact with air may therefore increase the fire risk onboard.
Self-ignition\Self-heating without external prolonged heating\ Self-heating following release\ Extreme mechanical stress		
Li-ion	X	
Charcoal	Not available	

[29] CINS, and International Group of P&I Clubs. (2017). Guidelines for the Carriage of Charcoal and Carbon in Containers. P. 3.
[30] CINS, and International Group of P&I Clubs. (2016). Guidelines for the Carriage of Calcium Hypochlorite in Containers. P. 3.
[31] IMO. (2020) International Maritime Dangerous Goods Code 2020 Edition (inc. Amendment 40-20). P. 218.
[32] IMO. (2020) International Maritime Dangerous Goods Code 2020 Edition (inc. Amendment 40-20). P. 61 IMDG Code, DGL list, 1361.
[33] BSU. (2014). Investigation Report 255/12 Fire and explosion on board the MSC FLAMINIA on 14 July 2012 in the Atlantic the ensuing events. P. 71.
[34] CINS, International Group of P&I Clubs, and TT Club. (2019). Guidelines for the Carriage of Divinylbenzene in Containers. P.4.

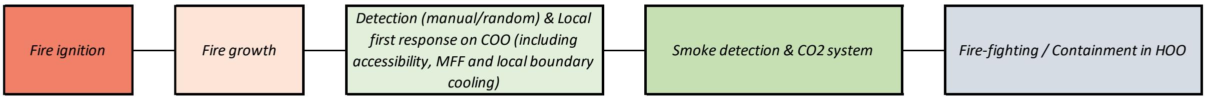
$Ca(ClO)_2$	X	
DVB		See note under *Self-ignition\Self-heating without external prolonged heating\ Self-heating following release\ Poor quality of packaging*
Self-ignition\Self-heating without external prolonged heating\ Self-heating following release\ Insufficient dunnage of goods		
Li-ion	X	
Charcoal	Not available	
$Ca(ClO)_2$	X	
DVB		See note under *Self-ignition\Self-heating without external prolonged heating\ Self-heating following release\ Poor quality of packaging*

Based on the expert workshop, review of available accident literature and IMDG Code, presented above, reflections on some of the bottom nodes are made below.

- ***Self-ignition\Self-heating without external prolonged heating\Water ingress*:**
  Experts during the validity assessment workshop summarized that since cargo hatches are not watertight, rain/sea spray/waves might get inside the cargo hold below deck. Thus, it is reasonable to consider that the containers below deck could be affected by water ingress. It would mostly be the containers in the bottom tier of the cargo hold that would be affected by water ingress, since water would accumulate at the bottom of the cargo hold. However, this means that water ingress as a bottom node below deck has a lower probability than above deck. Furthermore, according to our discussion with battery fire safety experts, it was pointed out that since batteries are typically shipped with a low state of charge and have requirements about packaging, the likelihood of this occurrence is uncertain.
- ***External ignition source\Lightning:***
  Lightning is an event that was perceived to be extremely rare during the expert workshop. This is due to the presence of lightning rods above deck that can absorb the lightning strike. However, removal of the bottom node was not considered as assigning very low probability was agreed to be the best way forward in the prevention fault tree.
  The expert input during the workshop also resulted in some smaller updates of the prevention fault trees. For example, inputs were received that the bottom node External ignition source\Lightning is not applicable if the dangerous goods is properly declared since the container would not be stored on top of the tier in that case. Hence, this bottom node was made not applicable for the fault tree under Ignition of dangerous goods that is properly declared. The final fault trees for prevention are presented in Annex D for prevention fault trees.
- ***External ignition source\Fire in reefer component:***
  During the discussions in the expert workshop in Task 2 and during the Prevention HAZID in Task 1, it was pointed out that fire in reefer component as an external ignition source is extremely rare. Although, several operators concurred that fire in refer component may be common, however the size of this fire is so small that it mostly dies out due to lack of oxygen inside the reefer component. Therefore, as the best way forward, it was agreed to refer this node as still relevant, however, to be extremely unlikely. No relevant initial fuels were mapped for this bottom node.
- ***External ignition source\ Fire in ship adjacent to containerized unit:***
  During the discussions in the expert workshop, it was pointed out that events arising from this node are reportedly extremely rare, although most initial fuels were mapped to be relevant should there be such a failure. Therefore, as the best way forward, it was agreed to refer this node as still relevant, however, to be extremely unlikely.

As mentioned earlier, the qualitative assessment identified the relevant failure pathways for the three most common initial fuels in previous containership fire accidents, namely, Li-ion batteries, charcoal, calcium hypochlorite and some other high fire risk goods such as DVB. The assessment showed that all three initial fuels are well represented in the prevention fault tree through several relevant failure pathways. This demonstrates the validity of the developed prevention fault tree. However, it should be noted that since the nature of the assessment is qualitative and partly based on expert judgement, this may entail some uncertainty in the results. Statistical evidence would deepen this assessment. Keeping this limitation in mind, support from accident literature, technical reports and IMDG Code was taken to strengthen the assessment.

3.6.2 In Hold – Description of the nodes



The different tiers of the risk model for a cargo fire originating in a hold are described in this part. The chain of events considered in the study is displayed in Figure 36 The whole firefighting event tree is presented in .

In this timeline, the following applies:

- COO stands for Container Of Origin (i.e. the container where the fire initiates).

Figure 36: Chain of events in case of a cargo fire starting in the hold.

- MFF stands for Manual Firefighting.
- HOO stands for Hold Of Origin (i.e. the hold where the container of origin is located).

This chain of events allows the identification of pivotal events which affect the outcome of different cargo fire scenarios in hold.

3.6.2.1 Tier 0 – Fire ignition

The initial event of the in-hold risk model is the ignition of a fire in a container inside the hold. Unlike the other nodes of the risk model, the quantified value fire ignition is not a conditional probability expressed in %, but a frequency expressed in ignition per shipyear. It is determined using the frequency of fire per shipyears (based on following equation), and finally the proportion of fire starting in the hold (59% according to paragraph 3.3.2.1):

$$f_{ignition}(fires\ in\ hold\ per\ SY) = f_{ignition}(fires\ per\ SY) * \frac{N_{FiresInHold}}{N_{Fires}}$$

The proportion of Declared/Misdeclared/Undeclared dangerous goods is taken into consideration in the calculation of the frequency, and hence will not be displayed in the coming event trees.

3.6.2.2 Tier 1 – Fire growth

This tier splits the firefighting event tree into three branches: slow fire, fast fire and fire initiating by an explosion. The definition of the fire growth here is not to be confused with the common description of fire growths in fire safety engineering (“T-squared” fires).
In this tier:

- A *Slow fire* is to be understood as a fire having a growing phase which can take from hours to days (e.g., charcoal, cellulosic materials, pellets, etc.). The heat release rate is controlled by the poor ventilation of a container and the limited amount of oxygen inside.
- A *Fast fire* is to be understood as a fire having a growing phase ranging from seconds to one hour (e.g., lithium batteries, flammable dangerous goods, self-oxidizing materials, etc.).
- An *Explosion leading to fire* is self-explanatory.

These three categories were created based on the three most represented sources of ignition in the database, often linked to three distinct scenarios: charcoal (slow), lithium-ion batteries (fast) and calcium hypochlorite (explosion).
It is to be noted that, self-extinguishing fires are not accounted for in the database, as well as explosions not leading to fires.

3.6.2.3 Tier 2 – Detection (manual/random) & Local first response on Container Of Origin (COO) (including accessibility, manual fire-fighting (MFF) and local boundary cooling)

Early detection of a fire and quick activation of the fire extinguishing means if often cited as the key to successful extinguishment. The purpose of having a faster detection in the hold would be to offer the possibility to do local firefighting (i.e., before the hold is full of smoke), to tackle it by manual means, to try to extinguish it without having to use stronger means. This is why Detection and Local first response on the container of origin (COO) have been

merged together. Local first response includes accessibility to the COO, manual firefighting inside the COO, and local boundary cooling of the COO (containment of the fire to the COO only).
It should be noted that currently early fire detection leading to possible local first response on COO is mostly based on random detection (crew member on round patrol for DG checks or reefer checks inside the hold, etc.) rather than automatic detection based on sample smoke extraction detection systems installed in the hold (which activation needs a certain amount of smoke in the hold). In practice, the common approach is to prevent crew from going inside the hold when the fire is detected. The presence of this node in the risk model is to anticipate the possibility of future solutions allowing for faster detection leading to possible local fire fighting in hold and faster CO_2 release.
In this context, a *Successful* Detection & Local first response on COO means that the fire has been detected early enough to allow for a successful local first response (fire extinguished or contained to the container of origin). *Unsuccessful* means either no detection happens (other than automatic detection and without considering future solutions) and/or manual firefighting on the container of origin is not possible, attempted, or successful.

3.6.2.4 Tier 3 – Smoke detection & CO_2 system

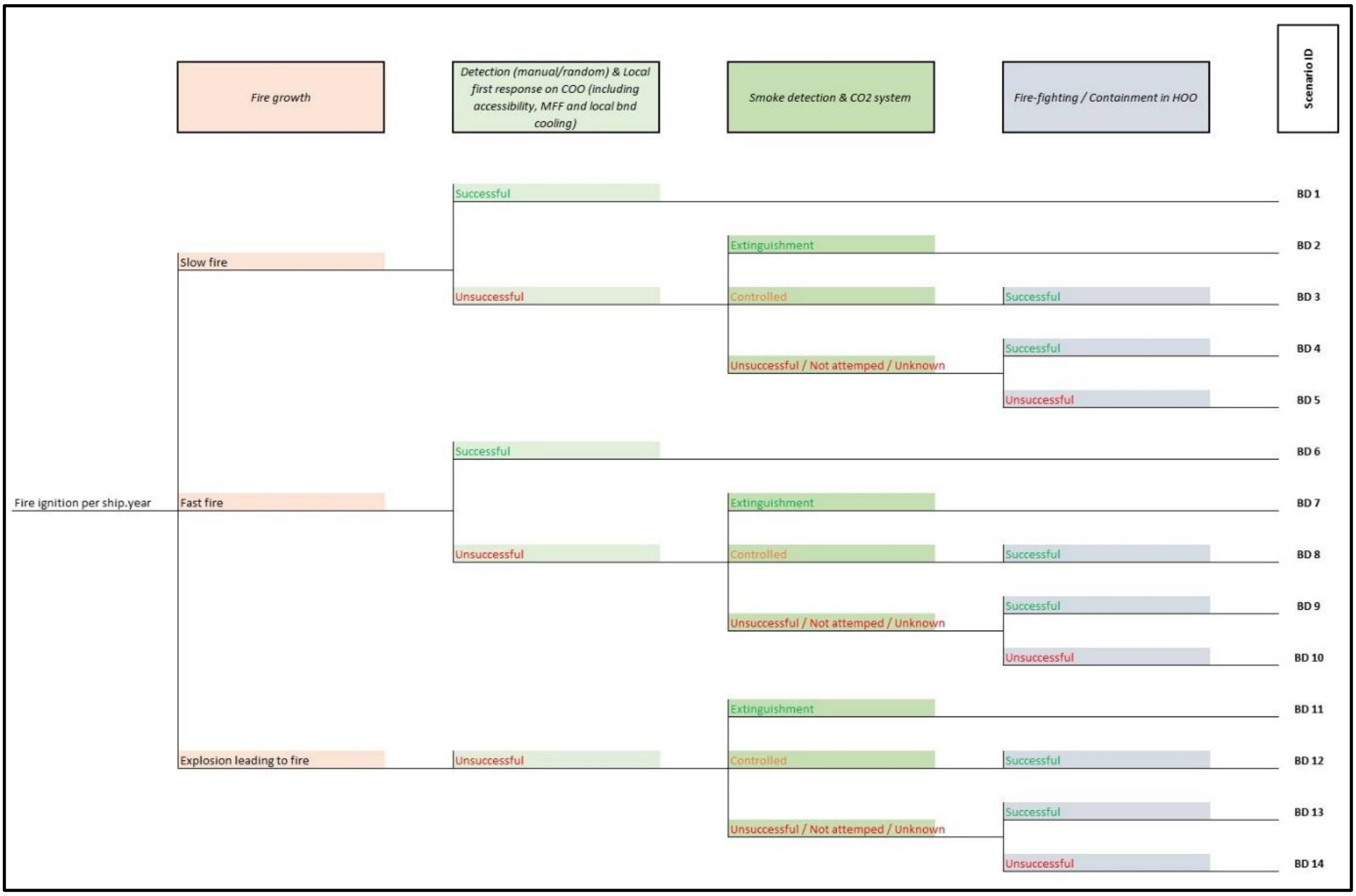
Automatic detection of smoke through the sample smoke extraction detection system in the hold would mean that a certain amount of smoke has been released. In this situation, for the reason explained before, sending people inside the hold to fight the fire is unlikely. Rather, the activation of the CO_2 system following an automatic smoke detection in the hold is more likely to happen. The same philosophy applies on this tier: the earlier the fire is detected, the earlier the decision to activate the CO_2 system, the more efficient the CO_2 system is likely to be. This is why Smoke detection & CO_2 system have been merged together.
As shown in Figure 23, 90% of the accidents involving a fire in the hold, an attempt to fight the fire with CO_2 is carried out. Thus, the CO_2 success or failure is a critical element for the determination of the subsequent consequences.

Three outcomes were taken into account in the risk model: *Extinguishment*, which means the fire is totally out and no assistance is required; *Controlled*, when the fire stops to spread and is brought under control but not totally out; and *Unsuccessful/Not attempted/Unknown*, when neither extinguishment nor suppression happened, or when no data is available in the CARGOSAFE database concerning the use of the CO_2 system. This latest assumption on unknown cases tends to increase the probability of failure of the CO_2 system. However, there is currently a doubt on the efficiency of such systems agreed by the different maritime stakeholders. This assumption has been made to reflect this doubt. In the sensitivity analysis, this probability should not be tested at higher value.

3.6.2.5 Tier 4 – Fire-fighting – Containment in Hold Of Origin (HOO)

In the case where the CO_2 failed extinguishing the fire, two outcomes were considered. First, the fire is contained to the hold where it originated (hold of origin). This containment is mainly due to the hold structure and the boundary cooling procedures, as well as water spray for holds designed to carry dangerous goods. In this case, the containment in the HOO is *Successful*. If the fire propagates to adjacent spaces (other holds and/or above deck), the containment is *Unsuccessful.*

It is to be noted that use of CO_2 system and boundary cooling procedures can have been used for fire-fighting operations. When the information on the efficiency of the CO_2 system is available in the CARGOSAFE database, the risk model reflects it first (e.g., if the fire is said to be extinguished by the CO_2 system, even if boundary cooling occurred, the risk model considers a successful extinguishment of the fire by the CO_2 system only).



3.6.3 On Deck – Description of the nodes

The different tiers of the risk model for a cargo fire originating on a deck are described in this part. The chain of events considered in the study is displayed in Figure 38 The whole firefighting event tree is presented in Figure 39.

Figure 38: Chain of events in case of a cargo fire starting on the deck.

In this timeline, the following applies:

- COO stands for Container Of Origin (i.e. the container where the fire initiates).
- MFF stands for Manual Firefighting.

This chain of events allows the identification of pivotal events which affect the outcome of different cargo fire on deck scenarios.

3.6.3.1 Tier 0 – Fire ignition

Figure 37: Structure of the firefighting event tree, for fire occurring in the hold.

The initial event of the on-deck risk model is the ignition of a fire in a container on a deck. Unlike the other nodes of the risk model, the quantified value fire ignition is not a percentage, but a frequency. It is determined using the frequency of fire per shipyears, and finally the proportion of fire starting on deck (41% according to paragraph 3.3.2.1):

$$f_{ignition}(fires\ per\ SY) = f_{ignition}(fires\ per\ SY) * \frac{N_{FiresOnDeck}}{N_{Fires}}$$

3.6.3.2 Tier 1 – Fire growth

This tier splits the firefighting event tree into three branches: slow fire, fast fire and fire initiating by an explosion. The definition of the fire growth here is not to be confused with the common description of fire growths in fire safety engineering ("T-squared" fires).
In this tier:

- A *Slow fire* is to be understood as a fire having a growing phase which can take from hours to days (e.g., charcoal, cellulosic materials, pellets). The heat release rate is controlled by the poor ventilation of a container and the limited amount of oxygen inside.
- A *Fast fire* is to be understood as a fire having a growing phase ranging from seconds to one hour (e.g., lithium batteries, flammable dangerous goods, self-oxidizing materials).
- An *Explosion leading to fire* is self-explanatory.

These three categories were created based on the three most represented sources of ignition in the database, often linked to three distinct scenarios: charcoal (slow), lithium-ion batteries (fast) and calcium hypochlorite (explosion).
It should be noted that self-extinguishing fires are not accounted for in the database, as well as explosions not leading to fires.

3.6.3.3 Tier 2 – Detection & Local first response on Container Of Origin (COO) (including accessibility, manual fire-fighting (MFF) and local boundary cooling)

On deck, automatic detection system is not required by the regulations. Detection and localization are done manually (view, smell, touch). Unlike a fire in a hold, when detected, the approach is to send a firefighting team to tackle a fire on a deck. This is why Detection and Local first response on the COO on deck have been merged together. Local first response includes accessibility to the COO, manual firefighting inside the COO, and local boundary cooling of the COO (containment of the fire to the COO only).
Although, the success of such an operation greatly depends on how early the fire was detected. The definition of "early" depends here on the type of fire considered. A slow fire will remain in an early phase longer than a fast fire, due to its lower growing phase. A fire caused by an explosion is considered not to have an early phase at all (so only late detection and no possibility to attempt a local first response on the COO).
In this context, a *Successful* Detection & Local first response on COO means that the fire has been detected early enough to allow for a successful local first response (fire extinguished or contained to the container of origin). *Unsuccessful* means the fire has spread to at least adjacent containers in the bay of origin.
The Local first response on COO can be done by mist lances or COO boundary cooling.

3.6.3.4 Tier 3 – Firefighting – First bay boundary cooling

In the case where the fire could not be tackled by a local first response, and hence spreads out of its container of origin, two outcomes are possible: either the fire is contained in its bay of origin -*Successful*- which is achieved by use of hoses and/or water mobile monitors, or the fire spreads to adjacent spaces (other bays and/or potentially below deck), implying more severe consequences. In this case, first bay boundary cooling is *Unsuccessful*.
It is to be noted that local first response and bay boundary cooling procedures can have been used for fire-fighting operations. When the information on the efficiency of the local first response is available in the CARGOSAFE database, the risk model reflects it first (e.g., if the fire is said to be extinguished/controlled on the container of origin, even if bay boundary cooling happened, the risk model considers a successful local first response).

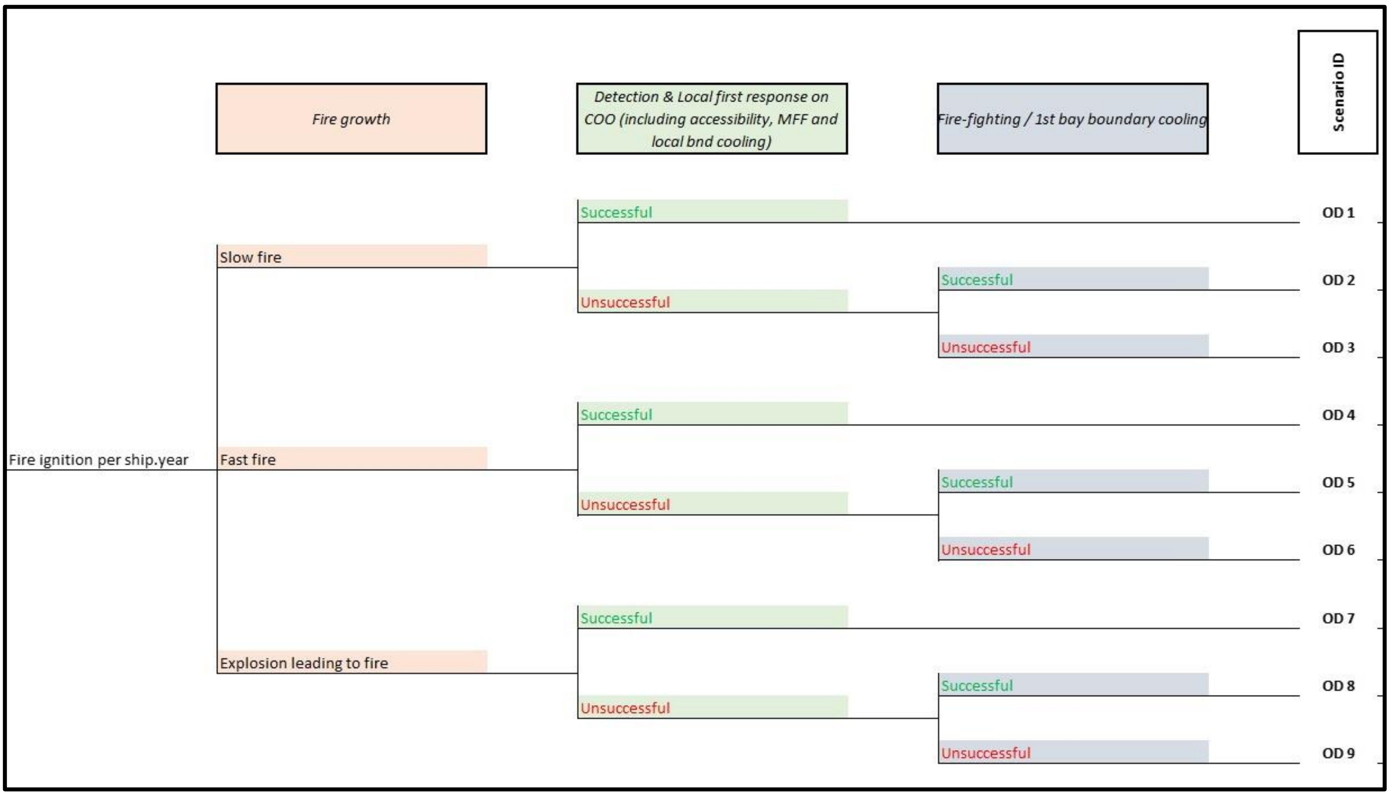


Figure 39: Structure of the firefighting event tree, for fire occurring on deck.

3.7 Quantification of the risk models

This part describes, for each node of the firefighting event trees, how the value used was determined. Among the 124 fire accidents, 116 are fully informed, i.e., contain the information for each node of the event tree. The remaining 8 only account in the frequency calculation.

3.7.1 Rules for quantifications

Quantification of the frequency of cargo fires in hold and on deck, as well as dependent probabilities of the risk models mainly originate from available accident reports and failure data and other sources of information.
In accordance with FSA Guidelines, if statistics were insufficient to produce reliable results, or when deemed appropriate, expert judgements have been used. For each node, the data sources selected are indicated.
One of the biggest questions that occurred during the quantification of the risk model is the choice of the values that shall be correlated with the size of the ship. The choices described below were made:

- The ignition frequency (in fires per shipyear) were considered proportional to the size of the ship (or to be more precise, to the capacity of the ship in TEU). The explanation for this decision is provided in 3.3.1. *Study of the frequencies*. Hence, three ignition frequencies were provided, for Generic Ship 1, for Generic Ship 2, and for Generic Ship 3.
- Some of the consequences linked to each scenario were deemed linked to the size of the ship. This concerns cargo loss and ship loss (a “total loss” on a small feeder will not have the same economic consequences as a “total loss” on an Ultra Large Container Ship).
- Without quantified fault trees that would enable to calculate conditional probabilities of the fire event tree, at this stage, the probabilities are not depending on ship size. This is correct for the median ship (cf. paragraph 3.2.2.2) having median characteristics of the world fleet since the ships present in the casualty database are

similar to the average characteristics of the world fleet. Once RCOs will be tested on three ship sizes, the probabilities depending on ship size should be modified.

3.7.2 Prevention fault trees - Quantification

The first level (level 1) of the prevention fault trees was quantified in Task 2. The lower levels were qualitatively assessed (cf. section 3.6.1.4). Level 1 was quantified using the statistics for ignition presented in Figure 19 and Figure 20 As described in section 3.3.2.1, the unspecified cases can be approached in different ways. For the quantification, it is assumed that the unknown cases are distributed the same way as the "known" cases. This means that the quantification is based on the following statistics:

- 81% of fires caused by dangerous goods.
- 63% of dangerous goods causing a fire being not properly declared.
- 37% of dangerous goods causing a fire being properly declared.
- 19% of fires caused by non-dangerous goods.

Based on this, the proportions for level 1 of the prevention fault trees are:

- *Ignition of dangerous goods that is not properly declared*: 51%.
- *Ignition of dangerous goods that is properly declared*: 30%.
- *Ignition of non-dangerous goods: 19%*.

3.7.3 "In Hold" firefighting event tree - Quantification

3.7.3.1 Tier 0 – Ignition

The ignition frequencies for the median ship and three ship types are:

- Median ship: 5.64E-4 fires/SY
- Gen ship 1: 3.91E-3 fires/SY
- Gen ship 2: 1.63E-3 fires/SY
- Gen ship 3: 7.67E-4 fires/SY

In the remaining nodes, 68 cases have been identified as relevant for further consideration in the "In Hold" event tree. The quantified firefighting event tree "In Hold" for the Median Ship is presented in Annex E.

3.7.3.2 Tier 1 – Fire growth

The proportion of *Slow fire*, *Fast fire* and *Explosion leading to fire* is first of all based on the identification of the combustible of origin of the fire, when known from the CARGOSAFE database.

When the combustible of origin was not specified, expert judgement has been used to identify the fire growth of the remaining accidents based on their consequences (when known) and/or their severity indicator (when known), extracted from the CARGOSAFE database. For such accidents, their identification has been made clear in the database, allowing for taking them into account in the uncertainty and sensitivity analysis.

Finally, the proportions of different fire growths for a cargo fire originating in hold are as follows:

- *Slow fire*: 42.6%.
- *Fast fire*: 35.3%.
- *Explosion leading to fire*: 22.1%.

3.7.3.3 Tier 2 – Detection (manual/random) & Local first response on Container Of Origin (COO) (including accessibility, manual fire-fighting (MFF) and local boundary cooling)

No data were made available in the CARGOSAFE database concerning any successful intervention on the container of origin following a detection of a cargo fire in the hold. Additionally, the discussions with the different maritime stakeholders involved in the TEG concluded that it was very unlikely for the Master to send crew members in the hold in case of automatic detection of smoke.

Therefore, expert judgement was used to quantify the nodes as follows:

- *Slow fire* and *Fast fire*: 99% of *Unsuccessful* Tier 2 event.
- *Explosion leading to fire*: 100% if *Unsuccessful* Tier 2 event.

The influence of this expert judgement will be assessed through the uncertainty and sensitivity analysis.

3.7.3.4 Tier 3 – Smoke detection & CO_2 system

In the CARGOSAFE database, no or few information was made available concerning the early detection of smoke in the cargo hold. For this tier, it has been preferred then to focus quantification on the use or not of the CO_2 system as a mean of firefighting, its reliability, and its efficiency.

When no data is given in the database concerning the CO_2 system (e.g., it is attempted but no information is given on its efficiency, or no information given on any attempt), the unknown cases are accounted for as an *Unsuccessful* attempt of the CO_2 system. For such accidents, their identification has been made clear in the database, allowing for taking them into account in the uncertainty and sensitivity analysis.

For *Slow fire*, the proportions for Tier 2 are given as follows:

- *Extinguishment*: 27.6%.
- *Controlled*: 13.8%.
- *Unsuccessful / Not attempted / Unknown*: 58.6%.

For *Fast fire*, the proportions for Tier 2 are given as follows:

- *Extinguishment*: 12.5%.
- *Controlled*: 8.3%.
- *Unsuccessful / Not attempted / Unknown*: 79.2%.

For *Explosion leading to fire*, the proportions for Tier 2 are given as follows:

- *Extinguishment*: 13.3%.
- *Controlled*: 13.3%.
- *Unsuccessful / Not attempted / Unknown*: 73.3%.

The approach selected here for the unknown cases is conservative. The choice to consider them in the *Unsuccessful* branch is guided by the discussions with the different maritime stakeholders involved in the TEG where the efficiency of the CO_2 system was questioned.

3.7.3.5 Tier 4 – Fire-fighting – Containment in Hold of Origin (HOO)

Information on fire propagation out of the hold of origin is based on the information provided in the CARGOSAFE database.

When not available in the CARGOSAFE database, expert judgement has been used to determine whether the propagation was likely or unlikely, depending on the consequences or the narrative of the event considered. For such accidents, their identification has been made clear in the database, allowing for taking them into account in the uncertainty and sensitivity analysis.

A second expert judgement was introduced for scenarios where accidents available in the database were leading to the same consequences. For such cases, it has been decided to introduce an arbitrary case having the opposite consequence. For example, if 100% of the cases in the database lead to a successful containment, the additional arbitrary case introduced will lead to an unsuccessful containment. This assumption is to cover possible consequences not identified in the database. Those branches have been clearly identified in the firefighting event tree, allowing for taking them into account in the uncertainty and sensitivity analysis.

For *Slow fire* AND *Fast fire* AND *Explosion leading to fire / Smoke detection &* CO_2 *system Controlled*, the proportion for Tier 4 is given as follows:

- *Successful*: 100.0%.

Indeed, in the CARGOSAFE database, when the fire is controlled by CO_2 system, there is no case of failure of containment. Having a fire not contained and controlled by the CO_2 system at the same time makes no sense. This node is “virtual” in the firefighting event tree to keep the information.

For *Slow fire / Smoke detection &* CO_2 *system Unsuccessful / Not attempted / Unknown*, the proportions for Tier 4 are given as follows:

- Successful: 94.4%.
- *Unsuccessful / not used or equipped*: 5.6%.

For *Fast fire / Smoke detection &* CO_2 *system Unsuccessful / Not attempted / Unknown*, the proportions for Tier 4 are given as follows:

- *Successful*: 73.7%.
- *Unsuccessful / not used or equipped*: 26.3%.

For *Explosion leading to fire / Smoke detection &* CO_2 *system Unsuccessful / Not attempted / Unknown*, the proportions for Tier 4 are given as follows:

- *Successful*: 66.7%.
- *Unsuccessful / not used or equipped*: 33.3%.

3.7.4 “On Deck” firefighting event tree - Quantification

3.7.4.1 Tier 0 – Ignition

The ignition frequencies for the median ship and three ship types are:

- Median ship: 3.98E-4 fires/SY
- Gen ship 1: 2.76E-3 fires/SY
- Gen ship 2: 1.15E-3 fires/SY
- Gen ship 3: 5.41E-4 fires/SY

In the CARGOSAFE database, 48 cases have been identified as relevant for further consideration in the “On Deck” firefighting event tree. The quantified firefighting event tree “On Deck” for the Median Ship is presented in Annex F.

3.7.4.2 Tier 1 – Fire growth

The proportion of *Slow fire*, *Fast fire* and *Explosion leading to fire* is first of all based on the identification of the combustible of origin of the fire, when known from the CARGOSAFE database.

When not specified, expert judgement has been used to identify the fire growth of the remaining accidents based on their consequences (when known) and/or their severity indicator (when known), extracted from the CARGOSAFE database. For such accidents, their identification has been made clear in the database, allowing for taking them into account in the uncertainty and sensitivity analysis.

Finally, the proportions of different fire growths for a cargo fire originating in hold are as follows:

- *Slow fire*: 54.2%.
- *Fast fire*: 29.2%.
- *Explosion leading to fire*: 16.7%.

3.7.4.3 Tier 2 – Detection & Local first response on Container Of Origin (COO) (including accessibility, manual fire-fighting (MFF) and local boundary cooling)

All information regarding the Tier 2 is extracted from the CARGOSAFE database.

For *Slow fire*, the proportions for Tier 2 are given as follows:

- *Successful*: 53.8%.
- *Unsuccessful*: 46.2%.

For *Fast fire*, the proportions for Tier 2 are given as follows:

- *Successful*: 21.4%.
- *Unsuccessful*: 78.6%.

For *Explosion leading to fire*, the proportion for Tier 2 is given as follows:

- *Unsuccessful*: 100.0%.

3.7.4.4 Tier 3 – Firefighting – First bay boundary cooling

Information on fire propagation out of the bay of origin is based on the information provided in the CARGOSAFE database.

When not available in the CARGOSAFE database, expert judgement has been used to determine whether the propagation was likely or unlikely, depending on the consequences or the narrative of the event considered. For such accidents, their identification has been made clear in the database, allowing for taking them into account in the uncertainty and sensitivity analysis.

A second expert judgement was introduced for scenarios where accidents available in the database were leading to the same consequences, e.g., leading only to a *Successful* containment of the fire in the bay of origin. For such cases, it has been decided to introduce an arbitrary case having the opposite consequence. For example, if 100% of the cases in the database lead to a successful containment, the additional arbitrary case introduced will lead to an unsuccessful containment. This assumption is to cover possible consequences not identified in the database. Those branches have been clearly identified in the firefighting event tree, allowing for taking them into account in the uncertainty and sensitivity analysis.

For *Slow fire / Detection & Local first response on COO Unsuccessful*, the proportions for Tier 3 are given as follows:

- *Successful*: 91.7%.
- *Unsuccessful*: 8.3%.

For *Fast fire / Detection & Local first response on COO Unsuccessful*, the proportions for Tier 3 are given as follows:

- *Successful*: 27.3%.
- *Unsuccessful*: 72.7%.

For *Explosion leading to fire / Detection & Local first response on COO Unsuccessful*, the proportions for Tier 3 are given as follows:

- *Successful*: 11.1%.
- *Unsuccessful*: 88.9%.

3.8 Consequence Model

The firefighting event tree outlined in the previous section ends with the development of several scenarios, identified as OD (on deck) or BD (below deck). In this section the consequences of these scenarios are quantified. This was undertaken through the development of an additional event tree with nodes attributed to the factors that will affect the outcomes of the events defined by the previous firefighting event trees.

3.8.1 Definitions

Definitions pertaining to the consequence quantification are outlined in Table 16.

Table 16: Definitions used in consequence model.

Term	Description of term with regards to median ship used in the consequence model	Values used in consequence quantification Median ship
TEU capacity	Ship total capacity of containers.	2600
POB	Number of persons on board (i.e., crew).	18
% of cargo OD	Percentage of the total TEU that is on deck.	68%
% of cargo BD	Percentage of the total TEU capacity that is below deck.	32%
Hatch (in % of total TEU capacity)	A hatch is defined as two bays on deck.	5,7%
Cargo hold (in % of total TEU capacity)	A cargo hold is defined as the space between two water-tight bulkheads. Containing 4 bays of containers.	6,4%
Row OD (in % of total TEU capacity)	A row on deck (OD) is defined as a hatch divided by the number of containers fitting laterally across the deck of the ship.	0.4%
Row BD (in % of total TEU capacity)	A row below deck (BD) is defined as the hatch equivalent below deck divided by the number of containers fitting across laterally in the cargo hold.	0.3%
Tier OD (in % of total TEU capacity)	A tier below deck (BD) is defined as the hatch divided by two bays	2,8%
Tier BD (in % of total TEU capacity)	A tier below deck (BD) is defined as the hatch divided by four bays	1,6%

3.8.2 Description of the nodes

Six separate consequence trees (CT) were developed for this study. These were split into three on deck and three below deck, with each of the three being attributed to either slow, fast or explosion scenario as shown in Table 17. The consequence tree is an extension of the firefighting event tree.

Table 17: Consequence tree designation.

Consequence trees (CT)	Slow fire	Fast fire	Explosion
On deck (OD)	CT1	CT2	CT3
Below deck (BD)	CT4	CT5	CT6

The tiers of the consequence tree were derived from information obtained from the CARGOSAFE database and are used to quantify the level of consequence of the given scenarios from the firefighting event trees. The choice of tiers is not affected by the position of the event (i.e., on deck or below deck or fire scenario), hence, they are the same in all cases as shown in Figure 40.

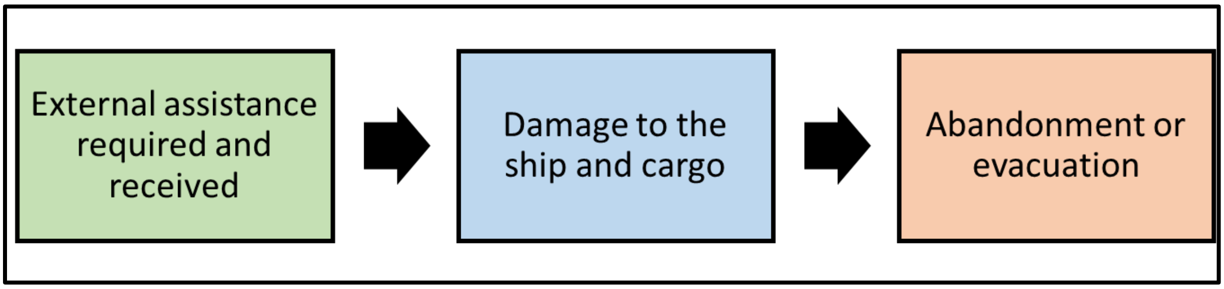


Figure 40: Tiers of the consequence tree.

3.8.2.1 Tier 1 – External assistance required and/or received

(yes/no) this tier designates whether or not external help was required and/or received.

It is assumed that all scenarios that resulted in an uncontrolled fire or were produced by an explosion would require external assistance. Suppose there was no information on the database related to external assistance. In that case, it is assumed that if the incident happened at the port or near the cost, external assistance would be received, regardless of the outcome of the fire.
The intervention of external help decreases the consequences of a given scenario, assuming that the crew received help to fight the fire. This is only valid for fires on deck or when the CO_2 system is unsuccessful. If the CO_2 was released and successful, it is assumed that external assistance would not impact the fire's consequence since boundary cooling would not be required.

3.8.2.2 Tier 2 – Damage to the ship and cargo

(no/minor/major) this tier designates whether there is damage to the ship and cargo and if so, whether it is considered minor or major.

When fire is contained to the COO no additional damage is considered.

It is assumed that only an uncontrolled fire could produce either minor or major damage to the ship and cargo. Tier 2: Damage to the ship and cargo is independent of the consequence to the ship. The final damage to the ship would depend on the combination of the three different tiers and the risk model outcome, not only on tier 2. It means that branches, where tier 2 is classified as a minor, could eventually be evaluated as superficial, minor, or major damage to the ship.

3.8.2.3 Tier 3 – Abandonment or evacuation

(yes/no) this tier is used to indicate whether or not the ship was abandoned or evacuated in a given scenario.
An abandonment/evacuation event increases the probability of injury and consequence.

It is assumed that all scenarios with slow or fast fire that resulted in an uncontrolled event below deck would be required to evacuate due to the high probability of upwards fire spread. If the uncontrolled fire originated on deck, there is the possibility of evacuation or staying on the ship.

If the damage to the ship and cargo (tier 2) is classified as major, it is assumed there would be a requirement for evacuation or abandonment of the ship, regardless of the fire type.

It is assumed that there would be no evacuation or abandonment in scenarios where the fire is controlled at some level. Except when an explosion generates the fire either on deck or below deck.

3.8.3 Structure

Consequence trees for slow fire, fast fire and explosion are presented here. First On deck, followed by below deck.

- ***On deck – Slow fire***

Figure 41:Consequence tree for on-deck, with a slow fire.

- ***On deck – Fast fire***

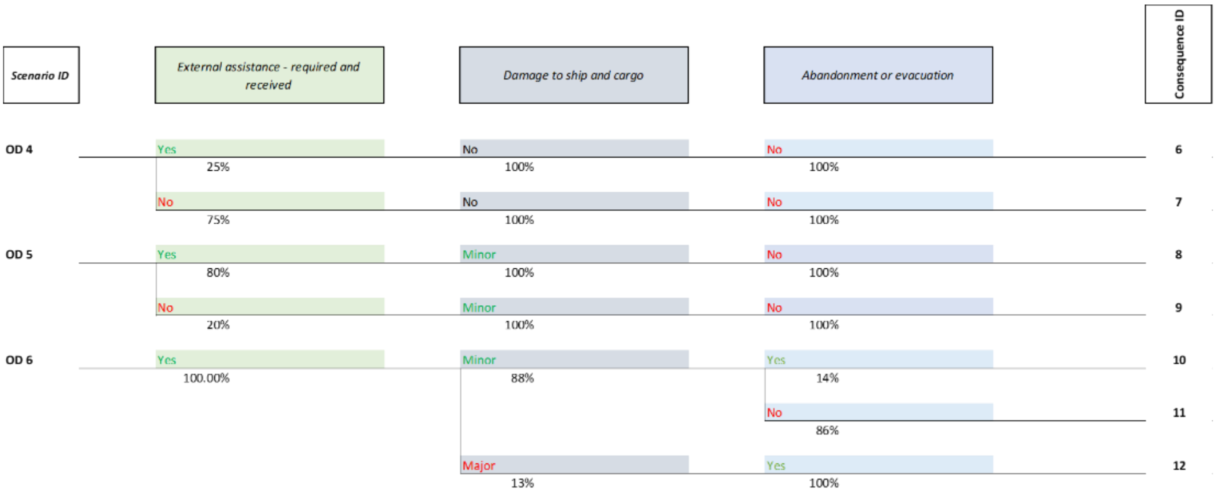


Figure 42: Consequence tree for on-deck, with a fast fire.

- ***On deck – Explosion***

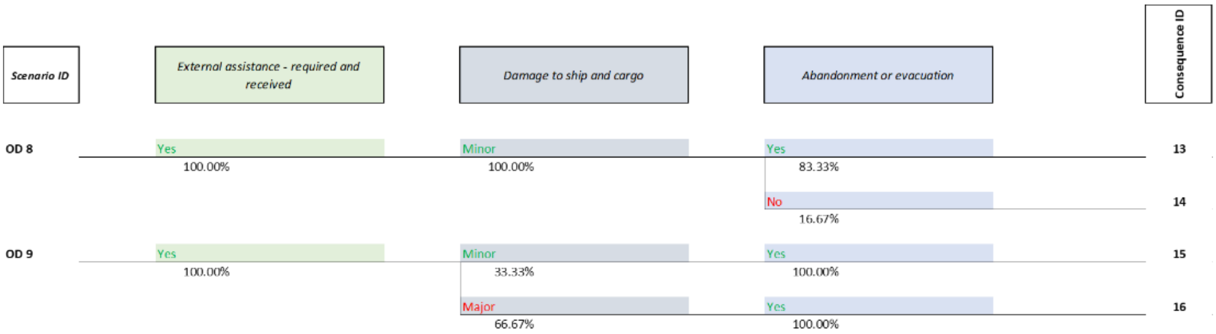


Figure 43: Consequence tree for on-deck, with an explosion leading to fire.

- ***Below deck – Slow fire***

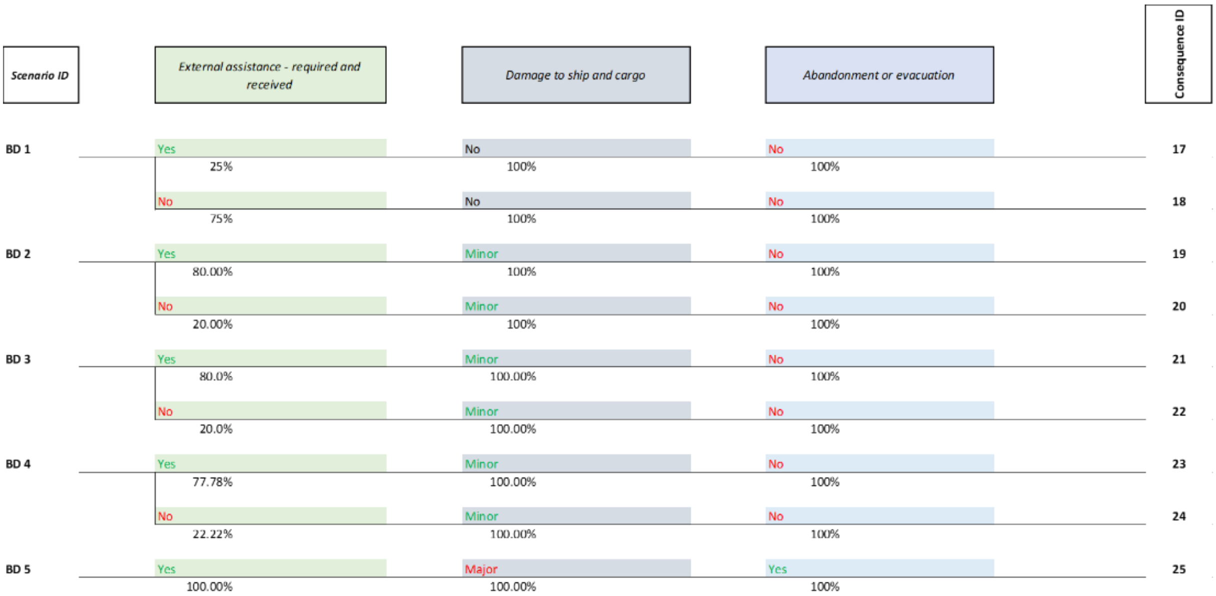


Figure 44: Consequence tree for below-deck, with a slow fire.

- ***Below deck – Fast fire***

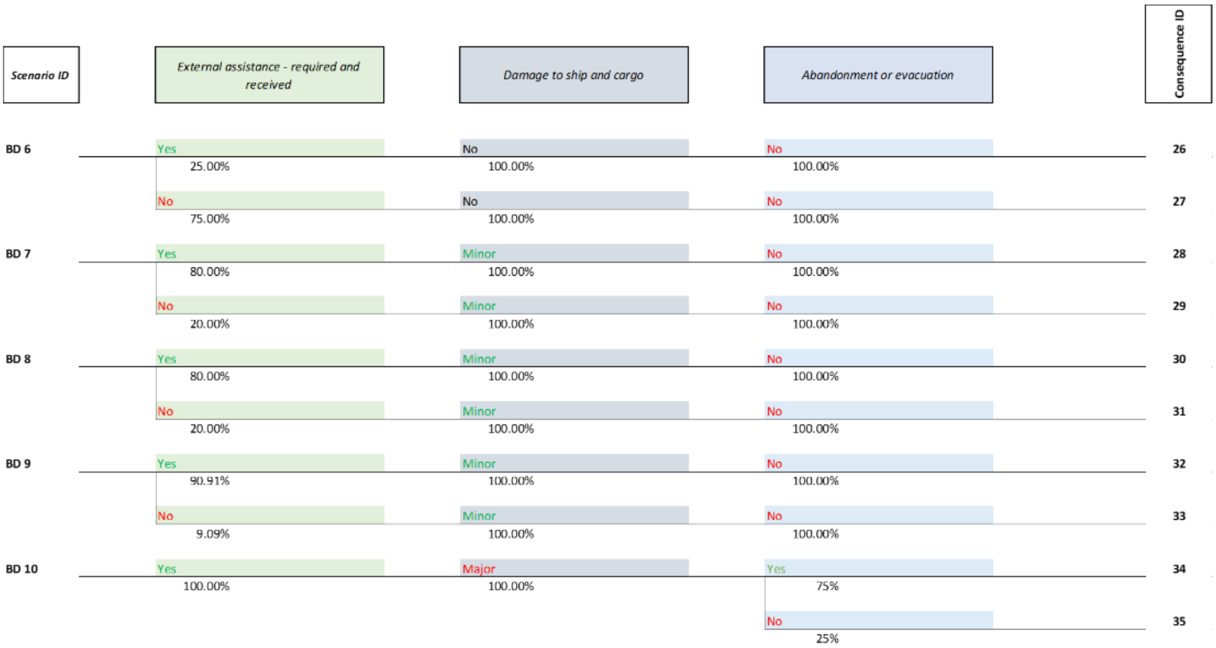


Figure 45: Consequence tree for below-deck, with a fast fire.

- ***Below deck – Explosion***

Figure 46: Consequence tree for below-deck, with an explosion leading to fire.

3.8.4 Quantification

3.8.4.1 Tier 1 – External assistance required and received

Information on external assistance is based on the information provided in the CARGOSAFE database.

When the information was not available in the CARGOSAFE database, expert judgment was used to determine whether the events after the fire were likely or unlikely, depending on the narrative of the event considered or the consequence described in the database. It was assumed within expert judgment that external assistance would always be received if the ship was in the port or near the coast. In addition, it was obtained from the database that 25% of the incidents occur when the ship is in the port.

The final consequence of the fire is linked to the firefighting event tree and the consequence tiers. If the fire is controlled and external assistance is received, even if it is not required, e.g. ship is in port, it is assumed that the fire outcome is less severe. Assuming there are more people to fight the fire.

In case of an uncontrol fire, external assistance does not have an impact on the fire outcome. It is assumed that the type of fire and the limited of firefighting equipment limits the consequence.

3.8.4.2 Tier 2 – Damage to ship and cargo

Information on the damage to the ship or the cargo is based on the CARGOSAFE database provided. This tier is a combination of the damage to both ship and cargo, assuming the damage to the ship will be to some extent related to the damage on the cargo, also, it is affected by other tiers. For example, if there was external intervention, it is assumed the damage is less severe. On the database this information is obtained in qualitative form, therefore the decision to catalogue the damage was based on expert judgement. On the scenarios when the fire is limited to the COO, it is expected that there will be no damage to the ship. Only the containers in the vicinity will be affected due to the firefighting task. In this case the tier is categorized as No damage to the ship or cargo.
For the scenarios where the fire compromised more than half cargo on deck or below deck, or it is expected a total loss, the tier is designated as Major damage to the ship or cargo. In all other cases, meaning the fire does not compromise more than five bays or five cargo holds, then the tier is designated as minor.

It is worth noticing that the classification of this tier is independent of the qualitative category assigned to the ship damage. It means that a minor category in this tier could end up being classified as superficial, minor, major on the ship damage. On the consequence quantification, only the ship damage qualitative categories (no, superficial, minor, major, total loss) will be assigned with a number to allow the quantification of the losses.

3.8.4.3 Tier 3 – Abandonment or evacuation

From the CARGOSAFE database, it is not possible to determine if there was a medical evacuation or safe evacuation due to the ship damage. Therefore, the tier is assumed to be any type of abandonment or evacuation, and information is taken from the CARGOSAFE database if possible.

When the information was not available, expert judgement was used to determine if the abandonment or evacuation took place. It is assumed that every time there is Major damage to the cargo or the ship tier, evacuation will occur. In the same line, it is assumed that every time there is evacuation or abandonment a higher number of equivalent fatalities is generated due to the inherent risk linked with an evacuation, or due to the severity of the fire and associated firefighting activities.

3.8.5 Loss quantification

The consequence model is developed for each of the scenarios previously created. It considers the loss of life, which is expressed as equivalent fatalities; the loss of cargo, in percentage of containers loss; the loss of the ship, which is specified qualitatively, and later, assigned with a value in Euros; environmental loss, quantify per TEU loss and ship damage impact; and salvage cost, linked to the ship damage.

3.8.5.1 Contributing factors

3.8.5.1.1 Equivalent fatalities

The number of equivalent fatalities was obtained from expert judgement and correlated with the CARGOSAFE database.

As general rules, more equivalent fatalities occur when the fire is located below deck, mainly due to the challenge of the firefighting operations. Likewise, the number of fatalities is proportional to the severity of the incident. This means there are more equivalent fatalities with an explosion event than in a slow fire.

On the other hand, when external help is received, more people are involved and therefore the probability of having an injury will increase. Also, if the damage to the ship or cargo is higher, more equivalent fatalities will be expected. Finally, if an evacuation or abandonment takes place, then it is likely to have more equivalent fatalities due to the evacuation process.

Table 18 present the equivalents in fatalities when there are minor injuries or more severe injuries.

Table 18: Severity index – Effects on human safety[35].

Effects on human safety	Equivalent Fatalities
Single or minor injury	0.01
Multiple or severe injuries	0.1
Single or multiple fatality	1

3.8.5.1.2 Cargo loss

The information on cargo loss is obtained from expert judgement and correlated with the CARGOSAFE database.

The cargo loss is expressed as percentage of containers lost due to the fire or firefighting operations. The percentages are equivalent to a section of the median ship, described in Table 16 These percentages will be later expressed as the number of containers lost and their value will be calculated in Euro for the risk quantification.

As a rule, a higher percentage of containers will be lost with a more severe fire. When the fire was limited to the COO, then the number of containers loss is limited not to a percentage but to three containers if there was external assistance or to five containers if no assistance was provided. This is assuming the neighbouring containers will be affected by the firefighting operations.

3.8.5.1.3 Ship damage

The information of ship damage is obtained from expert judgement and correlated with qualitative information in the CARGOSAFE database.

Table 19: Qualitative Ship damage class categorization.Table 19summarizes the qualitative information retrieved from the CARGOSAFE database. This table is used to assign a classification of ship damage for each of the scenarios. Later, a monetary value is assigned to each category to quantify the Euro loss.

Table 19: Qualitative Ship damage class categorization.

Ship damage categories	Examples taken from the database sources
None	No damage
Superficial	-Minor paint damage -Superficial damage to the coating on the hatch cover -If there is external help -Paint damage to number 4 cargo hold -Very slight damage -Limited damage
Minor	-Minor damage to the hull -Vessel returned to service after repair -Some deformation due to heat on two hatches of cargo hold -Hatch cover sustained some damage

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

	-Damage to hold -Dents in the hull but no structural damage -Ship declared fit for voyage -Damage to hold -Dents in the hull but no structural damage -Damage to hatch cover -Limited to one bay/hold
Major	-Severe damages affecting several holds -Substantial -Several bays -More than one cargo hold -Hold had been totally burned out -Several bays seriously damaged -Port side hatch cover of cargo 8 burnt, buckled and distorted -More than one bay/hold
Total loss	Ship lost

3.8.5.2 Loss narrative

The result of the consequence model is presented in Table 20.

Table 20: Consequence model - Scenarios narrative.

ID	Fire type	Event tree outcome	Consequence scenario description	Consequence aftermath
1	slow fire on deck	COO controlled	External assistance, no damage to the ship	3 container loss, no damage to the ship, 1 minor injury
2	slow fire on deck	COO controlled	No assistance, no damage to the ship	5 container loss, no damage to the ship, no fatalities
3	slow fire on deck	Bay controlled	External assistance, minor damage to the ship	1.4% container loss, superficial damage to the ship, 1 minor injury
4	slow fire on deck	Bay controlled	No assistance, minor damage to the ship	2.8% container loss, minor damage to the ship, no fatalities
5	slow fire on deck	Uncontrolled	External assistance, minor damage to the ship had to abandon	11.3% container loss, major damage to the ship, 2 injuries
6	slow fire on deck	Uncontrolled	External assistance, minor damage to the ship	8.5% container loss, minor damage to the ship, 1 injury
7	slow fire on deck	Uncontrolled	External assistance, major damage to the ship had to abandon	40.8% container loss, major damage to the ship, 3 injuries
8	fast fire on deck	COO controlled	External assistance, no damage to the ship	3 container loss, no damage to the ship, 2 minor injuries
9	fast fire on deck	COO controlled	No assistance, no damage to the ship	5 container loss, no damage to the ship, 1 minor injury
10	fast fire on deck	Bay controlled	External assistance, minor damage to the ship	4.3% container loss, minor damage to the ship, 1 injury

11	fast fire on deck	Bay controlled	No assistance, minor damage to the ship	5.7% container loss, minor damage to the ship, 5 minor injuries
12	fast fire on deck	Uncontrolled	External assistance, minor damage to the ship had to abandon	17% container loss, major damage to the ship, 3 injuries
13	fast fire on deck	Uncontrolled	External assistance, minor damage to the ship	14.2% container loss, major damage to the ship, 2 injuries
14	fast fire on deck	Uncontrolled	External assistance, major damage to the ship had to abandon	54.5% container loss, major damage to the ship, 4 injuries
15	explosion on deck	Bay controlled	External assistance, minor damage to the ship had to abandon	8.5% container loss, minor damage to the ship, 3 injuries
16	explosion on deck	Bay controlled	External assistance, minor damage to the ship	7.1% container loss, minor damage to the ship, 2 injuries
17	explosion on deck	Uncontrolled	External assistance, minor damage to the ship had to abandon	22.7% container loss, major damage to the ship, 5 injuries
18	explosion on deck	Uncontrolled	External assistance, major damage to the ship had to abandon	68.1% container loss, total loss damage to the ship, 1 fatality
19	slow fire below deck	Extinguished	External assistance, no damage to the ship	3 container loss, no damage to the ship, 1 minor injury
20	slow fire below deck	Extinguished	No assistance, no damage to the ship	5 container loss, no damage to the ship, 1 minor injury
21	slow fire below deck	Extinguished	External assistance, minor damage to the ship	1.6% container loss, superficial damage to the ship, 1 minor injury
22	slow fire below deck	Extinguished	No assistance, minor damage to the ship	1.6% container loss, superficial damage to the ship, no fatalities
23	slow fire below deck	Hold controlled	External assistance, minor damage to the ship	3.2% container loss, minor damage to the ship, 2 minor injuries
24	slow fire below deck	Hold controlled	No assistance, minor damage to the ship	3.2% container loss, minor damage to the ship, no fatalities
25	slow fire below deck	Hold controlled	External assistance, minor damage to the ship	6.4% container loss, minor damage to the ship, 1 injury
26	slow fire below deck	Hold controlled	No assistance, minor damage to the ship	9.6% container loss, minor damage to the ship, 1 minor injury
27	slow fire below deck	Uncontrolled	External assistance, major damage to the ship had to abandon	36.2% container loss, major damage to the ship, 1 fatality, 5 injuries
28	slow fire below deck	Uncontrolled	External assistance, major damage to the ship	48.2% container loss, major damage to the ship, 3 fatalities, 5 injuries
29	fast fire below deck	Extinguished	External assistance, no damage to the ship	3 container loss, no damage to the ship, 2 injuries
30	fast fire below deck	Extinguished	No assistance, no damage to the ship	5 container loss, no damage to the ship, 2 injuries

31	fast fire below deck	Extinguished	External assistance, minor damage to the ship	3.2% container loss, superficial damage to the ship, 2 minor injuries
32	fast fire below deck	Extinguished	No assistance, minor damage to the ship	3.2% container loss, superficial damage to the ship, 1 minor injury
33	fast fire below deck	Hold controlled	External assistance, minor damage to the ship	4.8% container loss, minor damage to the ship, 5 minor injuries
34	fast fire below deck	Hold controlled	No assistance, minor damage to the ship	4.8% container loss, minor damage to the ship, 2 minor injuries
35	fast fire below deck	Hold controlled	External assistance, minor damage to the ship	8% container loss, minor damage to the ship, 2 injuries
36	fast fire below deck	Hold controlled	No assistance, minor damage to the ship	11.2% container loss, minor damage to the ship, 1 injury, 5 minor injuries
37	fast fire below deck	Uncontrolled	External assistance, minor damage to the ship had to abandon	60.3% container loss, major damage to the ship, 1 fatality, 5 injuries
38	fast fire below deck	Uncontrolled	External assistance, major damage to the ship had to abandon	66% container loss, total loss damage to the ship, 3 fatalities, 5 injuries
39	explosion below deck	Extinguished	External assistance, minor damage to the ship	4.8% container loss, minor damage to the ship, 5 minor injuries
40	explosion below deck	Hold controlled	External assistance, minor damage to the ship had to abandon	6.4% container loss, minor damage to the ship, 1 injury
41	explosion below deck	Hold controlled	External assistance, minor damage to the ship	6.4% container loss, minor damage to the ship, 5 minor injuries
42	explosion below deck	Hold controlled	External assistance, minor damage to the ship had to abandon	12.8% container loss, minor damage to the ship, 5 injuries
43	explosion below deck	Hold controlled	External assistance, minor damage to the ship	9.6% container loss, minor damage to the ship, 5 injuries
44	explosion below deck	Uncontrolled	External assistance, major damage to the ship had to abandon	100% container loss, total loss damage to the ship, 3 fatalities

3.8.5.3 Costs quantification

To quantify the costs involved for each of the scenarios, monetary values needed to be designated to both loss of cargo (including the containers), ship damage, salvage operations and environmental impact. The following section describes how these values were assigned for each of the categories.

3.8.5.3.1 Containers and cargo

The value of cargo has been estimated considering the average value of the goods / commodities, and the average value of the container itself.

Container value

Containers come in many sizes and types. To simplify, there are TEUs, which are 20-foot containers and FEUs which are 40-foot containers. The two most common container types are refrigerated containers and dry containers. Therefore, the cargo value estimate will be based on the ratio between these common cargo unit sizes and types.

Containerships are described by the TEU-capacity, though the FEU is actually the most common type of container on large container vessels. The ratio of cargo is therefore set at 80/20, with 80% of cargo being FEUs.

The amount of refrigerated cargo on the container vessels varies significantly across trade lanes and services. Vessels sailing from Asia to Europe do not carry a high load of perishable goods that require refrigeration, so the ratio of dry vs reefer cargo split might be 95/5. Other services such as those from South America to Asia is an often-used trade for fruit transportation, so the ratio might for example be 40/60. The study assumes an average ratio of 75/25 for any vessels, with 25% being refrigerated cargo.

The value of the containers is based on the price of acquiring a new container of the same type. Prices for purchasing new containers have been estimated via various information sources[36], and are shown in Table 21.

Table 21: Container pricing.

Container Type	Price (EUR)	Amount (%)
20FT Container – Dry	3,000	15 %
40FT Container – Dry	5,000	60 %
20FT Refrigerated Container	19,000	5 %
40FT Refrigerated Container	22,000	20 %

Based on above data, the weighted average value of containers can be calculated to be 8,800 € / TEU.

Cargo value

The value of the cargo itself has been estimated using, among others, data from the IHM Markit study[37]

There is huge variation in cargo value across commodities. One container full of jewelry or rare metals can be worth many million Euro, and one with trash or scrap metal or plastics might be worth a thousand Euros. This study assumes a 2022 average value of 45,000 € per TEU of cargo. The total value of one TEU with both the cargo and container value included, is 53,800 €.

The number of containers onboard an average vessel should be estimated, as a container ship rarely carries only full containers and is at 100% capacity utilization. Most trade lanes and services between regions / countries are characterized by trade imbalances with respect to export and import cargo. For services between for example Asia, Europe and America, vessels are generally carrying many full containers in the main trade direction (head haul direction) vs many empty containers in the opposite direction (backhaul direction). The UNCTAD Review of Maritime Transport for 2021 give an indication of trade imbalances between the main regions, see Table 22.

Table 22: Container volumes between main regions for Asia, EU, and US trade lanes / services.

Route	mTEU to	mTEU return	% return
Asia to US	24.1	7.1	23 %
Asia to EU	18.5	7.8	30 %
EU to US	5.2	2.8	35 %

A simple calculation of average across trade routes, indicates that backhaul voyages on average carry 29.1 % export cargo compared to shipped export cargo volumes on head haul voyages. On average for the entire round trip, a vessel will be utilized with what is equivalent to 64.6% full containers.
Due to the trade imbalances, many empty containers have to shipped back empty to where cargo was exported from, as for example to Asia from Europe and the US. The empty containers are relatively easy to transport since they barely add anything to weight and balance constraints of the vessel compared to a full box. Assuming that backhaul

[36] For an insight into prices and recent historical developments of ISO containers, check for example: https://www.shippingcontainerdepot.com/how-much-are-shipping-containers/ or https://www.container-xchange.com/
[37] https://cdn.ihs.com/www/pdf/Vessel-Accumulation-Cargo-Value-Estimation.pdf

vessels are filled to max nominal slot capacity with empty containers, this means 70.9 % of the cargo is empty containers[38]. It was above mentioned that an empty container on average is worth 16.4 % of a full box with cargo (8,800 € empty, 53,800 € full). For the return trip, converting the value of 70,9% empty containers to an equivalent value of full containers, gives equal to additional 11,6% utilization. The cargo value for backhaul trips is therefore assumed to be 40.7 % of a head haul voyage. This increases the average cargo fill calculated only as full container equivalents to 70.3 % for the round trip.

The cargo value estimated to create a monetary value for the PLC, will be calculated with the formula below:

$$C\arg o\,Value = TEUCapacity * 0.703 * 53800EUR$$

With this formula, the following average cargo values have been set for the chosen generic ships, see Table 23.

Table 23: Average cargo values for the three generic ships.

Ship	TEU	Cargo value (EUR)
Twin Island	18,000	681,409,176
Single Island	7,500	283,920,490
Feeder	3,532	133,707,622

3.8.5.3.2 Ship

The recent fluctuations in demand for ocean transport (since outbreak of COVID19) with peaks in freight rates end of 2021 and early 2022, means that prices for new build container vessels have risen considerably compared to 2020. To avoid inflated prices, a model and value estimate for different ship sizes had been developed considering prices across a longer range of year. The formula was developed, based on historical data of 222 shipbuilding contracts over the period 2017-2022 which gave the newbuilding prices shown in Table 24.

Table 24: Newbuilding price for different ship categories and sizes.

Ship size	Median Ship	Twin island	Single island	Feeder
Est. price	32,856,000	129,876,000	63,726,000	38,727,600

The linear regression formula that created these values has an acceptable fit to the historical data of $r^2 = 0.969$.
Assigning damage costs to a ship for various scenarios has been simplified using a categorization approach. Ship damage has been classified into 5 levels of damage class based on qualitative information retrieved from the database source. A monetary value has then been assigned to each of these classes based on expert judgement and previous studies[39] as shown in Table 25. It should be noted that the costs of down-time while under repair have not been included in these figures. The same percentage is used for the all the ship types.

Table 25: Ship damage monetary assignment for median ship.

Qualitative ship damage categories	Monetary assignment (% of newbuilt cost)
None	0
Superficial	0.5
Minor	3
Major	23
Total loss	100

[38] The average vessel utilization measured in slots filled with full and empty containers will in realty be less than 100% on most trips and legs.
[39] REVIEW OF FIRE PROTECTION REQUIREMENTS FOR ON-DECK CARGO AREAS, FSA – Container fire on deck, Details of the Formal Safety Assessment, Submitted by Germany, IMO FP54 INF.2, 2009

3.8.5.3.3 Salvage and other cost

Salvage is also an important part of a maritime vessel incident. The model includes four categories.
First, there are Off-hire costs which reflects the general market or business value that the ship provides to its operators and owners while being in service. Costs for a vessel out of service are assessed based on the time the vessel is not sailing due to inspections and repairs, or for a total loss or major loss case; the amount of time that the ship owner will have to charter a temporary replacement vessel. The off-hire costs have been estimated via a review of recent charter rates provided by industry charterers[40] and are summarized in Table 26.

Table 26: Charter rates per day for the three ships.

Ship size	Charter rates per day
Twin island	80.000 €
Single island	40.000 €
Feeder	20.000 €

These rates are mainly based on the newest month of data for charter rates. The reasoning behind this is because the container shipping industry is returning to normal freight and vessel charter rates after a huge demand boom during the recent pandemic, which lead to abnormal high freight rates and thus inflated charter rates that most likely will not remain as a representation of rates in the near future.

With the different ship damage-levels, the time to have the operations back to normal is determined based on an estimation on for how long time the vessel will undergo repairs. For superficial damage, the ship will only sustain cosmetic damage, the ship is still seaworthy and can continue its route without problems. The estimated off-hire is set at two days, which includes the additional time to unload burnt containers, inspection, and repainting of damaged surfaces.

With minor damage, the ship will have damage to some of its hatch covers, but it would still be seen as seaworthy. In this case the ship will need to undergo some more extensive repairs on the hatch covers, yet the superstructure is unharmed and therefore the ship will not require a full drydock to undergo these repairs. The estimated off-hire is set at two weeks, which includes, unloading burnt containers, unloading containers on damaged hatch covers, docking for repairs of hatch covers, inspection.

When we go to major damage, the vessel will have some extensive damage to both hatch covers but also the superstructure of the vessel. In this case the vessel will not be deemed seaworthy and would require the assistance of a salvage operation team to get the vessel to a safe harbour. Since the damage includes the superstructure, the ship will require a full drydock to undergo any repairs. The estimated off-hire is in this case half a year, which covers towing the vessel, discharging all containers, inspection, drydocking, extensive repairs.

In case of a total loss, the vessel will either be uneconomical to repair because of the amount of damage, or it might have sunk. As an average for all the possible scenarios, the off-hire is set at one year. This will be longer in case that the ship owner decides to order a completely new vessel as a replacement. This will take a minimum of one and a half years to complete, with current wait times being as long as three years. It might also be possible that the owner replaces the vessel with a used vessel, in which case the wait might be less than a year.

The second part of salvage includes the Lloyd’s Open Form, which is a standard contract that is signed between ship owners and salvage companies when a ship requires any form of salvage operations. This contract will make sure the salvage company is paid out based on the value that is salvaged. This includes both the remaining value of containers and remaining value of the vessel. Talking with industry experts and looking at multiple fire incidents at sea. An average pay out for a salvage company was around 13-19% of the remaining value.

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[40] For recent developments in charter rates, check for example November 2022 data:
https://theloadstar.com/carriers-consider-laying-up-box-ships-as-blanking-fails-to-prop-up-rates/ and
https://splash247.com/exposed-carriers-struggling-to-pay-sky-high-charter-rates/

For superficial damage, the LOF cost is set at zero. This is because these small incidents will be solved by the crew onboard the vessel without ever calling for external help from a salvage company. The minor case is set at 2 %, which is because some of these cases will be solved by the crew, and some will have contact with a salvage company. In some cases, for larger companies, there might be yearly contracts with a salvager, which results in cases where the salvage company is called on alert for an incident but might end up not being utilized and the bill still being at zero. The major and Total loss case is both set at 15 % of the remaining value. In a major case this indicates the salvage company helping with firefighting, towing the vessel to a safe harbour, and being paid this percentage for 2/3 of the ship's newbuilding value, and 2/3 of the total cargo value. In case of a total loss, there are some cases where the ship will get to a safe harbour, and some where it will sink. In case the ship sinks, a clause in the form makes sure that the salvager is still partially paid for their efforts towards salvaging the vessel. Therefore, it is set at only paying 15 % of 1/3 the total cargo value.

3.8.5.3.4 Environmental

Environmental costs were categorized using the ship damage categories outlined previously and using information from the CARGOSAFE database. Table 27 provides estimates of potential environmental costs associated to each ship damage category.

Table 27: Environmental costs classified in ship damage categories

Ship Damage	Environmental costs (EUR)
Superficial	1.000
Minor	100.000
Major	5.000.000
Total loss	40.000.000

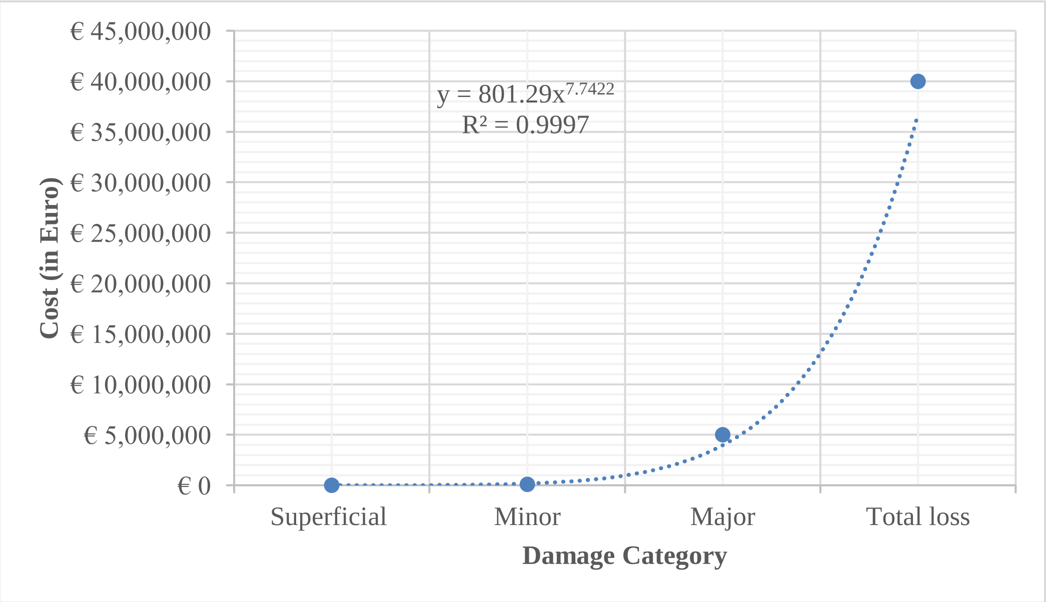


Figure 47: Environmental cost in Euros.

The cost presented is intended to cover the environmental impact of a fire. This includes the release of toxic substances to the environment, like CO, CO_2, and NOx, among others. To a reasonable extent, it should also cover the cleaning of toxic substances, both airborne and marine pollutants. Finally, it is intended to compensate for the impact on local communities due to the lost containers and the release of its cargo, either overboard due to reducing stability or intentionally thrown overboard in case of fire. It does not cover any heavy fuel oil spill generated by the total loss of the ship or by the fire. The values presented are taken from the aftermath of some significant incidents; this is, however, a rough approximation of the environmental cost.

The final environmental cost is directly linked with the among of TEU involved in the fire. Therefore, the cost presented on previous table was normalized by the number of containers involved on the incidents where the price came from.

Then this value was used, in combination with the ship damage and the total TEU involved on the fire for each of the consequence scenarios.

3.9 Risk analysis result

3.9.1 Potential Loss (Life - PLL, Cargo - PLC, Ship - PLS, Total - TPL, Environmental - EPL, Salvage)

The corresponding Potential Losses for the median ship is presented in Table 28. The potential loss of life, cargo, ship and cost of salvage operations and environmental cost will vary with the TEU units assumed for each ship.

Table 28: Potential Loss for median ship.

PLL	3.93E-04	EqFat/shipyear
PLC	€ 14,184	/shipyear
PLS	€ 3,719	/shipyear
TPL	€ 29,213	/shipyear
EPL	€ 2,325	/shipyear
Salvage	€ 8,984	/shipyear

In addition, the risk is presented in Annex 2 (FN curve for median ship) using FN curves. However, it is not publicly available. For a better understanding of the risk and where the risk control options (RCOs) would have a greater impact, the following section presents the risk matrix. They show the severity of the loss (life, cargo, or ship) on the x- axis and frequency on the y- axis, for each of the scenarios.

3.9.2 Scenario plot for ranking (dots in frequency/severity plan)

The purpose of this section is to present the results on a plot diagram similar to a Risk Matrix (with x- axis representing the loss and y- axis representing the frequency).

The results on the median ship representing the whole container ship fleet are provided. The results on the three generic ships 1, 2, 3 (18000TEU, 7500TEU and 3500 TEU) are also provided.

3.9.2.1 Assumptions made on the three generic ships

While the conditional probabilities of the three generic ships could not be changed yet, the influence of ship design and TEU was taken into consideration on the initial frequency (see 3.7.3) and consequences of fire events as explained below (refer to Table 16 and Table 25 for the median ship).

Table 29: Values used in consequence model for generic ships 1, 2, 3 (18000TEU, 7500TEU and 3500 TEU.

	Values used in consequence quantification		
	Gen Ship 1: 18000 TEU	**Gen Ship 2: 7500 TEU**	**Gen Ship 3: 3500 TEU**
TEU capacity	18,000	7,500	3,532
POB	21	19	18
% of cargo OD	61%	63%	68%
% of cargo BD	39%	37%	32%
Hatch (in % of total TEU capacity)	2.5%	2.9%	6%
Cargo hold (in % of total TEU capacity)	3.6%	3.3%	6%
Tier OD (in % of total TEU capacity)	1.3%	1.4%	2.8%
Tier BD (in % of total TEU capacity)	0.9%	0.9%	1.6%

Table 30: Values used in consequence model for generic ships 1, 2, 3 (18000TEU, 7500TEU and 3500 TEU).

Qualitative cargo and ship damage categories	Monetary assignment (in Euros)		
TEU	45,000	45,000	45,000
None	-	-	-
Superficial	10,000	10,000	10,000
Minor	692,308	135,846	288,462
Major	6,923,077	1,358,462	2,884,615
Total loss	692,307,692	135,846,154	288,461,538

3.9.2.2 Risk Matrix

Risk model quantitative results have been plots on a 2D graphic using severity on the x- axis and frequency on the y- axis. The log-scale is used.

For the crew individual risk FSA guidelines suggest using 1E-6 as negligible fatality risk per year and 1E-3 as maximum tolerable fatality risk per year.

Assuming exposure among approximately 20 crews onboard 6 months per year, the correspondence between IR and PLL is IR = PLL / 40(the risk for one specific crew to be one the ones included in the PLL is 1/20 x 6/12).

Using this relation negligible (green) and intolerable (red) zones were defined with an ALARP (yellow) zone in between. The reader should, however, carefully consider this choice since other maritime risks and fire risks are not considered in this study. According to FP54-INF.2[41] fires and explosions on container ships contribute to 16.7% of the total PLL with an historical PLL_{Fire} of 1.5E-3 fatality per shipyear including machinery and accommodation fires.

For life safety, the correspondence between the axes and the risk matrix used in HAZID proposed in FSA Guidelines can be made using

- For the frequency, the correspondence between the Frequency Index and the numerical frequency FI = 6 + log(f) and
- For the severity, the correspondence between the Severity Index and the numerical number of equivalent fatalities SI = 3 + log(EqFat).

For the Cargo Loss and the Ship Loss risk matrix, similar bands were placed arbitrarily since to the knowledge of the authors there is no IMO/FSA criterion for these monetary losses. The intolerable zone starts around a 1 M€ loss every ship year (depending on the individual ship owner). The yellow zone is shifted down of 3 decades.

3.9.2.3 Results

The results are presented for the median ship and the three generic ships. The average equivalent fatalities expected per fire is provided ($PLL_0/f_{ignition}$) at $f_{ignition}$ for the four ships. The corresponding equivalent risks (iso-risk having the same PLL_0) are given by the straight-line diagonal[42] (slope -1) and is also provided for the Median ship PLL (PLL_0). This straight line is kept for every risk matrix graphs for comparison purpose to the Median ship. Note that the line passes at point EqFat=1 at $f_{ignition}$=PLL in numerical values.

[41] REVIEW OF FIRE PROTECTION REQUIREMENTS FOR ON-DECK CARGO AREAS, FSA – Container fire on deck, Details of the Formal Safety Assessment, Submitted by Germany, IMO FP54 INF.2, 2009
[42] straight line of slope -1 in log-scale according to the relation : $PLL(f) = PLL_0/f \Leftrightarrow Log(PLL(f)) = Log(PLL_0) – Log(f)$

The same is done for Cargo Loss and Ship Loss *mutatis mutandis.* As mentioned above, due to the assumption the results are however preliminary.

Round dark dots represent each consequence branch for the scenarios on deck, and the tags indicate their reference numbers in Table 20 In the same way, orange Triangles apply to scenarios below deck.

3.9.2.3.1 Life Safety scenarios plots on a Risk Matrix

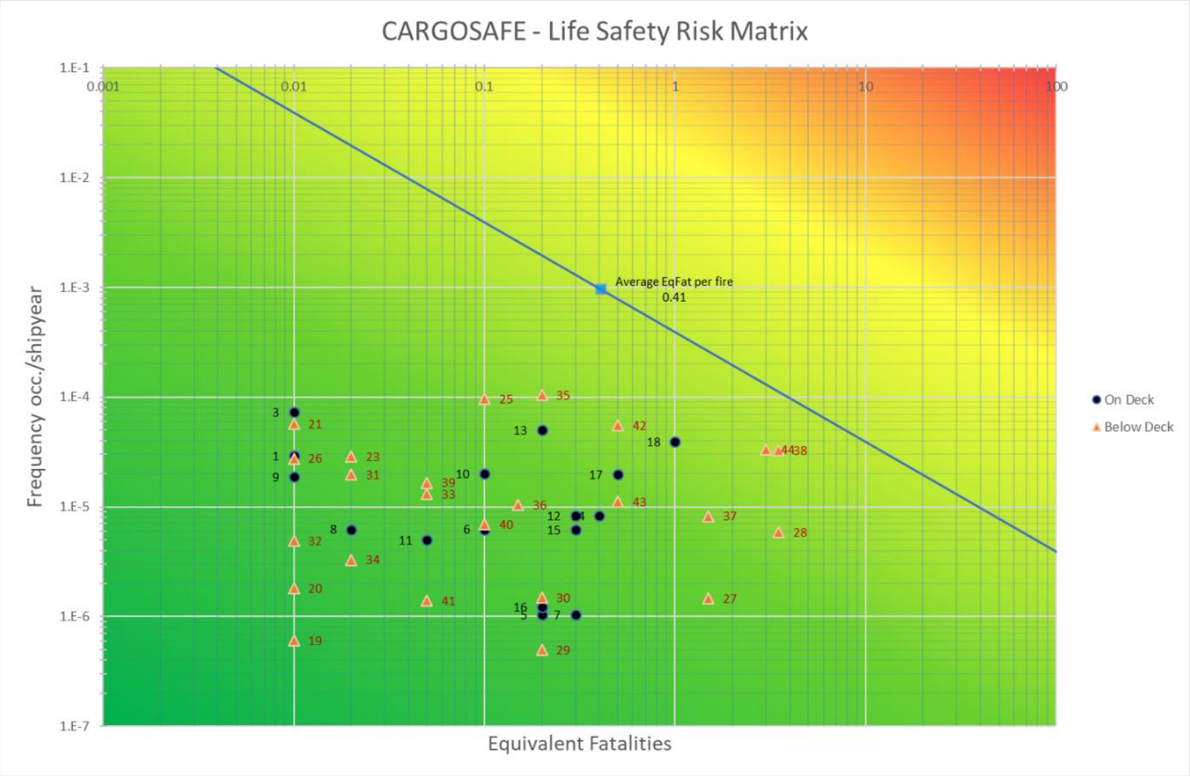


Figure 48: PLL distribution for 2 600 TEU Median Ship with PLLCargoFire=3.91E-4 EqFat/shipyear

The graph above displays the distribution of the PLL amongst the different scenarios for the median ship. The most contributing scenarios (which represent more than 10% of the PLL when summed) are the following:

Table 31: Most contributing scenarios in terms of PLL.

Scenario Id.	Scenario description
38	fast fire below deck, uncontrolled, Total Loss.
44	explosion below deck, uncontrolled, Total Loss.
18	explosion on deck, uncontrolled, major damage to the ship.

The three graphs below also display this PLL distribution for the three generic ships.

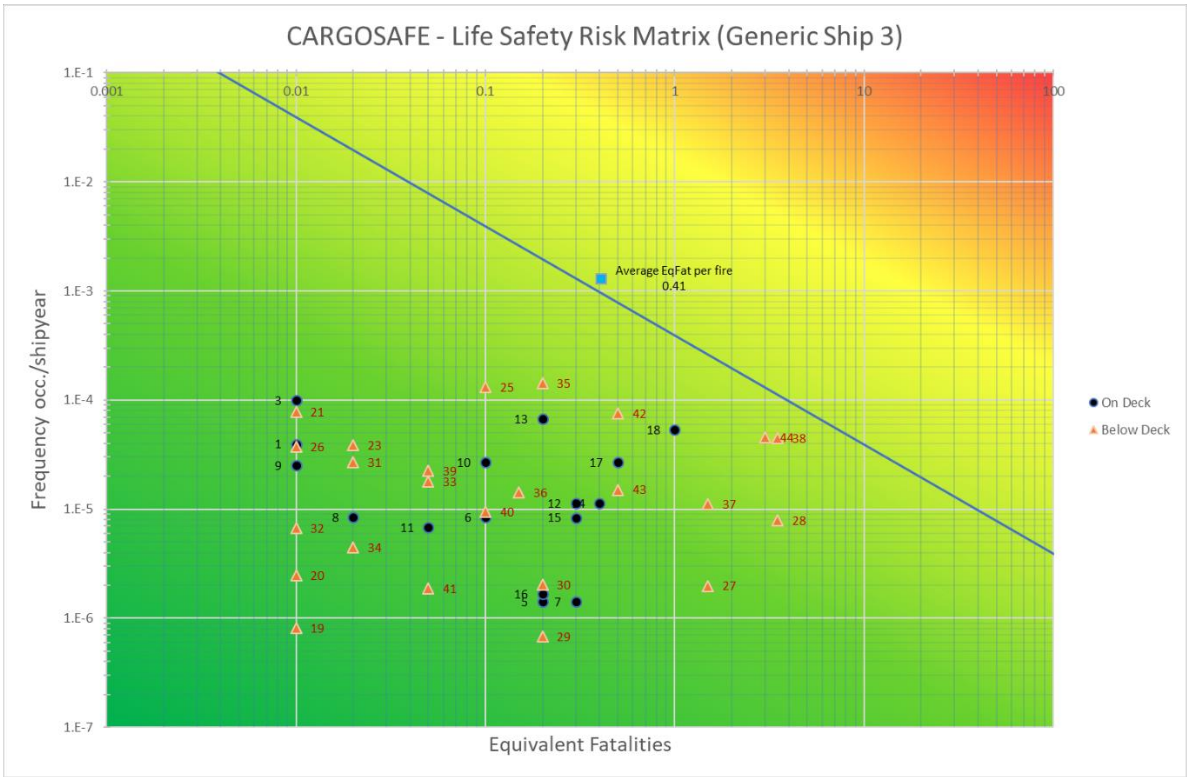


Figure 49: PLL distribution for 3 500 TEU Generic Ship PLLCargoFire=5.31E-4 EqFat/shipyear.

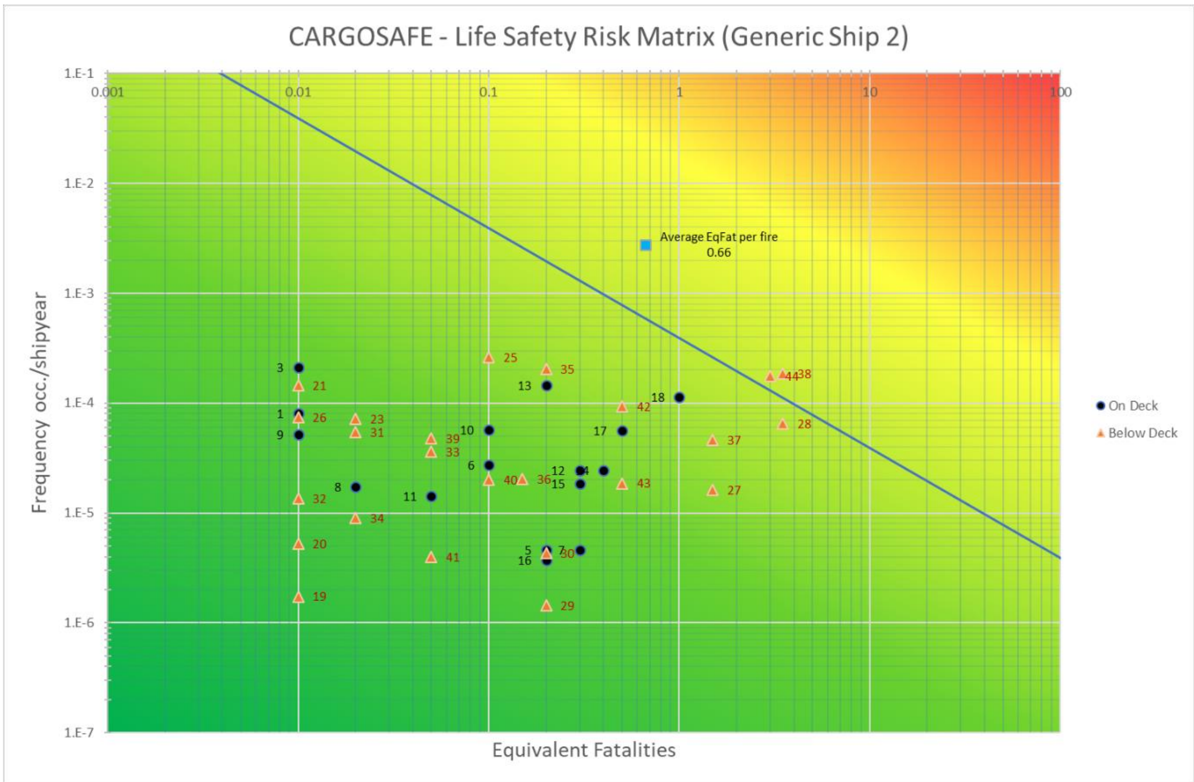


Figure 50: PLL distribution for 7 500 TEU Generic Ship PLLCargoFire=1.84E-3 EqFat/shipyear.

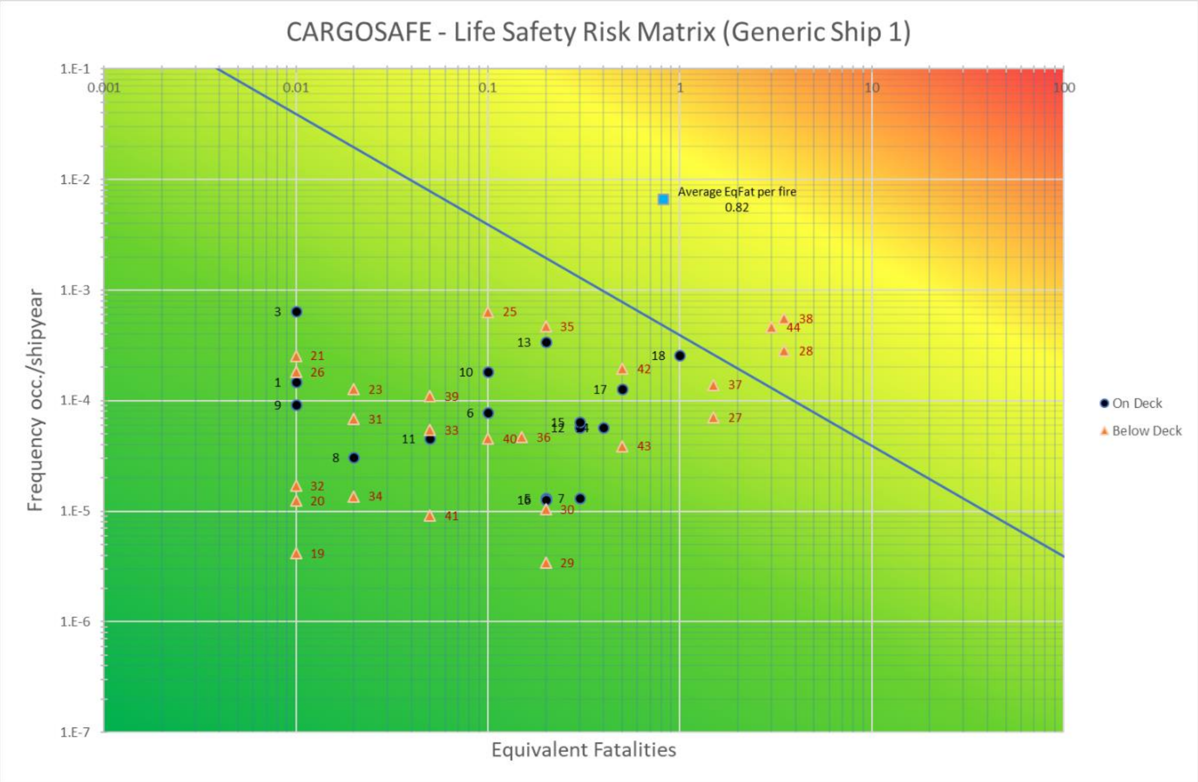


Figure 51: PLL distribution for 18 000 TEU Generic Ship PLLCargoFire=5.45E-3 EqFat/shipyear.

Based on the risk model developed for the study, the graphs for the three generic ships have the same aspect as the median ship, only shifted in the upper frequencies and fatalities (the 10 highest scenarios in terms of PLL remains the same for the three generic ships). Hence, the bigger the ship in terms of TEU, the higher the probability and the consequence of a fire. The line crossing each of these graphs, representing the iso-risk of the median ship, can be used as a reference.

It is particularly blatant for the generic ship 1 (twin island, 18 000 TEU) and generic ship 2 (single island, 7 500 TEU): several scenarios have a higher individual PLL than all the scenarios combined for the median ship.

It should be noted that the severe scenario, for most of them, is fire happening below deck.

3.9.2.3.2 Cargo Loss scenarios plots on a Risk Matrix

Figure 52 displays the distribution of the PLC amongst the different scenarios for the median ship. Once again, as for the PLL, the most contributing scenarios (which represent more than 10% of the PLC when summed) are the following:

Table 32: Most contributing scenarios in terms of PLC.

Scenario Id.	Scenario description
38	fast fire below deck, uncontrolled, Total Loss.
44	explosion below deck, uncontrolled, Total Loss.
18	explosion on deck, uncontrolled, major damage to the ship.

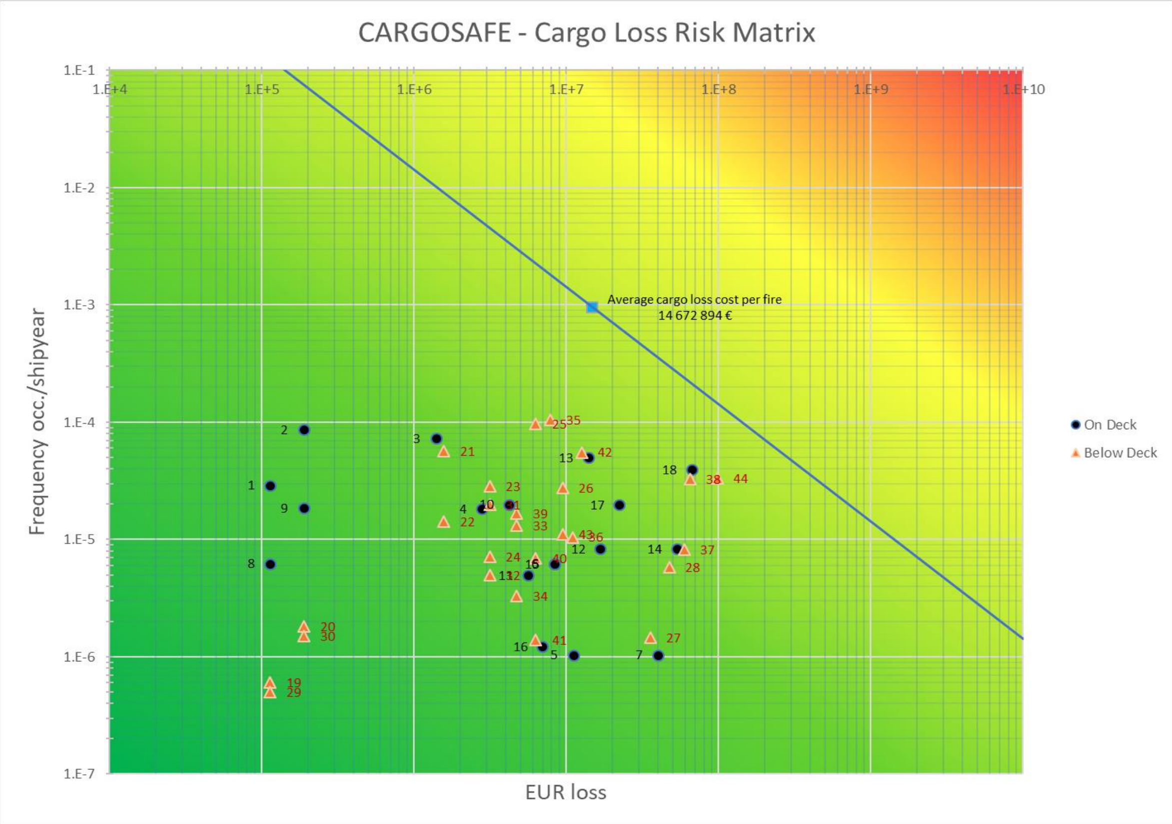


Figure 52: PLC distribution for 2 600 TEU Median Ship with PLCCargoFire=14 125 €/shipyear.

Figure 53-Figure 55 also display this PLC distribution for the three generic ships.

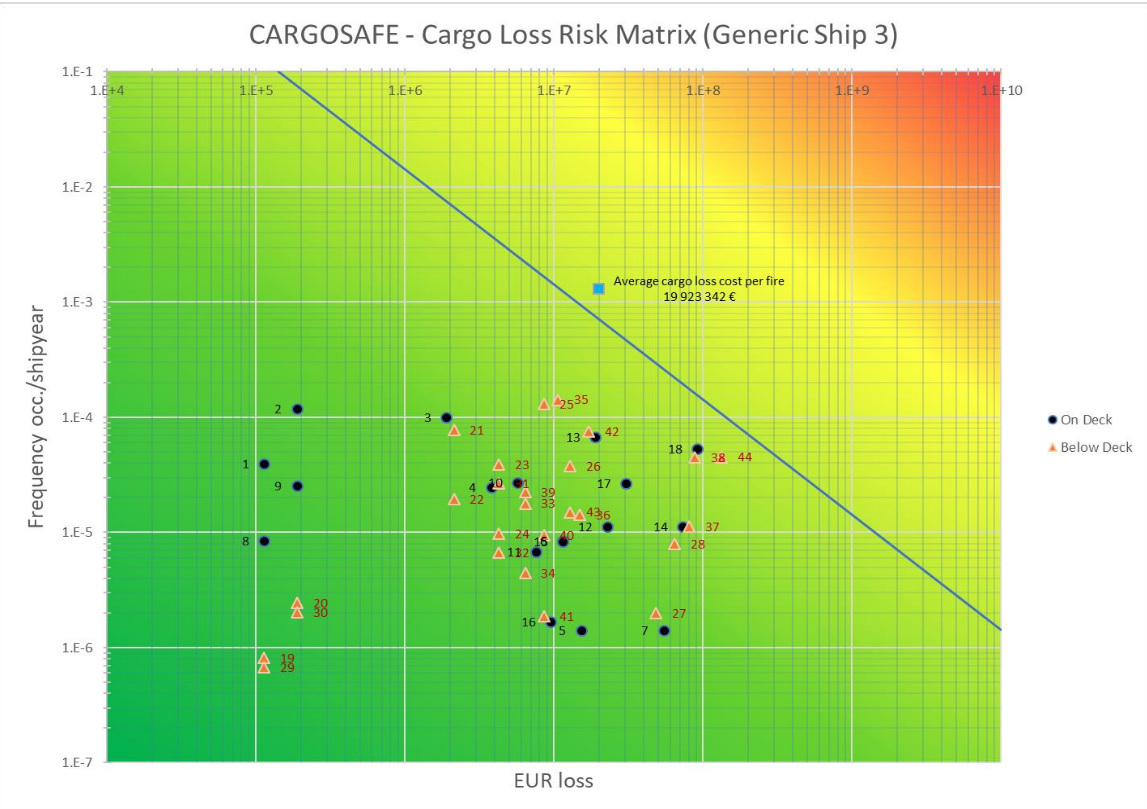


Figure 53: Distribution of PLC for 3 500 TEU Generic Ship PLCCargoFire=26 055 €/shipyear.

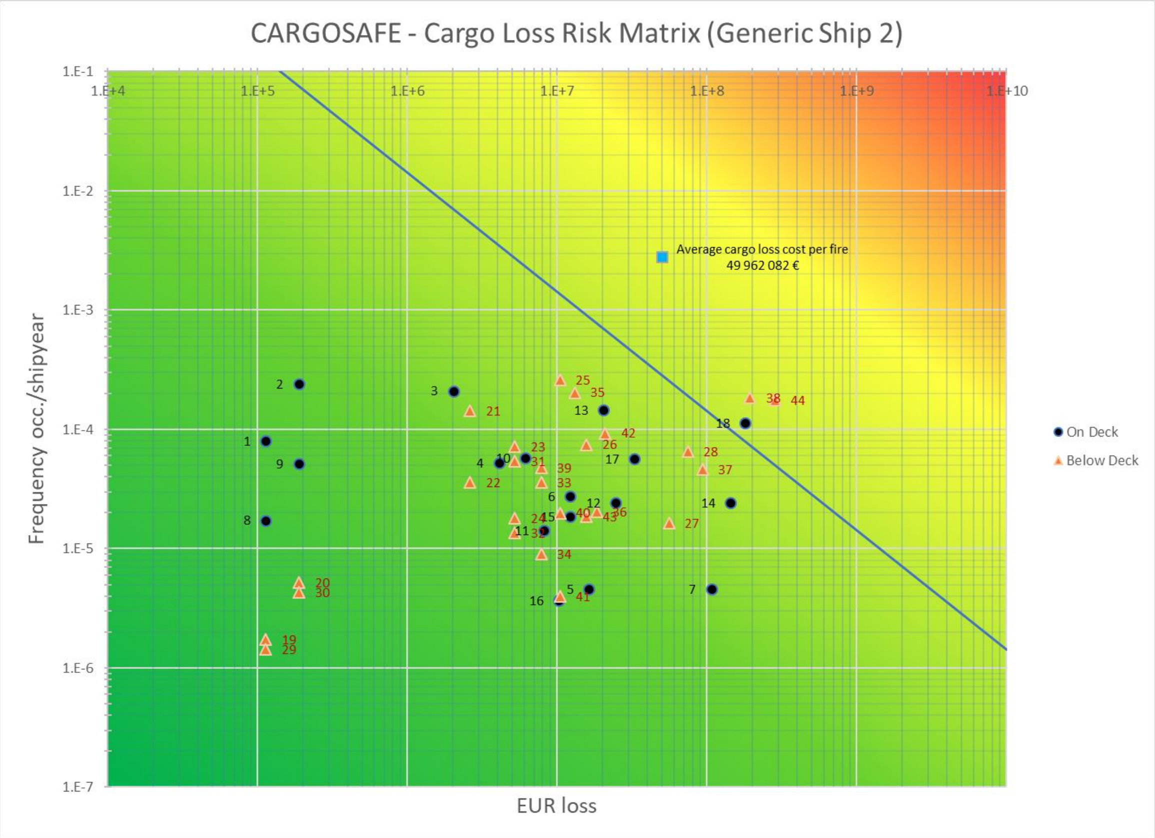


Figure 54: Distribution of PLC for 7 500 TEU Generic Ship PLCCargoFire=138 744 €/shipyear.

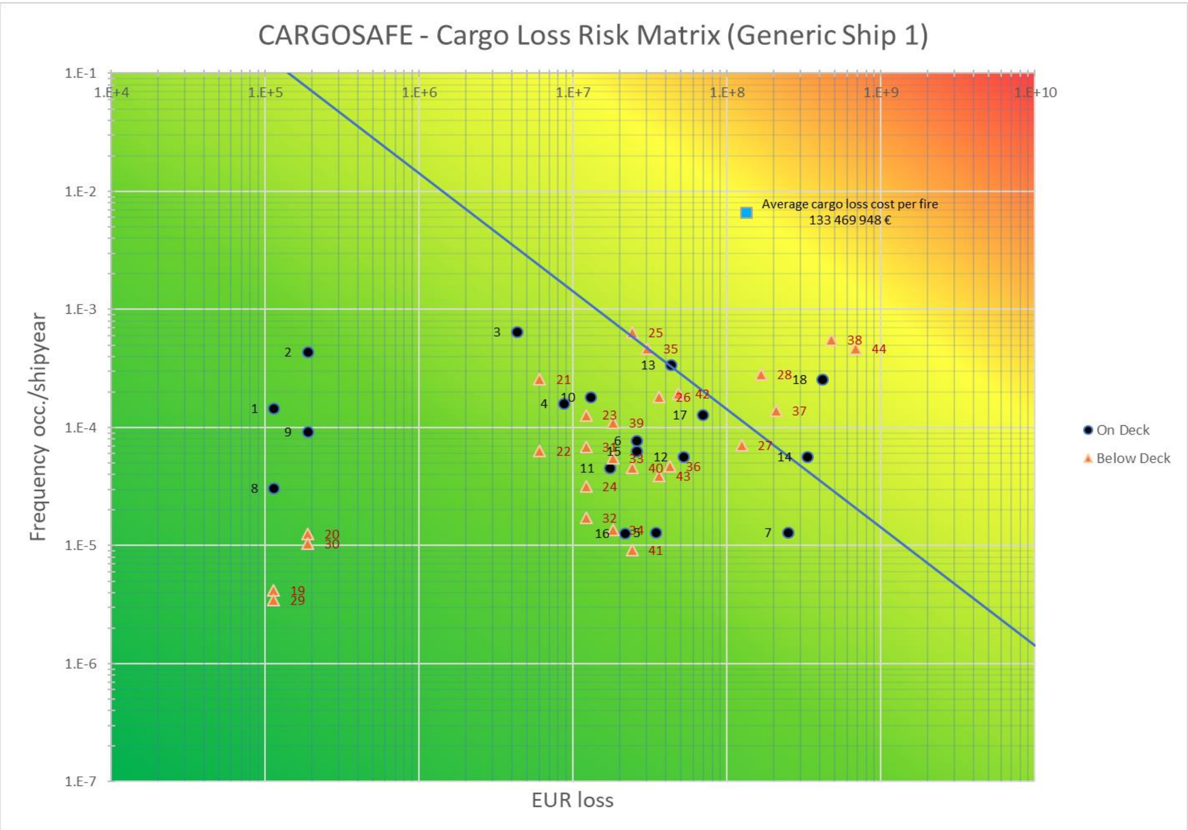


Figure 55: Distribution of PLC for 18 000 TEU Generic Ship PLCCargoFire=889 546 €/shipyear.

Based on the risk model developed for the study, the graphs for the three generic ships have the same aspect as the median ship, only shifted in the upper frequencies and fatalities (the 10 highest scenarios in terms of PLC remains the same for the three generic ships). Hence, the bigger the ship in terms of TEU, the higher the probability and the consequence of a fire. The line crossing each of these graphs, representing the iso-risk of the median ship, can be used as a reference. Scenario 28 (uncontrolled slow fire below deck) is growing in importance as the capacity of the ship increases.

It is once again particularly blatant for the generic ship 1 (twin island, 18 000 TEU) and generic ship 2 (single island, 7 500 TEU): a great number of scenarios have a higher individual PLC than all the scenarios combined for the median ship.

Like for the PLL, PLS seems to be dominated by below deck fires.

3.9.2.3.3 Ship Loss scenarios plots on a Risk Matrix

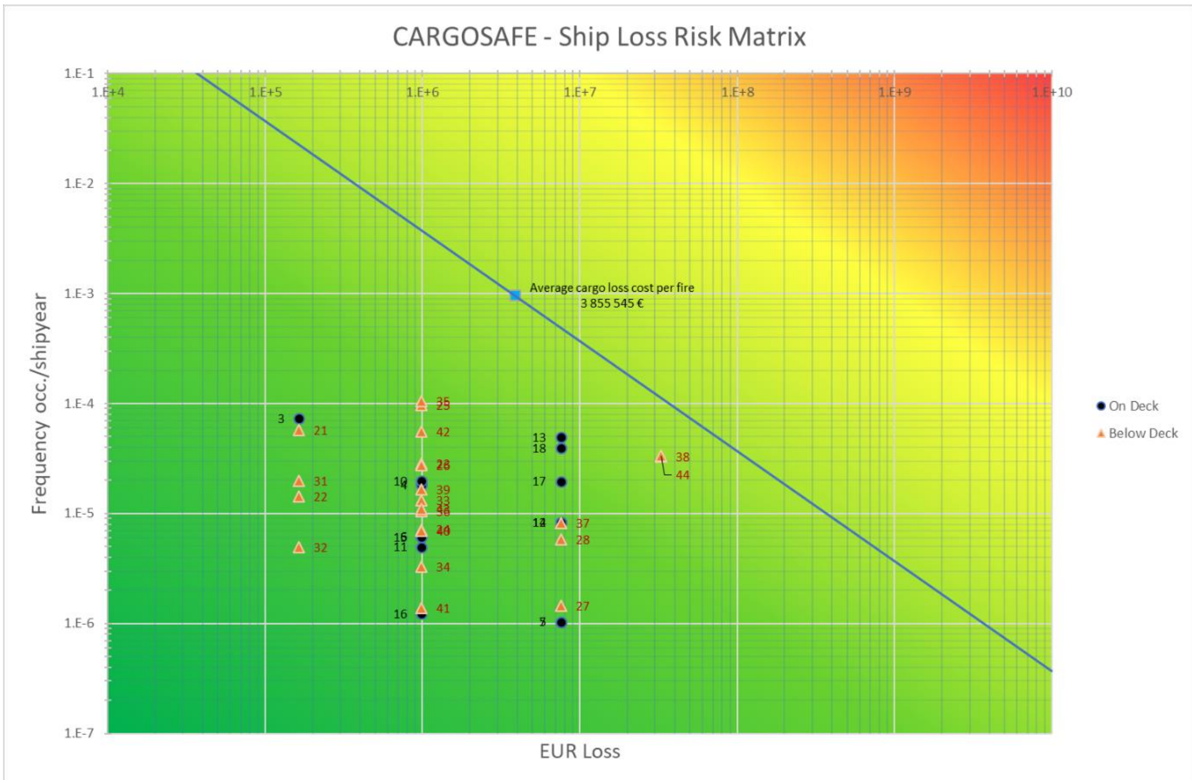


Figure 56: Distribution of PLS for 2 600 TEU Median Ship with PLSCargoFire= 3 712 €/shipyear.

The graph above displays the distribution of the PLS amongst the different scenarios for the median ship. Once again, as for the PLL, the most contributing scenarios (which represent more than 10% of the PLS when summed) are the following:

Table 33: Most contributing scenarios in terms of PLS.

Scenario Id.	Scenario description
38	fast fire below deck, uncontrolled, Total Loss.
44	explosion below deck, uncontrolled, Total Loss.
13	fast fire on deck, uncontrolled, major damage to the ship.

Figure 57Figure 59 also display the PLS distribution for the three generic ships.

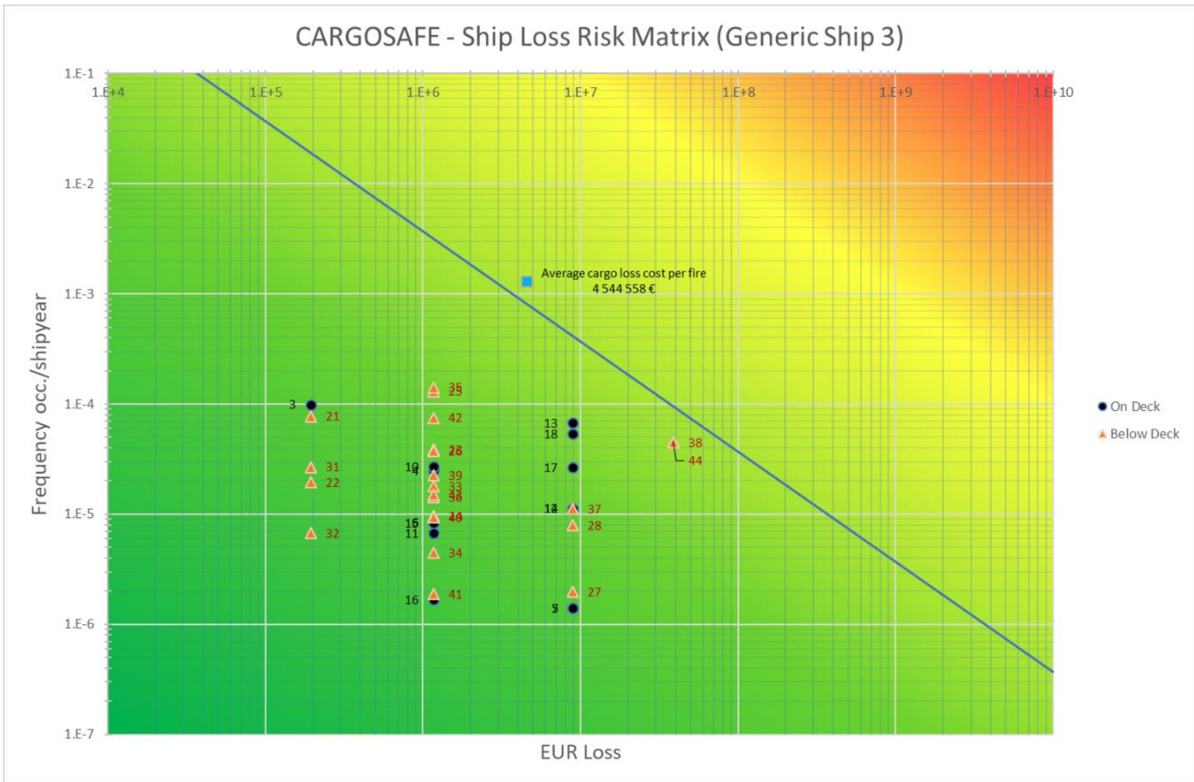


Figure 57: Distribution of PLS for 3 500 TEU Generic Ship PLSCargoFire=5 943 €/shipyear.

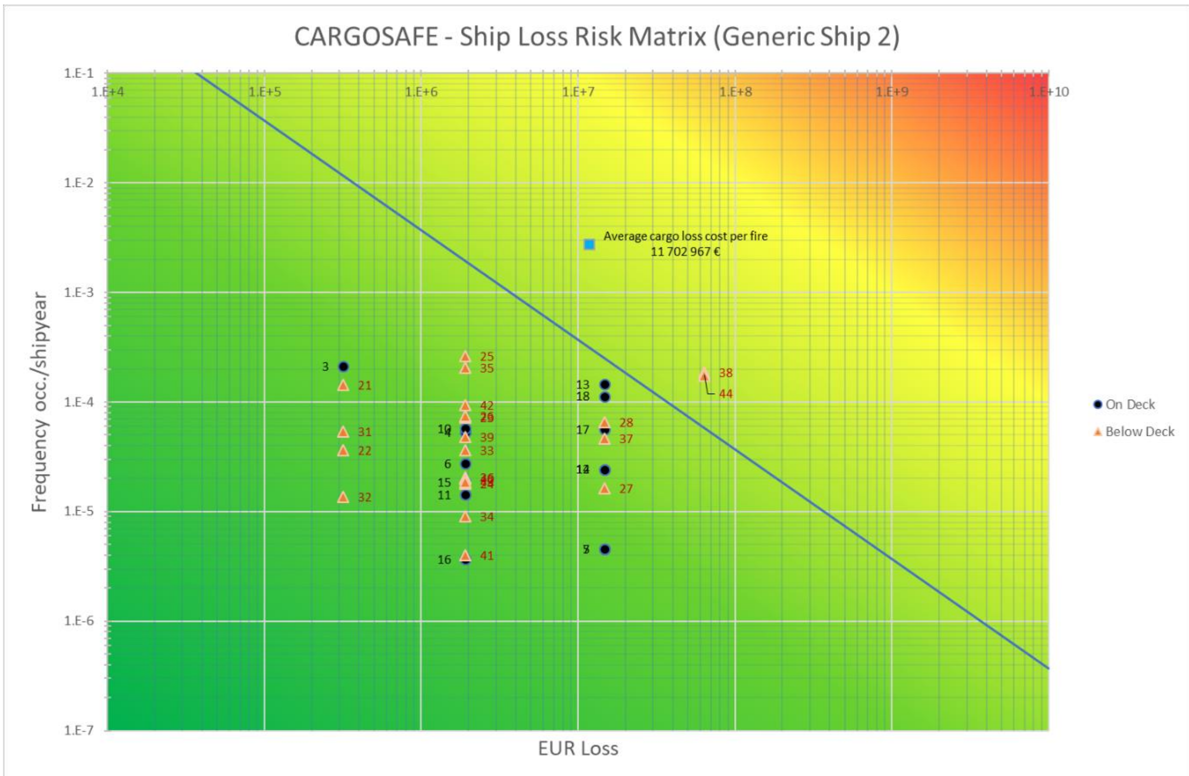


Figure 58: Distribution of PLS for 7 500 TEU Generic Ship PLSCargoFire=32 499 €/shipyear.

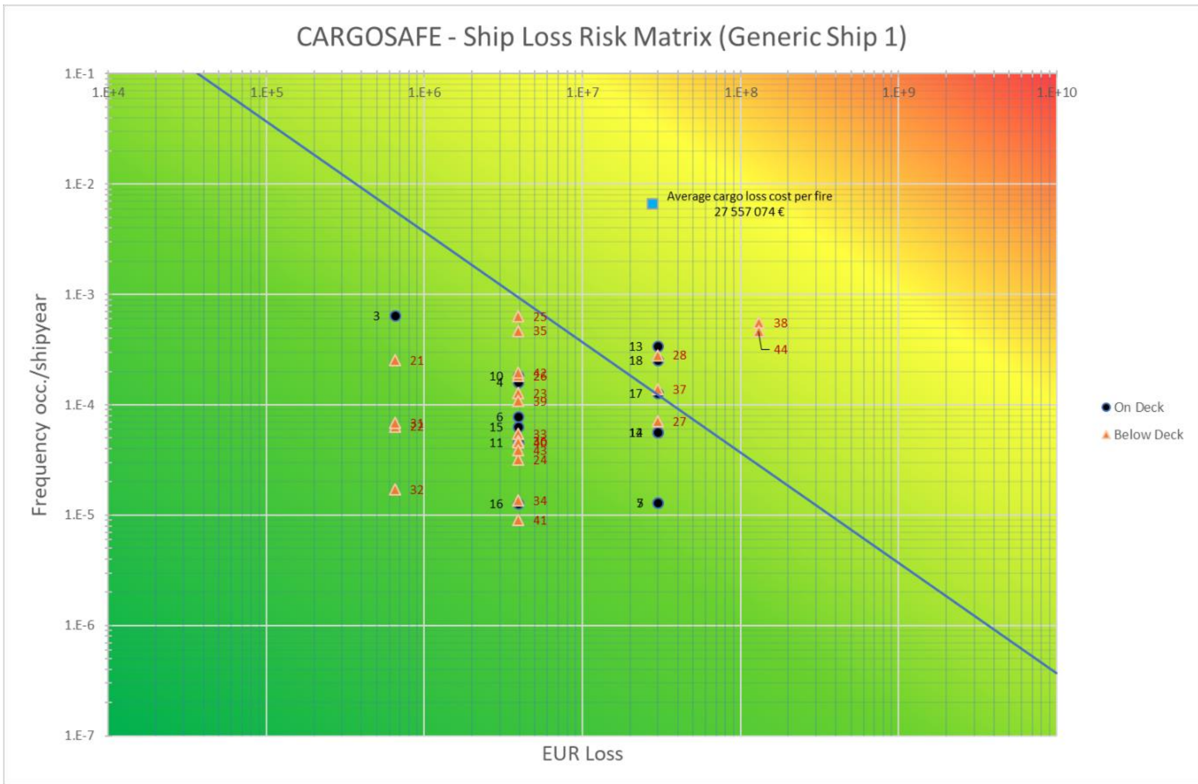


Figure 59¨Distribution of PLS for 18 000TEU Generic Ship PLSCargoFire= 183 661 €/shipyear.

Based on the risk model developed for the study, the graphs for the three generic ships have the same aspect as the median ship, only shifted in the upper frequencies and fatalities (the 10 highest scenarios in terms of PLS remains the same for the three generic ships). Hence, the bigger the ship in terms of TEU, the higher the probability and the consequence of a fire. The line crossing each of these graphs, representing the iso-risk of the median ship, can be used as a reference. Again, scenario 28 (uncontrolled slow fire below deck) is growing in importance as the capacity of the ship increases.

It is once again particularly blatant for the generic ship 1 (twin island, 18 000 TEU) and generic ship 2 (single island, 7 500 TEU): a great number of scenarios have a higher individual PLS than all the scenarios combined for the median ship.

Unlike the PLL distribution, there is not any clear dominance of the below deck fires in term of impact on the PLS.

3.10 Sensitivity analysis

A sensitivity analysis is the study of how much a variation in a model input (numerical or otherwise) impacts the output results.

This paragraph investigates the variation of several parameters and dependent probabilities in the risk models (both in hold and on deck). The purpose is to assess how sensitive the output is to variations in each input variable and identify the main risk contributors.

3.10.1 Method

The method used for the sensitivity analysis is as follows:

a. Selected parameters and probabilities of the risk and consequence models were increased and decreased by a certain percentage or by adding fictitious occurrences of an event or by changing the rules (e.g. expert judgement to manage “unkown” cases, e.g. smoke detection y/n/unknown, and how they were be distributed in the risk model) used for the model when data was missing; and

b. In general, each parameter was changed individually, except when dealing with “Unknown” cases related to the efficiency of the CO_2 system (“In Hold” risk model), which had a direct impact on the following tiers “Containment in HOO”.

3.10.2 Risk model sensitivity analysis

3.10.2.1 Range of parameters’ variations

Table 34 presents the different parameters selected for the sensitivity analysis and the range of variations considered.

Table 34: Ranges of variations for the parameters considered.

Risk model	Where in the model	Parameters	Description of range of variation
Both	Initial frequency / Tier 0	Fire frequency per TEUyear	Refer to Table 11. The calculation of the initial fire ignition frequency per shipyear based on the fire frequency per TEUyear is: - overestimating the value for the Generic Ship 1 (few number of vessels in this category); and - underestimating the value for the Generic Ship 3 (large number of vessels in this category). Assumes a variation of +30% for Generic Ship 1 and -30% for Generic Ship 3. The calculation of the initial fire ignition frequency per shipyear based on the fire frequency per TEUyear for Generic Ship 2 is acceptable.
	Initial frequency / Tier 0	Ratio cargo On Deck / Total cargo	Assumes +/- 10% for On Deck / Total cargo based on questionable accidents in the CARGOSAFE database.
	Fire growth / Tier 1	Slow and Fast fires	Assumes: - 2 Slow fires become 2 Fast fires; and - 1 Fast fire becomes 1 Slow fire. The total number of events remains unchanged. No variation on “Explosion leading to fire”.
	Consequence model	Cost of total loss	Assumes +10%/-10% of the cost to take into account possible approximations in the cost evaluation.
On Deck	Detection & Local first response in COO / Tier 2	Manual detection of fire and local fire fighting on the container of origin	Assumes +1/-1 successful event, considering the total number of events remains unchanged.
	Firefighting / Tier 3	Containment of fire in bay of origin	Assumes +1/-1 successful event, considering the total number of events remains unchanged.
In Hold	Detection & Local first response in COO / Tier 2	Manual detection of fire and local fire fighting on the container of origin	Expert judgement. Assumes “*Unsuccessful/Successful*” ration of 95/5 instead of 99/1 for “Slow fire” and “Fast fire”.
	Smoke detection & CO_2 system / Tier 3	Automatic detection and use of CO_2 system	Assumes a distribution of Unknown cases for use of CO_2 according to known cases for "*Extinguishment*", "*Controlled*" and "*Unsuccessful*". Need to consider effect of this distribution on Tier 4, where the same assumption is made.
	Firefighting / Tier 4	Containment of fire in hold of origin	Assumes +1/-1 successful event, considering the total number of events remains unchanged.

3.10.2.2 Results

Figure 60 presents the effects of the parameters' variations on the reference PLL of the model (median ship).

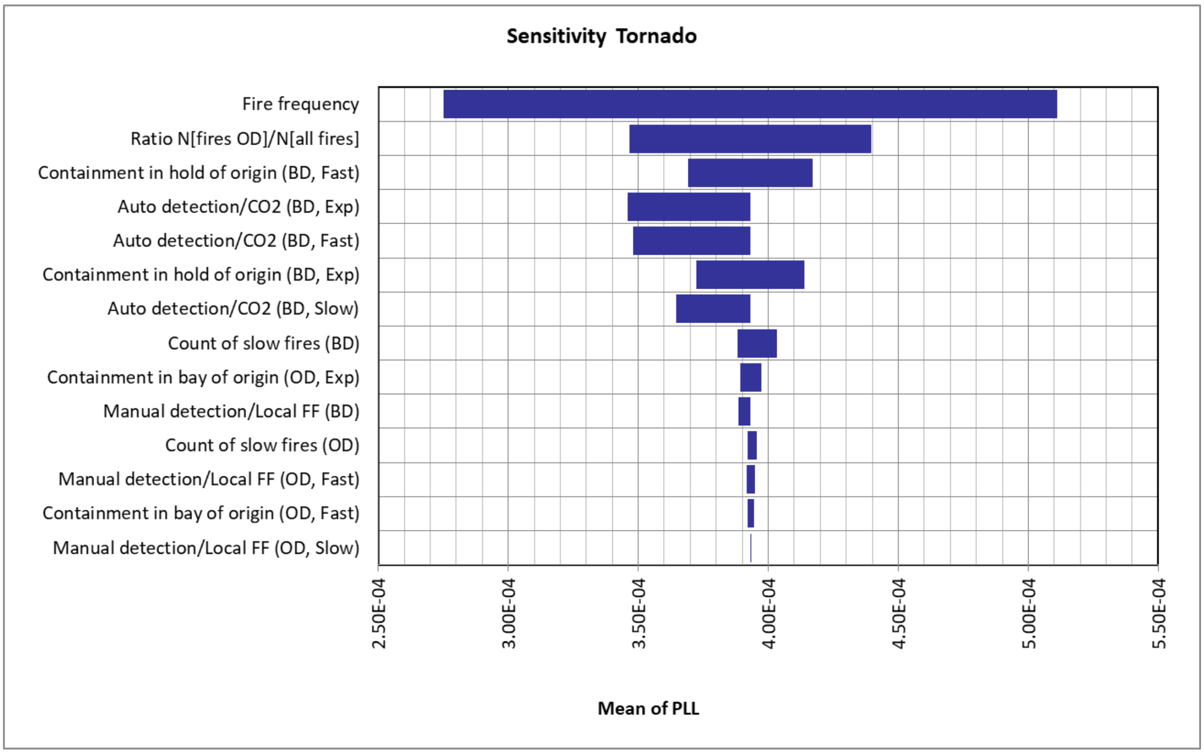


Figure 60: Tornado diagram - Effects on the reference PLL.

Figure 60 presents the effects of the parameters' variations on the reference TPL of the model (median ship).

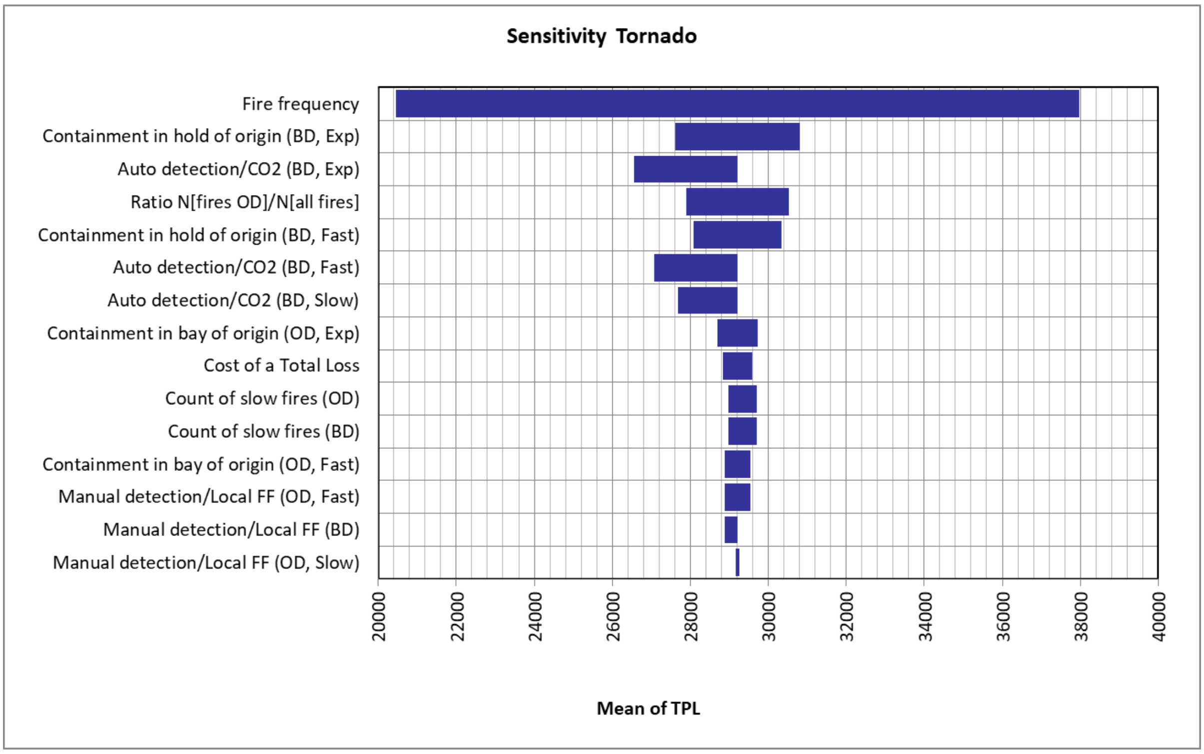


Figure 61: Tornado diagram - Effects on the reference TPL.

As it can be observed in Figure 60, the model is quite sensitive to the frequency of fires per TEUyear, which was expected based on Table 34. There is also a noticeable sensitivity related to the distribution of unknown cases for use CO_2 system as well as the containment in the hold of origin, followed by the ratio of fires On Deck / Total cargo on board. The model is more driven by the “below deck” cases: amongst the 10 most sensitive parameters, 7 of them are applied to “below deck” scenarios.

Figure 61 shows a high sensitivity of the reference model to the frequency of fires per TEUyear, followed by the distribution of unknown cases for use CO_2 system, as well as the containment in the hold of origin. Then comes the cost of a Total Loss and the ratio of fires On Deck / Total cargo on board. As for the PLL, the calculation of the TPL in the model is more driven by the “below deck” cases: amongst the 10 most sensitive parameters, 6 of them are applied to “below deck” scenarios. The cost of the total loss of the vessel appears in 9^{th} position.

3.10.2.3 Risk model sensitivity of generic ships

The reference risk model presented applies for the Median Ship (cf. paragraph 3.2.2.2). By construction, the Median Ship and the Generic Ship 3 are very similar. Hence, the fire-fighting risk model presented for the Median Ship is also applicable to the Generic Ship 3 (cf. appendices E and F).

However, Generic Ships 1 and 2 differ. Based on quantified fault trees and contribution trees, the different aspects and impact of ship size were evaluated and taken into account into their respective risk models.

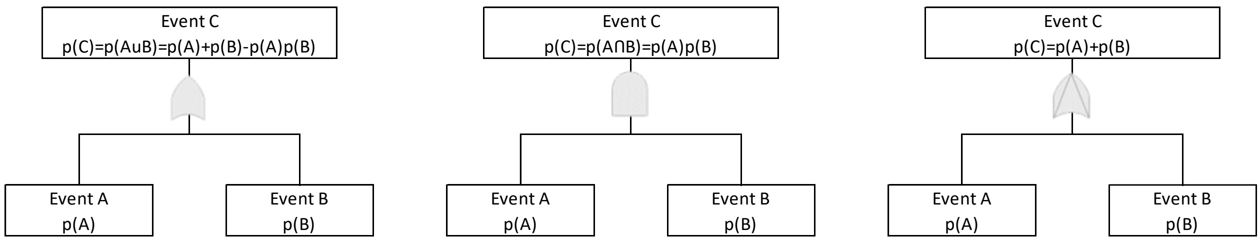
The fault trees are presented in annexes H, I, J, and K.

The fault trees were populated based on expert judgement, past studies (FIRESAFE), and calibrated on firefighting event trees values (top event). The fault trees probabilities influenced by event trees parameters or ship size were evaluated based on geometrical and expert considerations.

Some fault tree events are duplicated in the fault trees presented in appendices. However, given the contribution of each in the full calculation, the influence is low. This is detailed in the next section.

3.10.2.3.1 Bias while quantifying the fault trees

One of issues encountered while creating the fault trees was handling the dependence between several nodes. The formulas used in the fault trees are presented in Figure 62.



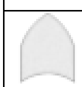
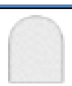
Symbol	Meaning
	“Or” (both events can happen at the same time)
	“And”
	“Or” (both events are mutually exclusive)

Figure 62: Different formulas used to populate the fault trees.

Indeed, it is assumed in these formulas that the events A and B are independent (this assumption is necessary for the formula p(A∩B)=p(A)p(B) to be valid). This cannot be the case when the same event is repeated at the bottom of the fault tree, for instance when the weather has an impact on several events. Figure 63 displays an example of this case.

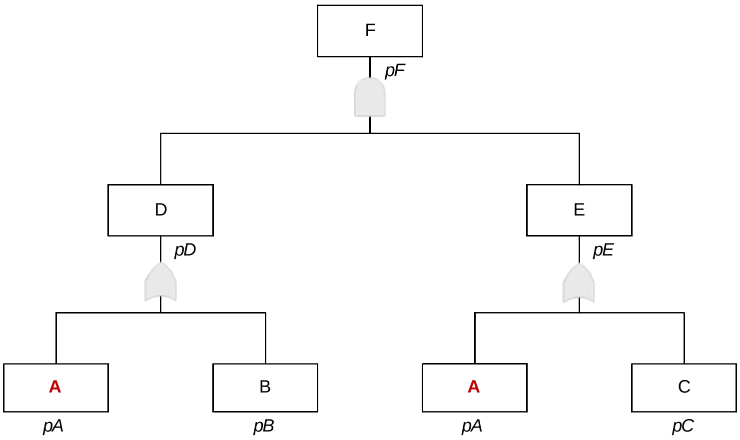


Figure 63: Simple case where the formulas presented above cannot be used.

the calculation of p_F is the following:

$$\begin{cases} p_D = p_A + p_B - P(A \cap B) = p_A + p_B - p_A p_B \\ p_E = p_A + p_C - P(A \cap C) = p_A + p_C - p_A p_C \end{cases}$$

$$p_F = P(D \cap E) \neq p_D p_E$$

A, B and C are assumed independent, but due to the presence of the event A in the events D and E, the two latter are not. Hence, the simple formula cannot be used.

The two options were either to consider this bias minimal, or to reshape the fault trees to take this repetition into account. Due to the small value of the probabilities concerned by this issue, the choice of whether of these options has a minor impact on the results (less than 1% difference between the two).
It has been decided to correct the fault tree when the correction did not reduce its readability, and otherwise to ignore the bias.

Annex L presents the quantified fire-fighting risk models for Generic Ship 1 and 2.

3.10.3 Consequence model sensitivity analysis

3.10.3.1 Range of parameters' variations

Table 35 presents the different parameters selected for the sensitivity analysis and the range of variations considered.

Table 35:Ranges of variations for the parameters considered.

Risk model	Where in the model	Parameters	Description of range of variation
Both	General cost estimation	Ship damage cost	Refer to Table 25.

			Assumes a variation of +10%/-10% for median ship. Accounting for any extra or overestimation of the repair cost for different accidents.
	General cost estimation	Cargo and container cost	Assumes +20%/-20% of the total cost of cargo and container cost. Assuming the variance on cargo shipped.
	General cost estimation	Environmental cost	Assumes +25%/-25% variation on all categories of Table 27. Due to high uncertainty on the environmental cost of an incident.
	General cost estimation	Salvage cost	Assumes +10%/-10% of the cost to take into account possible approximations in the cost evaluation.
On Deck	All scenarios that result in *bay controlled* as the risk model outcome	Cargo loss	Assumes +0.25/-0.25 tiers involved on the fire, considering the fire is highly dependent on the cargo being transporter.
	All scenarios that result in a *bay uncontrolled* fire as the risk model outcome	Cargo loss	Assumes +1/-1 bay involved on the fire, considering the fire is highly dependent on the cargo being transported.
	All scenarios that result in an *uncontrolled* fire as the risk model outcome	Cargo loss	Assumes +10%/-10% cargo involved on the fire, considering the fire is highly dependent on the cargo being transporter.
	Slow fire on deck consequence model	External assistance required and received	Assumes +1/-1 event, considering the total number of events remains unchanged.
	Fast fire on deck consequence model	Damage to ship and other bay	Assumes +1/-1 event, considering the total number of events remains unchanged.
	Fast fire on deck consequence model	Abandonment or evacuation	Assumes +1/-1 event, considering the total number of events remains unchanged.
	Explosion on deck consequence model	Damage to ship and other bay	Assumes +1/-1 event, considering the total number of events remains unchanged.
In Hold	All scenarios in which the fire was *extinguish* using the CO_2 system	Cargo loss	Assumes +0.5/-0.5 tiers involved on the fire, considering the fire is highly dependent on the cargo being transporter.

	All scenarios in which the fire was *controlled* using the CO_2 system	Cargo loss	Assumes +1/-1 tiers involved on the fire, considering the fire is highly dependent on the cargo being transporter.
	All scenarios in which the fire was *successful controlled* at the HOO	Cargo loss	Assumes +1.5/-1.5 tiers involved on the fire, considering the fire is highly dependent on the cargo being transporter.
	All scenarios in which the fire was *uncontrolled*	Cargo loss	Assumes +1/-1 cargo holds involved on the fire, considering the fire is highly dependent on the cargo being transporter.
	Slow fire below deck consequence model	External assistance required and received	Assumes +1/-1 event, considering the total number of events remains unchanged.
	Slow fire below deck consequence model	External assistance required and received	Assumes +1/-1 event, considering the total number of events remains unchanged
	Fast fire below deck consequence model	External assistance required and received	Assumes +1/-1 event, considering the total number of events remains unchanged
	Fast fire below deck consequence model	Damage to ship and other bay	Assumes +1/-1 event, considering the total number of events remains unchanged
	Explosion fire below deck consequence model	Abandonment or evacuation	Assumes +1/-1 event, considering the total number of events remains unchanged

3.10.3.2 Results

Figure 64: Tornado diagram - Effects on the reference TPL.Figure 64 presents the effects of the parameters' variation on the reference TPL of the median ship. As can be observed, the parameter with the highest influence on the consequence model is the cost of the cargo, including the container. As previously mentioned, this parameter comes also with a high uncertainty, due to the variety of transporter goods. On the same line, within the tenth rank influential parameters in found to be all the parameters related to estimated cost. All of which also carry a high uncertainty due to the limited public information available.

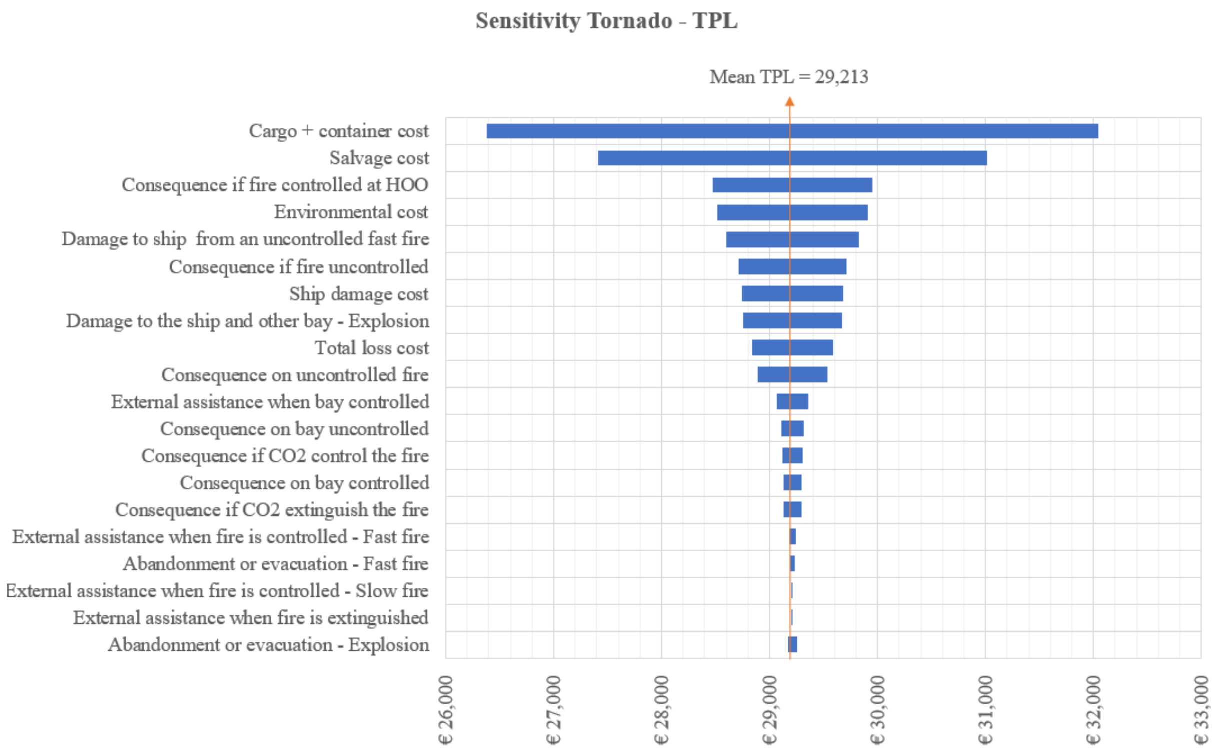
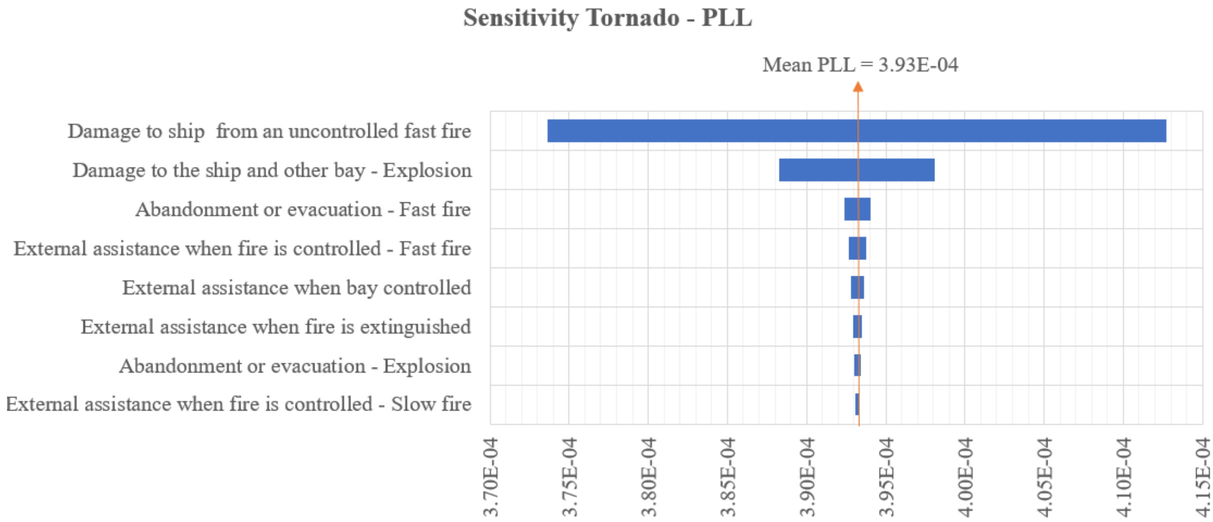


Figure 64: Tornado diagram - Effects on the reference TPL.

Figure 65 shows the effects of the parameters' variation on the reference PLL of the median ship. The parameter with the largest influence on the PLL is the damage that an uncontrolled fast fire below deck can produce. This is the case for famous incidents like the MOL Prosperity, MSC Flaminia, or MAERSK Honam. It would highly depend on the definition of major and minor damage. On the same line, the damage to the ship produced by an explosion is also one of the parameters that affects the potential loss of life. The impact radius of an explosion highly depends on



the material involved. Therefore, there is a high uncertainty on this parameter.

Figure 65: Tornado diagram - Effects on the reference TPL.

4. RISK CONTROL OPTIONS

The objective of Task 3 was to identify and select the most promising RCOs that shall be pushed forward for Cost Effectiveness Analysis in Task 4. As specified in the project tender, the following steps were to be followed:

- Identify a range of Risk Control Measures (RCM) and, subsequently, Risk Control Options (RCO).
- Evaluate the effectiveness of the RCMs in reducing risk.
- Select the most promising RCOs, in terms of cost, Technology Readiness Level (TRL) and risk reduction, to be subject to effectiveness assessment by computational modelling and analysis, or by testing.
- RCOs not selected for modelling/ analysis/ testing shall be subject to qualitative assessment or quantitative one based on expert judgement.
- Finally select the most promising RCOs to be subject to Cost Effectiveness Analysis.

To distinguish RCMs and RCOs the following definition is used: A risk control option (RCO) is a combination of two or more risk control measures (RCMs). A risk control measure is a mean of controlling a single element of risk.

Task 3 corresponds to Step 3 – Risk Control Options in the IMO FSA Guidelines [43].

4.1 Determination of areas needing control

On median ships and lower size ships the PLL, PLC and PLS are of values that may not offer a large budget for risk control options. With the size increasing the budget should considerably increase both on cost to avoid a fatality and on cost to avoid Cargo loss and ship loss. While the previous FP54-IN2 could not conclude on hardware RCOs positively, the larger ships may offer sufficient budget for hardware RCOs and with focus on cargo hold fires which are the main risk contributors.

As discussed in HAZID workshops with the TEG, and in correspondence to the findings above, the main areas of interest will be:

- Prevent fire of occurring and in relation to the misdeclaration/undeclaration or dangerous cargo.
- Detect the fire sufficiently early to try a local extinguishment by crew or release a first shot of extinguishing agent.
- Extinguish or at least control the fire in the hold of origin for a long period of time.
- Control the fire at the bay of origin or the bay above the hold of origin.

The added value of task 2 was to provide quantified reference risk level of cargo fire risks and the respective contribution of every aspect, all dynamically implemented in a risk model. The RCOs developed in task 3 will need to derive the task 2 risk model and evaluate the safety gains over the three ship types.

4.2 Methodology

4.2.1 Risk Control Measures (RCMs)

RCMs were identified by reviewing the results and notes from the HAZID in Task 1, from Technical Expert Group (TEG), from risk analysis and experience from Task 2, and from the project team's research. From here, each fire protection barrier was subject to separate assessment to define RCOs.

4.2.2 Risk Control Options (RCOs)

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

The process of selecting RCOs for analysis in Task 3 was achieved in several stages. In the first stage, the summary from the hazard identification (HAZID) workshops that were performed in Task 1 was used. In the second stage, this summary was used to arrive at a list of potential RCMs. Thus, these two steps included a compilation of potential RCOs that were interesting and considered relevant according to the feedback from the practitioners in HAZID workshops, expert judgement from the Technical Expert Group (TEG), and the engineering and scientific judgement of the project team for each fire protection barrier (Prevention, Detection, Firefighting, and Containment).

4.2.3 Effectiveness assessment

Effectiveness assessment of each RCO was derived by comparing three parameters qualitatively, namely, TRL (Technological Readiness Level), cost and risk reduction potential.

i. TRL (Technological Readiness Level)

Relevant TRL of respective RCOs is assigned based on the maturity of the RCO, its availability in its current format in the market and its utility[44].

ii. Risk reduction potential and method of analysis

Risk Reduction Potential of an RCO refers to the potential change in probability of ignition and the consequence of an event onboard a containership by implementing the specific RCO. Thus, Risk Reduction Potential of an RCO demonstrates whether there is any change in the probability of UHE compared to the probability of the reference case.

A combination of qualitative and quantitative approaches is used to arrive at the Risk Reduction Potential of each RCO as recommended by the FSA Guidelines[45]. Available accident statistics, accident literature and expert judgement were used to identify the failure pathways that were relevant for each RCO in the compiled list agreed with EMSA.

Prevention:

The risk reduction potential of each Prevention RCO (P-RCO) was derived by using quantified nodes in the Prevention Risk Model. The procedure was as follows: Starting at the top tier in the Global Risk Model for Prevention (the left side of the Bow Tie) which consists of the fault tress (FTs). Each failure pathway was then matched all the way to the bottom nodes by anchoring them with accident literature, available data, and engineering estimates. This was followed by the consideration of whether that a specific P-RCO has any observed effect on the top tier of the respective FTs. And if there is an observed effect, then to what extent does this have an impact on reducing ignition risk onboard compared to the base case. Since only the first tier in the Prevention Risk Model is quantified based on the available accident statistics, expert judgement among the project team was used to arrive at new probability.

It was also considered whether implementation of each P-RCO has any impact on the subsequent chain of events and their consequence, as depicted in the Event Tree (ET) for the Global Risk Model in CARGOSAFE (See sections 3.6.2, 3.6.33.6.3 , and Figure 36, Figure 37 Figure 38, Figure 39). In other words, whether implementation of a specific P-RCO onboard shall delay the fire growth, i.e., whether it shall have any effect on slow fire, fast fire, or explosion and how big of an overall risk reduction impact is expected was also qualitatively assessed. As a result, this informs whether severity of consequence is affected by the implementation of a P-RCO.

Detection:

The risk reduction potential for the D-RCOs was assessed using several methods. For scenarios below deck (BD), firstly, the performance of the current smoke detection system was assessed quantitatively using a computational model to assess the smoke movement and quantify the potential detection times for the 3 generic ship types. These

[44] Héder, M. (2017). From NASA to EU: The evolution of the TRL scale in Public Sector Innovation. *The Innovation Journal*, *22*(2), 1-23.
[45] IMO, MSC-MEPC.2/Circ.12/Rev.2: Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process, 2018.

results acted as a baseline for assessing the effectiveness of D-RCOs for BD scenarios. Further simulations and fault tree analysis were then used to assess the potential quantitative improvements in performance from the designated RCOs. For RCOs applicable on deck (OD), having no defined detection system in place, simulation results for the RCOs (i.e., no baseline results) and fault tree analysis were used. Combining these methods, the potential effectiveness of the RCOs was then qualified using the "k-factor" method cf. section 5.2.4.1 in an internal core team workshop held at DBI on 8th June 2022.

Firefighting & Containment:

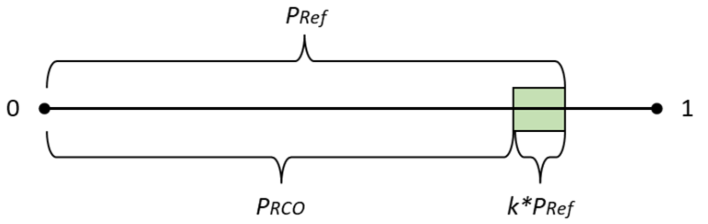
For both firefighting and containment RCOs, fault tree analysis and expert judgment were used together during internal workshops at DBI on the 8. and 15. November 2020 in discussion with members of the core team. These resulted in an estimation of the risk reduction potential via the same "k-factor" method used for detection RCOs.

4.2.4 Risk reduction potential

4.2.4.1 Effectiveness in reducing risk

When an RCO is applied, it will cause some effect on the probability of an event designated in the developed ET (cf. section 4). To quantify this effect, a parameter k is defined to determine the risk reduction effectiveness of the RCO (which can be positive or negative).

The reference probability of an event occurring is numerically defined as being between 0 and 1. To account for the



relative impact of the RCO on the event, a k-factor was defined as a complementary probability to the event. If the effect is positive it is subtracted from the reference probability, and if the effect is negative, it is added to the reference probability.

$$P_{RCO} = P_{Ref} \pm k * P_{Ref}$$

For example, the probability that a fire is detected on the container ship is 0.7, if an RCO is applied which has been assessed to have a k-factor (risk reduction rate) of 0.4, the probability for this node is then updated via the above equation and set to 0.42 in the relevant node on the event tree.

$$P_{RCO} = 0.7 - 0.4 * 0.7 = 0.42$$

4.2.4.2 Sensitivity analysis

Sensitivity analysis is the study of how uncertainty (numeric or otherwise) in the model output is assigned to different sources of uncertainty in the model input. Sensitivity analysis can be used to study the relationship between model output and model input, and to determine which input factors have lesser or greater influence on the output. A related practice is uncertainty analysis, which focuses on quantifying uncertainty in model outputs.

Uncertainty analysis involves quantitatively assessing the uncertainty of model components (input variables, parameters) for a given situation and deriving an uncertainty distribution for each output variable. Uncertainty analysis is a key component of model-based risk analysis and decision making because it provides risk assessors and decision makers with information about the accuracy of model outputs.

4.3 Prevention

RCOs for Prevention are identified with the purpose to mitigate the risk for ignition onboard.

Ignition sources onboard can be various and were already discussed by participants in HAZID (Task 1) and during construction of the Global Risk Model using Bow Tie approach with Fault Tree depicting Prevention failure pathways. This was further discussed in detail in Risk Analysis (Task 2). From Task 1 and 2, it was concluded that dangerous goods (DG) that are not properly declared, were among the key contributors of ignition sources on board containerships. This led to especially consider the following two contributors of ignition while recommending Prevention RCOs:

- Incorrect or missing declaration of DG:

When dangerous goods are incorrectly declared, misdeclared, or undeclared it may cause consequent incorrect stowage and incorrect separation between containers carrying DG. This may lead to self-heating causing spontaneous combustion or explosion.

- Packing/stuffing condition of containers:

Although the Code of Practice for Packing of Cargo Transport Units (CTU-Code) provides clear instructions for packing and stuffing of containers carrying DG and non-DG, there remains the risk of broken packages causing leakage of critical contents leading to subsequent exothermal reaction either due to limitations within the CTU-Code itself or due to non-compliance of the CTU-Code.

RCOs identified for Prevention were, as specified in the Project Tender, subject to qualitative evaluation. The procedure and outcome are further described in the following sections.

4.3.1 Risk Control Measures (RCMs)

A list of 18 RCMs was identified following the generic process described in section 4.2.1

From this list of 18 RCMs, a qualitative assessment with the project team together with EMSA was performed. The aim was to arrive at a smaller selection of RCMs that were considered most viable for further assessment which aligned with EMSA's interest for the project. In general, safety measures of technical nature were of interest in this project. This means, potentially interesting and relevant RCMs are those that can be implemented onboard, rather than procedural or operational RCMs. Although, for Prevention, it is natural to include RCMs that are safety measures which can be applied before a container is loaded onboard. Following discussion and dialogue with EMSA, some of the RCMs were considered out of scope and some were considered interesting to proceed further with. The timeline to frame the Prevention work used in HAZID was also used in this task to further frame the context and scope of the RCMs and following RCOs in Prevention. See timeline in Figure 6.

A summary of the 18 RCMs together with reference to timeline, on deck (OD) and below deck (BD) and comments from the process is presented in Table 36.

Table 36: Summary of RCMs for Prevention with timeline reference, on deck (OD) and below deck (BD) note and comments.

RCM No	RCM Description	Timeline reference	OD or BD	Comment
1	Improved training of shore side personnel throughout the supply chain; consideration of identification / certification regimes for shippers / handlers	in port	N/A	Listed by several on Hazid. (x3) Considered out of scope for CARGOSAFE.
2	Photo documentation of cargo for AI analyses to provide risk rating of the unit	in port	N/A	Listed by several on Hazid. (x5) Potentially interesting to proceed with. Could be combined with RCM 12.

3	Declaration must be verified by reliable third party	preparation	N/A	Listed by several on Hazid. (x2) Considered out of scope for CARGOSAFE.
4	Revision of the IMDG Code "special provisions and limited quantities"	preparation	OD	Considered out of scope for CARGOSAFE.
5	Communication between carriers about booking rejections so if a booking is rejected partner shipping lines can be aware if the booking is then presented to them.	booking	N/A	Could be combined with RCM 6.
6	Develop common shared keyword database for screening to detect mis-declared or nondeclared DG	preparation	N/A	Could be combined with RCM 5.
7	Communication channel between parties carrying out screening and the regulatory body doing the screening	preparation	N/A	Considered out of scope for CARGOSAFE.
8	Develop common protocol and reporting tools; experienced surveyors to provide instruction to improve quality of inspections	in port	N/A	Considered out of scope for CARGOSAFE.
9	Stowage software planning with comprehensive DG, special cargo functions	in port	OD/BD	Considered out of scope for CARGOSAFE.
10	Stowage planning according to the "Risk-Based Stowage of Dangerous Good on Containerships" (e.g., developed by CINS)	in port	OD/BD	Potentially interesting to proceed with.
11	Increased control by ship operators and stevedores during loading and additional checks that positions agree with stowage plan	in port	OD/BD	Considered out of scope for CARGOSAFE.
12	Container screening tool before/while loading	in port	OD/BD	Could be combined with RCM 2. Potentially interesting to proceed with.
13	Detection methods (gas or temperature detection tools to be used by the crew)	at sea	OD/BD	Preferably combined with Detection RCM.
14	Individual sensors for cargo at risk of self-heating (In container)	in port/at sea	OD/BD	Preferably combined with Detection RCM.
15	Improved monitoring of lashing arrangements	at sea	OD	Promising RCM to proceed with.
16	Improve identification of self-heating goods	in port/at sea	OD/BD	Preferably combined with Detection RCM.
17	Improve test method for self-heating (the test for self-heating may not be sufficient as how it is today)	preparation	N/A	Promising RCM to proceed with.

18	Offer cost incentives for properly declared DG to curb misdeclaration	preparation	N/A	Potentially interesting but not prioritized by EMSA.

From this table 10 RCMs were considered for further development into Risk Control Options (RCOs).

4.3.2 Risk control options (RCOs)

From Table 36 a qualitative assessment with the project team and EMSA was performed. The aim of this was to further filter and group RCMs to generate RCOs deemed most viable for further assessment. The results of this assessment are presented in Table 37.

Table 37: List of RCOs for Prevention.

RCO- P	RCO Title	OD or BD	Combination of RCM(s)
P1	Container screening tool	OD/ BD	RCM 2 + RCM 12
P2	Common database for rejected screening cargo	OD/ BD	RCM 5 + RCM 6
P3	Stowage planning tool	OD/ BD	
P4	Improved control of lashing	OD	
P5	Improve test methods for self-heating cargo	OD/ BD	

In the following sections the five Prevention RCOs are further described.

4.3.2.1 RCO P1 – Container screening tool

The amount of unknown cargo is high today. This surpasses the safety measures related to for example cargo stowage which is based on IMDG Code that dictates where to stow a certain type of cargo, safely. A container screening tool as an RCO shall work in combination with a software with artificial intelligence (AI) and machine learning (ML). This is likely to identify cargo that is not properly declared DG (e.g., mis declared / undeclared dangerous goods) but also to detect poorly packed containers, or containers with poor dunnage and thereby reduce the risk of ignition onboard. The screening shall take part in the port cargo handling. The AI and ML software shall be programmed to screen random number of containers during terminal handling or inspection. In this project the estimated screening amount is 20% of the total cargo. The AI and ML analyses can be compared to how it should be, i.e., how a container carrying properly declared DG must be packed and must be dunned. Deviations from this ideal state are detected or flagged as non-compliant. Based on the extent of deviation, a risk rating is derived. Since the nature of the RCO is such that it is expected to detect potentially hazardous cargo before it is loaded onboard, therefore, this RCO is expected to have better control on ignition onboard.

The screening technology using X-ray envisioned in this RCO is already existing, see for example the container scanner in Mumbai port in India[46] used for detecting contraband or prohibited cargoes, and solutions in the industry such as Rapiscan [47]. It is the AI and ML part of the software that is new and forward-looking in this RCO, as well as the purpose to scan for hazardous cargo. It is envisioned that the AI and ML software is continuously fed with enormous number of photograph analyses of cargo and machine learns to detect a hazardous cargo. Whilst there is

[46] Drive through container scanning begins at the port - APM Terminals
[47] Eagle® P60 | Drive-Through Inspection System- Rapiscan Systems

no algorithm already widely used on the market that could automatically flag what this RCO is aimed for there are intelligent image analytics that can be set out with X-ray scanners, today mainly used to spot guns, smuggling, drugs etc. Therefore, this RCO relates to more development by industry, researchers, users etc.
How effective a scanner would be at detecting some of the issues encountered with hazardous cargo (e.g., finding charcoal or lithium batteries) would depend on a number of factors mentioned by manufacturer, including, but not limited to:

- Size / amount / placement of the goods inside the container.
- What else is in the container (if one large lithium battery is mistakenly still within an electrical item, when all other similar items are empty, then this might be easier to detect).
- The type of cargo in the container (organic, non-organic etc.).
- How that cargo is packed (uniform, mixed etc.).

Costs for implementing such a screening tool in a port is including for example the investment cost, personnel costs, maintenance cost and cost for electricity. Side effects or limitations are the organization needed, communication and to follow up what arises from a scanning process like this. It can be understood that human supervision is necessary to confirm that the AI-ML analysis was made correct, perhaps more in the beginning of the implementation phase and can be reduced after a time. Further human intervention can be necessary to decide what should be the next step depending on the high-risk rating of the screened cargo inside the container. For example, whether a container needs to be opened to inspect or sent back, and how this shall be communicated.

Feedback sessions from one of the currently existing technology suppliers and one of the end users at terminal handling located in Sweden, further revealed that at present, it is external screening or optical recognition which is primarily used to control the container information and mandatory labelling etc. The available technology, therefore, does not cover aspects such as poor dunnage of containers. It is an ocular scanning, where only the information visible from the outside of the container is captured. This may typically include information related to container number, equipment type, DG declaration among others. This documented information related to container number, equipment type, labelling etc., is also configured to identify externally visible damage to the container and seals. The scanning is carried out at the gates of terminals.

4.3.2.2 RCO P2 – Common database for rejected screening cargo

Common database for rejected screening cargo as an RCO enables to share the minimum rejection criteria among the shipping companies. This means with the help of this RCO, a container that is detected with an anomaly, when flagged for rejection by one shipping company, is also flagged by other shipping companies. The purpose behind this RCO is to encourage shared communication among shipping companies and thereby subsequently reduce the risk of moving a hazardous container from one shipping company to another. Thus, the risk shall not be pushed from one vessel to another vessel if the grounds minimum rejection criteria for all shipping companies are common and shared on a common database. This RCO is expected to have better control over booking and preparation stages.

Containership operators are today screening their booking documents to comply with IMDG Code. There is also a shared database initiative, the common industry library offered by National Cargo Bureau[48]. In this technology the customer has the common library, which is shared with the other operators using the same service, and a private library which is not shared. In this screening, the tool will flag bookings depending on a setup of keywords and rules, it can search different documents i.e., any part of bill of lading scheme, and respond direct to the team on the containership operator side. It is up to the operator to act on the flagged hits from the scanning, hence the ship operator / booking department needs to manage a private database, to send the data to be screened, to take care of the result and to follow up the hits. The operator can give feedback on the hits which go into the service and thus generate a more comprehensive service and common shared database.
A limitation stated in the HAZID is that certain information, i.e., shipper information, cannot be shared in public and thus not included in a shared industry library, this is regulated in legislation such as competition laws.
An RCO like this relates to fees for usage of the screening service and access to the common library. Also, costs for personnel and training for usage, maintain/update of database and procedures shall be considered.

4.3.2.3 RCO P3 – Risk based stowage planning tool

[48] Hazcheck - IMDG Code 40-20 - Exis Technologies

Risk based stowage planning tool as an RCO offers a plan of location of where a container can be stowed based on risk rating. This RCO aims at preventing extreme incidents onboard and is not affecting the ignition frequency and is rather combined with other safety measures. To divide the cargo area on a containership in more detail can i.e., help the crew in decision making on how to fight a fire or to setup more specific systems depending on what dangerous cargo are expected in that area. A risk-based stowage needs training and education for those who shall use it, thus, costs for implementing this RCO relates to personnel costs.
Risk-based stowage planning tool developed by Cargo Incident Notification System (CINS)[49] is already in use as guidance and best practice in risk-based stowage of dangerous goods on containerships. This tool is taking dangerous goods into account and as shown previously, the number of unknown in declaration makes such an RCO worth less than if all the cargo is properly declared.

Feedback from currently existing end users in terminal handling in Sweden revealed that increased guidance, best practices, and recommendations on the stowage is beneficial, particularly from a terminal handling perspective. Use of different stowage codes and guidelines are positively received.

4.3.2.4 RCO P4 – Improved control of lashing

Improved control of lashing as RCO aims to avoid fire incidents arising from poorly lashed containers. This RCO have technical, procedural, and ergonomic aspects. There are already regulations and rules that must be followed by those who load and operate the containership, for the lashing supplier and for the container owner.

SOLAS Chapter VI is the chapter with requirements for carriage of cargoes. It is required that *“Cargo units and cargo transport units shall be so packed and secured within the unit as to prevent, throughout the voyage, damage or hazard to the ship and the persons on board.”* (SOLAS VI-5.2). According to SOLAS VI-5/6 all cargoes, other than solid and liquid bulk cargoes, cargo units and cargo transport units shall be loaded, stowed, and secured throughout the voyage in accordance with the Cargo Securing Manual (CSM). The instructions given in CSM for the use of the lashing system onboard shall always be followed. CSM is prepared by the supplier for loose lashing, and it is approved by the same classification society that approves the vessel. CSM is an official document that must be found onboard. CSM shows the drawings of lashing fittings (fixed and loose) used onboard, the location of application of each loose lashing item and the maximum allowed container stack weights and weight distributions within the stacks on each bay (calculated according to classification society rules). Feedback from European lashing supplier states that there are several factors that can influence the lashing, some examples are:

- Exceeded the maximum stack height.
- Over or under tighten the turnbuckles.
- Lashing pattern, order of lashing bars, not following the CSM.
- Incorrect twist locks used.
- Damaged equipment used for lashing.
- Weather conditions.

Also, the container itself can have an influence on the lashing. A poorly maintained container can have worn out or rusty corner fittings, making it hard for the loose lashing to get a good grip on the container. The International Convention for Safe Containers (CSC) states that it is the owner that is responsible for maintaining a container in safe conditions. A first examination of the container status must be done within 5 years from manufacturing, followed by re-examination at least every 30 months (CSC Ch.1-2.1).

Containers can also have a real weight which is not corresponding to what has been declared, which can lead to loading too heavy container too high up to the container stack. This may lead to more tension than accounted for on the containers and the lashing equipment, especially in bad weather. The fire on Eugen Maersk in 2012[50] included a collapse of containers leading up to fire. The scenario on Eugen Maersk also included harsh weather and containers started to sway and lashings were broken.

[49] Safety Considerations for Ship Operators Related to Risk-Based Stowage of Dangerous Goods on Containerships (cinsnet.com)
[50] eugen-maersk-fire-on-18-june-2013.pdf (dmaib.com)

The Code of Safe Practice for Cargo Stowage and Securing (CSS) state that *“The proper stowage and securing of cargoes is of the utmost importance for the safety of life at sea.”*. The Code also reminds that *“the Master is responsible for the safe conduct of the voyage and the safety of the ship, its crew and its cargo”.*

According to research and data presented by American Bureau of Shipping (ABS) as part of the ABS Mariner Safety Research Initiative (MSRI), poor lashing has been identified as one of the leading causes of incidents onboard[51]. ABS recommends improved lashing arrangements as well as better lashing equipment to limit container movement, prevent falling of containers or crushing effect due to instability. Correct lashing therefore also has the potential to reduce the number of containers falling overboard and prevent injury to dock workers or crew members.

In Annex 14 section 4.3 in the CSS it is stated that containerships are to be provided with a Cargo Safe Access Plan (CSAP) to demonstrate that personnel have safe access for container securing (lashing/unlashing) operations.

Section 4.4 in CSS is about training and familiarization for personnel engaged in cargo securing operations with purpose to ensure that securing is carried out in a safe manner and with gear that is in good shape and relevant for the work. Improved platforms, ladders, distances etc. to have better ergonomic (and possible more effective) to perform and monitor lashing during voyage and in port can be one way of achieving improved monitoring of lashing. Based on above discussed background, an improved control of lashing to avoid fire incidents arising from poorly lashed containers can be applied in various ways. Education and information are needed in addition to existing codes and regulations to steadily ensure that containers are properly stowed throughout the whole voyage. The aspect highlighted in this RCO is to revise the amount of personnel and available time to perform monitoring of lashing during voyage, to have time to follow requirements, manuals and plans correctly and safely.

Feedback from end users at terminal handling located in Sweden further revealed that implementing lashing improvements is welcomed even from a terminal handling perspective. While for newbuild container vessels this might be easier to implement as safety measures can be implemented already during the design phase, for existing container vessels, this might be often more costly to implement. Furthermore, terminal handling is involved in lashing only for selected container vessels. This means, improved lashing procedures, improved control of lashing as well as improved lashing equipment are likely to positively impact the terminals.

Implementation of this RCO does not contain any outstanding concern or limitation, apart from the fact that there are several aspects of this RCO which may require to be considered separately before implementation. For example, to improve control of lashing, whether to focus on improvement of training of personnel doing the lashing monitoring, whether to increase the number of personnel performing the lashing monitoring, revised rules, or should the focus remain on ergonomics, availability, and accessibility of lashing monitoring. It must be understood that the implementation of improved control of lashing in practical terms would include improving training of personnel and better monitoring of lashing. From cost perspective, implementing either of these aspects might be perceived as a “low hanging fruit” to implement onboard to prevent fire onboard containerships.

4.3.2.5 RCO P5 – Improved test method for self-heating cargo

Improved test method for self-heating cargo as an RCO aims to improve the test method for identification of self-heating cargo for transport of dangerous goods. The currently existing test for self-heating goods for transport is the United Nations Recommendations on the transport of dangerous goods, Manual of Tests and Criteria[52], section 33.4.6 Test N.4: Test method for self-heating substances. Tests are performed to determine if the goods shall be classified as a self-heating substance. Tests are made in a small-scale method, using so called basket heating tests; the material to be tested is put in a wire mesh cube, ($25\times25\times25$ mm^3 or $100\times100\times100$ mm^3) and evaluated at 100 ℃, 120 ℃ or 140 ℃. Depending on the result, different volumes of the goods may be transported as a not self-heating substance. A test scheme for self-heating substances is illustrated in Figure 66.

[51] Guide for Ergonomic Container Lashing 2021 (eagle.org)
[52] United Nations, Manual of Tests and Criteria, 7th revised edition, sub-section 33.4.6

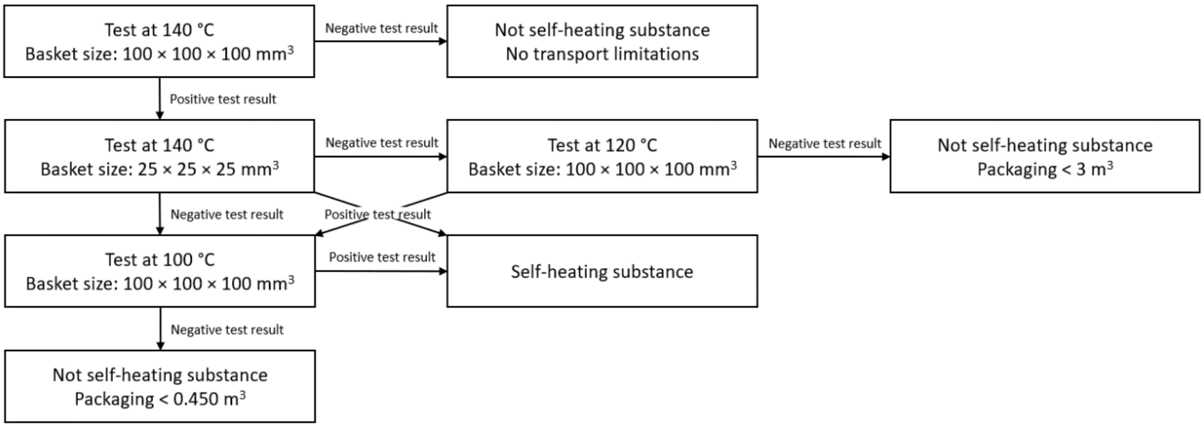


Figure 66: N.4 Test-scheme for self-heating substances.

The substance that undergoes the testing is placed in the wire mesh cube and the cube is placed in an oven. The oven temperature is kept constant at the testing temperature, the sample is kept in the oven for 24 h. A positive result is achieved if spontaneous ignition occurs or if the sample exceeds the oven temperature with 60 ℃. To determine whether the self-heated sample can be assigned to packing group II which according to IMDG Code is a medium hazard (packing group III is low hazard) a second test with the smaller cube is performed.
The N.4 test was originally developed for charcoal and the classification scheme is based on the self-ignition temperature of charcoal, 50 ℃ for a sample cube of 27 m^3 (3×3×3 m^3)[53]. The test method mentions that substances with higher temperature of spontaneous combustion than 50 ℃ for a volume of 27 m^3 should not be classified as a self-heating substance.

Since the test method for self-heating is based on performance of a charcoal, the results are not necessarily applicable to “new” materials or different stowage geometries. Self-heating can be caused by biological, chemical, or physical processes. Changes in weather conditions, such as temperature and humidity, may start a self-heating-process. S. Moon et al[54] demonstrates that the UN test of self-heating substances can result in false negative classification when testing sulfide materials and this can lead to incorrect conclusions regarding potential self-heating behaviour. Also, at RISE (part of CARGOSAFE project team) that performs the standardized N.4. test and have expertise in self-heating, experiences from reactive, moist materials that passes the self-heating test, but still may self-heat and eventually self-ignite (after evaporation of the water). Thus, when using the same test method to other types of self-heating cargo than charcoal the interpretation of the results cannot be guaranteed to be appropriately applicable, hence a potential safety risk for ignition to occur inside a container when onboard a containership.
This RCO relates to the revision of the current test method into one or more test methods for different types of self-heating substances and thus reduce false negative classification and risks of ignition inside a container.

4.3.3 Effectiveness assessment

[53] United Nations, Manual of Tests and Criteria, 7th revised edition, sub-section 33.4.3.3
[54] S. Moon et al. Examination of the United Nations self-heating test for sulphides, Canadian Metallurgical Quarterly, 58(4) pp.438 – 444. DOI: 10.1080/00084433.2019.1617498

Effectiveness assessment for Prevention was mainly made qualitatively, as prescribed in the tender specification. The qualitative assessment was based on above descriptions, feedback from users, discussions within the project team, with partners from the TEG and with EMSA.

Two Prevention RCOs were specified with quantified effect on the risk model based on accident literature, available data, and engineering estimates. These were P1 and P4. P1 was selected due to the estimated large risk reduction potential and a high TRL. P4 was selected because this RCO is intended to be implemented on board, which was very compatible with the scope of the project and EMSA's interest. The remaining three RCOs are presented in qualitative terms.

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Table 38 presents the effectiveness assessment on Prevention RCOs and presents the estimated TRL, effect on Risk model and list of interested entities.

Table 38: Effectiveness assessment of Prevention RCOs.

P-RCO	RCO Title	TRL	Effect on Risk Model	List of interested entities
1	Container screening tool	6	**Assumptions:** All the different components of the RCO, i.e., the screening analyses, the AI-ML detector, the heat detection to detect self-heating or damaged or decayed DG and the risk rating are fully functional as intended by design and concept. The terminal handling has the necessary available infrastructure to randomly screen at least 20% of containers. **Estimated effect on relative probability reduction of ignition:** Very high. **Explanation:** Relative probability reduction is up to a maximum of 6.19% from the base case probability (reference case). All 6 FTs in Prevention Risk Model are affected. Therefore, rated very high in risk reduction. **Estimated effect on ET and chain of events:** For RCO - P1, the highest impact is observed for Dangerous Goods (DG) that are not properly declared. Shows some impact on DG that are properly declared. No impact is observed for non-DG. From the Global Risk Model perspective, this consequently means, fast fires, slow fires and explosions are impacted by implementation of RCO - P1. Although, no specific trend can be seen to claim that one type of fire growth would be more affected than others. **Summary:** Upon implementation of RCO- P1, risk of fire spread from slow fires, fast fires and explosion from DG that are not properly declared are expected to be equally reduced.	Terminal handling, private/ public security firms, port authorities, container shipping companies, IT suppliers developing AI-ML software, X-ray detection suppliers, heat detection suppliers etc.
2	Common database for rejected screening cargo	8	**Assumptions:** Not applicable. **Estimated effect on relative probability reduction of ignition:** Medium to Low. **Explanation:** Maximum effect on FT 1 and 4. FT 2 and 5 are affected moderately to low. No effect on FT 3 and 6. **Estimated effect on ET and chain of events:** Upon implementation of RCO- P2, medium effect of risk reduction is observed on DG not properly declared. Limited or low effect is observed on properly declared DG while non- DG remain unaffected by this RCO. **Summary:** Upon implementation of RCO-P2, we can expect moderate to low risk reduction of ignition arising from DG not properly declared. There trend of risk reduction in fire spread can be expected to be similar on all 3 fire spread types, namely	Shipping companies, software suppliers offering database solutions, shippers, container owners, etc.

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			slow fire, fast fire, and explosion. No special effect is observed on any particular type of fire spread.	
3	Risk based stowage planning tool	8	**Assumptions:** Not applicable. **Estimated effect on relative probability reduction of ignition:** Low. **Explanation:** Upon implementation, effect of RCO-P3 is observed only on FTs 3 and 5. **Estimated effect on ET and chain of events:** RCO-P3 has an impact only on the severity of consequence. Upon implementation, the effects of this RCO are limited to properly declared DG. Rest remains unaffected by this RCO. RCO-P3 works very well when implemented in combination with other fire tiers such as Detection, Firefighting and Containment. **Summary:** Although in isolation, RCO-P3 has low effect on reducing the probability of ignition, when interdependency of this RCO is considered with respect to other fire tiers, we find significant effects on ET and fire spread. This means, when RCO-P3 is implemented in conjunction with other RCOs from the right side of the ET, the severity of fire accident and fire spread on-board arising from a high-risk cargo can be mitigated.	Shipping companies, port handlers, terminals, crew etc.
4	Improved control of lashing	7	**Assumptions:** Not applicable. **Estimated effect on relative probability reduction of ignition:** Low. **Explanation:** Only parts of the risk model that are affected are FTs 1 and 2. Relative probability reduction of ignition is up to a maximum of 1.63% from the base case probability (reference case). **Estimated effect on ET and chain of events:** Only affects the declared DG on deck. Limited effect is observed for DG that are not properly declared. No impact is observed for non- DG. **Summary:** Upon implementation of RCO - P4, risk of fire spread from slow fires, fast fires, and explosions from DG that are properly declared are expected to be equally reduced.	Onboard crew, shipping companies, ship owners, fleet owners etc.
5	Improved test methods for self-heating cargo	3	**Assumptions:** Conditions applicable to type of self-ignitable goods, declared DG or undeclared DG, the chemistry of the self- ignitable goods, self-heating test sensitivity and parameters. **Estimated effect on relative probability reduction of ignition:** High to Medium. **Explanation:** This is because RCO- P5 significantly affects all the nodes under "Self-ignition" parts of the Global Risk Model, i.e., FTs 1, 2, 4 and 5. **Estimated effect on ET and chain of events:** The effect of this RCO-P5 depends largely on how it is implemented. • Should the tests for self-ignitable goods are to be performed on ONLY properly declared DG, the effect is estimated as **medium.**	Material suppliers, test laboratories, researchers, stakeholders affected by safe transportation of DG.

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			• Should the tests be extended to all types of cargo including those that are NOT properly declared/ misdeclared DG, the effect is estimated as **high**. **Summary:** Upon implementation of RCO – P5: • Highest impact is observed on DG that are not properly declared. • Medium impact is observed on DG that are properly declared. • No impact is observed on non-DG. • Risk of fire spread from DG that are not properly declared is expected to be reduced. Similar trend of risk reduction from all 3 types of fire spread, namely, slow fire, fast fire, and explosion.	

4.4 Detection

4.4.1 Current system evaluation

4.4.1.1 Below deck: Smoke sampling system

4.4.1.1.1 IMO Requirements

The SOLAS convention stipulates requirements for detection methods in cargo spaces, on board cargo vessels. The requirements are described in SOLAS chapter II-2 regulation 19.3.3.

The requirements for the three vessels sizes used in CARGOSAFE, (section 3.2.2.3) are the same and are in general described below:

SOLAS Chapter II-2- Regulation 19.3.3:

All other types of cargo spaces shall be fitted with either a fixed fire detection and fire alarm system or a sample extraction smoke detection system complying with the requirements of the Fire Safety Systems Code.

The Fire Safety Code chapter 10 details the specification of sample extraction smoke detection systems in cargo spaces as required by chapter II-2 of the Convention. Unless expressly provided otherwise, the requirements of this chapter shall apply to ships constructed on or after 1 January 2012.

In general, a sample extraction smoke detection system consists of smoke accumulators, sampling pipes, three-way valves, and a control panel.

The system shall be designed, constructed, and installed so as to prevent the leakage of any toxic or flammable substances or fire-extinguishing media into any accommodation space, service space, control station or machinery space.

Furthermore, the system and equipment shall among other things, be suitably designed to withstand supply voltage variations and transients, ambient temperature changes, vibration, humidity, shock, impact and corrosion normally encountered in ships and to avoid the possibility of ignition of a flammable gas-air mixture.

As for the component requirements, the sensing unit shall be certified to operate before the smoke density within the sensing chamber exceeds 6.65% obscuration per meter. The control panel for the smoke detection system shall be tested according to standards EN 54-2 (1997), EN 54-4 (1997) and IEC 60092-504 (2001), and the sampling pipes shall be a minimum of 12 mm internal diameter. The fan suction capacity should be adequate to ensure the response of the most remote area within the required time criteria of 300 s for container and general cargo holds, after smoke is introduced at the most remote accumulator.

4.4.1.1.2 Current system

The detection timeline in a cargo hold consists of several steps. All these steps must be completed to have an alarm/detection event. The timeline is approximated as follows:

- Fire in container/Smoke leakage from the container.
- Smoke travelling from COO to sampling points.
- Smoke being extracted through the sampling pipes and travelling to the detector location.
- The concentration of smoke at detector location is high enough to reach alarm criteria.

After the smoke detector is activated a subsequent alarm sound. This alarm only highlights which cargo hold the alarm is coming from, thus the exact location of COO and state is unknown to the crew. Ultimately, a crew member must be sent to confirm alarm and report back with the state of the situation (this can be done via radio). The time for the crewmember to confirm the alarm depends on the distance to the COO which could, in worst case, be as much as length of the ship (for a twin island approx. 400m albeit this is a highly unlikely scenario, as it would require all the crew and the COO to be on opposite extreme ends of the vessel). Secondly, the time will depend on the accessibility of the particular location.

To estimate expected detection times from the current smoke sampling system, to enable comparison with the relevant suggested RCOs, time estimates for each step in the timeline need to be determined. This was undertaken through a series of fire and smoke simulations and flow calculations. With the methods used described below:

I. Fire in container/smoke leakage rate

Dry cargo shipping containers often consist of several vents on the corners of the container walls predominantly to avoid pressure build up inside the containers during temperature changes and unexpected gas leaks. The ventilation provided also minimizes the condensation of water. The vents are usually fitted next to the high corners of each container. The dry cargo containers are fabricated according to the ISO standards which include container dimensions and different ratings. However, the design of the vents is governed by the Transports Internationaux Routiers convention 1975[55] . As per the requirements mentioned, a vent consists of a lattice of nine 10 mm holes in a 3 × 3 arrangement as shown in Figure 67. A cover is attached covering the vents in order to avoid contamination of goods inside.

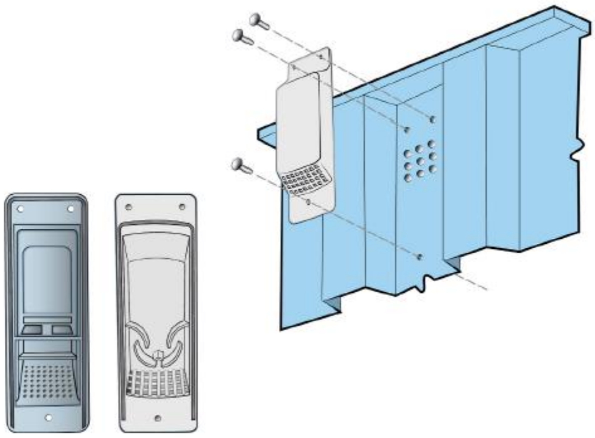

Figure 67: ISO vent and the vent cover for cargo containers.

During a fire inside a container these vents provide a small but clear exit path for the smoke which can then propagate outside the container. Though the smoke detection arrangement differs from below the deck to above the deck in a cargo hold, smoke detection is only possible at the level of the topmost container on the stack. A cargo hold can be as high as nearly 30m, which implies that the amount of time taken for smoke leaked from an early-stage container fire should reach detectable levels at the highest point of a stack could be substantial.
To estimate the smoke leakage rate from a container during a fire, computational fluid dynamics (CFD) calculations were performed using the well-known software, Fire Dynamics Simulator (FDS) 6.7.8[56]. The numerical set-up of these simulations is discussed below.

− Numerical Set-up

The simulation domain was set to a cube with dimensions of 14.2 m × 4.6 m × 3 m. The 40 ft container with dimensions of 12.2 m × 2.6 m × 2.6 m was placed on the centre of the domain at ground level (z = 0). The larger domain size allowed the leaked enough space outside the container to reach a more realistic flow downstream of the leak. The container was set be made of steel of which the thermal properties are given below in Table 39.

[55] United Nations, Customs convention on the international transport of goods under the cover of TIR carnets (TIR convention), Geneva, 1975.
[56] https://pages.nist.gov/fds-smv/

Table 39:Material/ thermal properties of container walls.

Thermal conductivity	45.8 W/(m. K)
Specific heat capacity	0.46 kJ/(kg. K)
Density	7850 kg/m3
Emissivity	0.95

A propane burner of 1000 kW with an area of 1 m × 1 m was placed at the centre of the container with the burning surface at 0.32 m above the floor level. The smoke leak was modelled following the localized leakage model in FDS.

The cell size for the calculations was 4 cm × 4 cm × 4 cm which was more than fine enough as per the guidelines in the users' guide[57] for FDS. The recommended cell size was estimated to be approximately 9 cm. The recommended cell size, δx can be calculated by:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}}$$

Where, $\dot{Q}$ is the heat release rate (HRR) of the fire (1000 kW) in kW, ρ_∞, c_p and T_∞ are the density (1.2 kg/m^3), specific heat capacity (1 kJ/kg. K) and temperature (293 K) of ambient air respectively. g is gravitational acceleration (9.81 m/s^2). The recommended cell size, δx is given by:

$$\frac{D^*}{\delta x} = 10$$

Substituting the values in these equations, both D^* and δx can be calculated. As mentioned before, a value of 9cm for δx or lower is recommended for the calculations. A value of 4 cm was selected which increases the accuracy of the calculation while still being computationally feasible.
There are several ways a leak from a very small opening can be modelled in FDS. The localized leakage model in FDS was used to model the leakages from the container. This model allows the preservation of energy across the leak unlike the other models where the leaked gas is assumed to be at ambient temperature. The vents for the leakage were placed at the corners of the 40ft container with an area of 0.0007 m^2 (7 cm^2) which is the total area of a single lattice with 9 openings.
The leakage mass flow rates and the temperature of the leaked smoke were measured to be used in the calculations afterwards where detection times are analysed. The smoke flow rates, and the temperature of the leaked smoke are provided below in Table 68Figure 68.

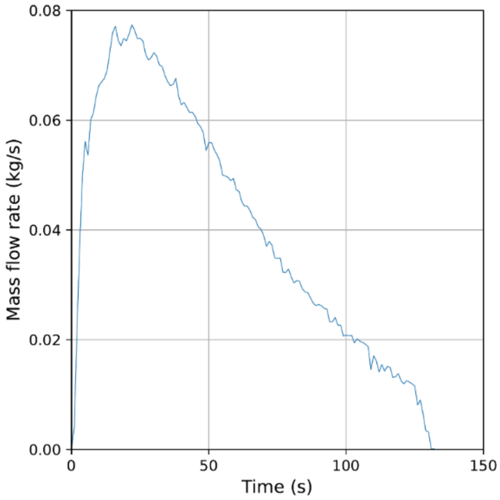

Figure 68: Smoke leak rates from a 40 ft container from a 1000 kW fire.

[57] McGrattan K., Hostikka S., Floyd J., McDermott R., Vanella M., Fire Dynamics User's Guide, NIST Special Publication 1019, http://dx.doi.org/10.6028/NIST.SP.1019, 2022.

The smoke leak rate increases rapidly initially before hitting its peak value of around 0.08 kg/s around 25 s into the fire before the rapidly decaying as the fire dies out inside the container due to lack of O_2 available to feed the fire. The peak value was chosen as the input flow rate for the calculation of smoke travel time between the container vent and the smoke collection points. Nevertheless, in some scenarios the smoke generated from a heating event or from a slow growing fire can be much less in the earlier stages of the fire. To take this into account, a lower value for the flow rate was also chosen which represents the development stage of a slow growing fire. The flow rate for this case was taken as a 0.5 g/s but leaked from an equally sized vent.

Once the smoke has leaked outside, it will enter a buoyancy driven flow where the hot smoke will continue to rise between the gaps of container stacks eventually reaching a collection point. Since this flow is buoyancy driven, the temperature of the leaked smoke is also an important parameter which directly affects the upward flow of the smoke. The temperature field within the container and the leaked smoke is shown below in Figure 69

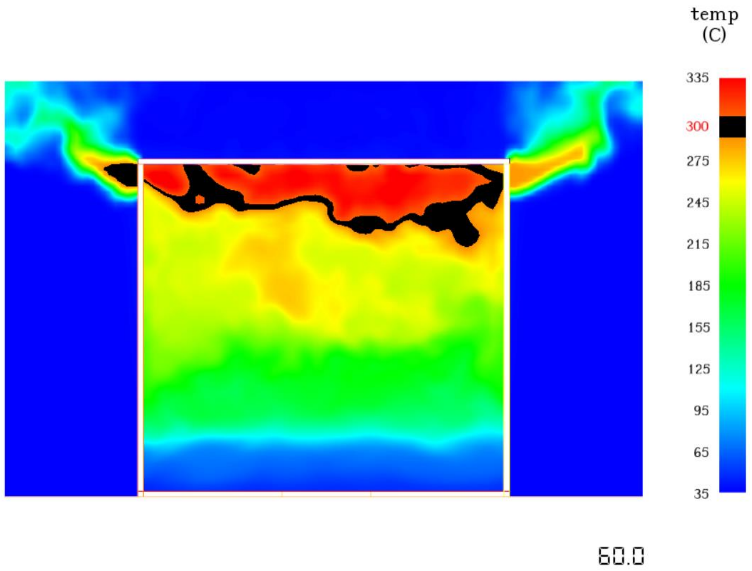

Figure 69: Temperature profile of the smoke inside and outside the COO.

As shown in the figure above, the temperature of the smoke layer at the level of the vents is in the range of 315 ºC – 285 ºC. It should be noted that the uncertainty in this value is rather high due to the smoke layer temperature can vary depending on the type of fuel, amount of fuel burning and the fire growth characteristics. A value of 300 ºC was used in the smoke flow calculations within the cargo hold.

In FDS, the container is modelled as a fully sealed compartment with only the leakage vents placed at the top corners as the only vents. This limits the available oxygen within the container which makes the fire inside grow weaker and eventually completely die. However, due to the detection of smoke concerns the earlier stages of the fire the maximum value for the smoke leakage rate at this stage.

II. Smoke travelling from COO to sampling points

As discussed briefly in the previous section, the leaked smoke from a container fire will continue to propagate along the gaps among the neighbouring containers and stacks before reaching a collection point which can then be extracted and analysed at the main detector unit. The time taken by leaked smoke to reach the collection point with detectable amounts is discussed in this section. This was done using CFD calculations using FDS version 6.7.8. The numerical set-up of the simulations and the results regarding different ship types for both above and below deck configurations are discussed.

Smoke flow simulations were done looking into the tree generic ship's cargo holds and both below deck and above deck conditions were considered. The most notable difference between the different vessel types is the stack height. The twin island vessels (generic ship 1) carry stacks of 10 - 40 ft - high cube containers put on top of each other whereas in the single island vessels (generic ship 2) and in feeder vessels (generic ship 3) the stacks are only 8 and

6 such containers high respectively. In all the cases, the below deck represents a fully enclosed space while above deck the container stack is placed in open air which makes the environment more sensitive to the movement of the ship and weather conditions such as wind.

Figure 70 shows a sketch of two stacks of containers which shows the different key geometric features that might differ from one vessel type to the other in the below deck configurations. The values for a, b, c, d and e for each vessel type are given in Table 40.

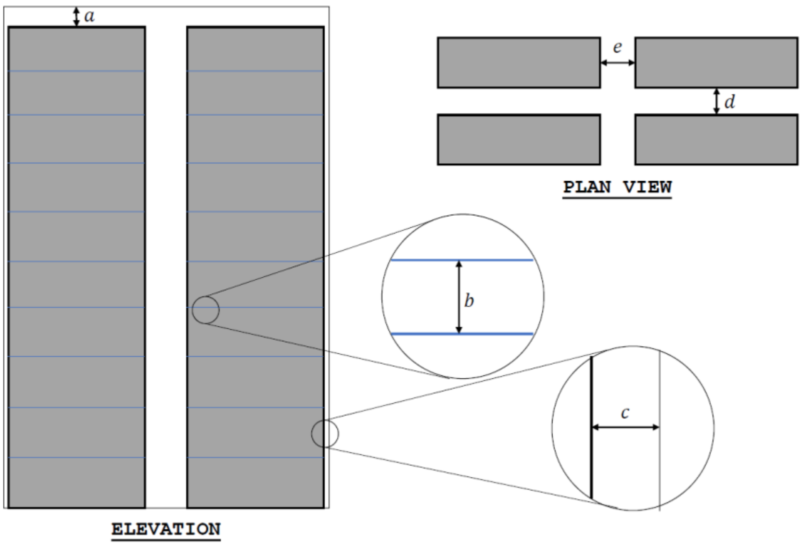

Figure 70: Dimensions of the gaps between container stack in a cargo hold (notation only).

Where, a is the overhead clearance between the deck and the topmost container on the stack (only applicable to below deck arrangement), b is the vertical gap between two containers on a single stack, c gives the gap between the side wall and the door side of the container, e and d are respectively the horizontal gap between the two door sides of two neighboring stacks and the horizontal gap between two container stacks from the side walls direction.

Table 40: Dimensions of the gaps between container stack in a cargo hold (in mm).

		a	b	c	d	e
Below deck	Feeder vessel	100	13	184	28	1980
	Single island	100	13	184	28	1980
	Twin island	100	13	184	50	1980

- **Numerical set-up**

The most critical region of the simulation was identified as the gap between two side walls of two containers where most of the smoke is supposed to flow through. This gap is the measured d value as shown in Figure 70. For the calculation to be accurate, it is essential that this gap is resolved reasonably well during the meshing process in FDS. The gap is extremely narrow compared to the total height of the interested domain which is around 24m for single island vessels (generic ship 2) and 30m for twin island vessels (generic ship 1). Resolving the narrow gap is crucial for the accuracy of the calculation but due to the extreme nature of the geometry resolving the whole domain with a small cell size is not feasible in terms computational costs and time consumption.
The selected cell sizes were chosen for each scenario such that there are 8 cells across the narrow gap along the full height of the domain. The selected cell sizes are given in Table41 for all cases.

Table 41: Chosen grid resolutions for the simulations (in mm).

	Ship type	Cell size
Below deck	Feeder	200 × 4 × 6
	Single island	200 × 4 × 6
	Twin island	200 × 6 × 6

The computational domain for the CFD simulations were chosen such that it includes only a single gap between two container stacks and the vertical gaps between containers along the height of the stacks. The computational domain for the case of feeder vessels is shown below in Figure 71. The rest of the cases were simulated using a similar layout with their respective geometries.

The container stacks placed below deck are confined within the vessel such that there is no contact with the atmosphere. These container stacks vary in height depending on the type of vessel as previously mentioned. In addition, the horizontal gap between two stacks and vertical gap between two containers in a single stack also vary

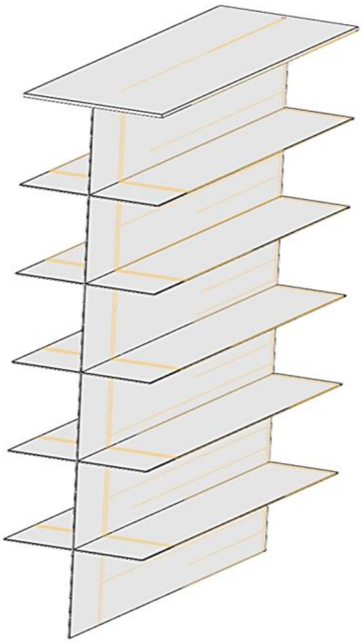

Figure 71: Computational domains for a feeder vessel below deck configuration.

depending on the type of vessel. These subtle variations were taken into consideration during the smoke flow calculations and are presented for each vessel type in the following sections.
Below the deck, as aspiration smoke detector unit is used for smoke detection which consists of several smoke collection points covering all the cargo holds on the vessel. For a single container stack, there are four smoke collection points two of which are hanging above the stack near the corners of the stack and the remaining two are facing the sides of the stack as shown in Figure 72.

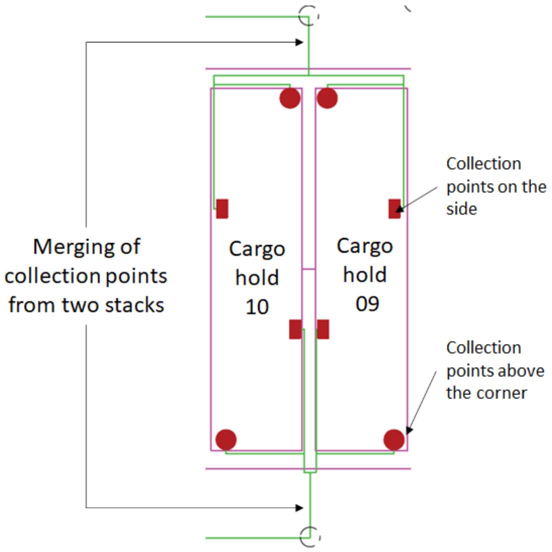

Figure 72: Detection systems layout below the deck.

As shown in Figure 72, the smoke extracted from two container stacks are merged into a single pipe which then connects all smoke collection points to the main detector unit. The drawback of this merged connection is that the smoke extracted from a single hold will be mixed with the fresh air extracted from its neighbouring stack. This allows the extracted smoke to be diluted by around half inside the pipes due to mixing with the fresh air extracted from the other end. This dilution can increase the detection/ alarm times due to the detector unit can only process the diluted smoke/ air mixture. This phenomenon was considered in the simulations as well. Further details will be discussed in the upcoming sections.

The mesh was generated for below deck simulations as shown in Figure 73, which had closed boundaries on the top and on the side where the dimension c was measured in Figure 70. The heat transfer between the hot smoke and the container walls was also considered in the simulations as the heat transfer between the two phases could potentially reduce the buoyancy effects of the smoke rising through the container walls. The material properties listed in Table 39 for container walls were used in these simulations as well.

The detection system was modelled considering the effects of dilution of smoke once extracted from a collection point. This adjustment was made in the detector obscuration parameter where the IMO recommended value is 6.65 %/m. This value was adjusted to be 13.3 %/m for the detectors which requires approximately two times the smoke concentration required to trigger a detector with an activation obscuration level of 6.65 %/m.

Results from the simulations focusing on the leakage flow rates and temperatures were used as input for these simulations. The smoke vent was modelled as a supply vent which injects soot into the domain at a temperature of 300 ℃. Due to the chosen aspect ratio of the cell size, the vent dimensions were also adjusted to be 200 mm × 30 mm which results in a larger vent (60 cm^2 vs 7 cm^2). This is a limitation due to the chosen cell size and computational limitations. The dimensions of the vents were chosen such that there are at least 5 cells across the vent to allow for an accurate calculation of the flow as shown in Figure 73. The vent is marked by the pink outline. The mass flux through the vent was adjusted so that the final mass flow rate out of the vent is equal to 80 g/s for the larger fire and 5 g/s for the smaller or very early-stage fire.

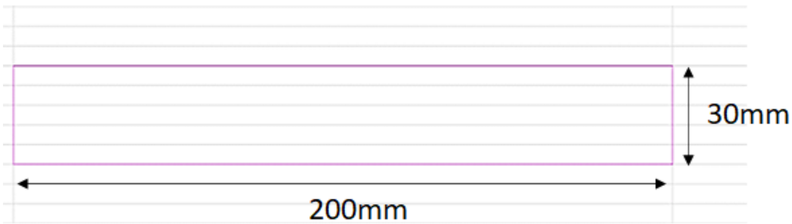

Figure 73: Dimensions for the vent for smoke leak simulations inside the cargo hold.

All the walls and doors of the containers were modelled as thick obstructions to allow the vent to be able to properly operate. An obstruction must be at least one cell thick for a vent to inject or extract gases in a reliable way as per the FDS User's guide.

The simulations were run for 1000 s initially to get an estimate of the detection times. Afterwards, the simulations times were adjusted accordingly so that detection is achieved within the chosen period.

Three sets of simulations were run including one simulation for each vessel type. The smoke flow and the time for the smoke to reach the collection point with detectable concentrations were the focus in these simulations. The results of the smoke flow calculations are presented below with figures and a discussion.

The smoke travel times recorded for below deck scenarios are given below in Table 42 and is followed by the discussion of the obtained results.

Table 42: Summary of smoke travel times in seconds (minimum and maximum) for below deck scenarios.

Type of vessel	Minimum detection time (Large fire)	Maximum detection time (Small fire)
Feeder (generic ship 3)	57	235
Single island (generic ship 2)	85	285
Twin island (generic ship 1)	107	591

Snaps taken at the exact time when the detectors were activated for each vessel type in below deck scenarios are shown in Figures 74 -76 for feeder vessel (generic ship 3), single island vessel (generic ship 2) and twin islands vessel (generic ship 1) respectively.

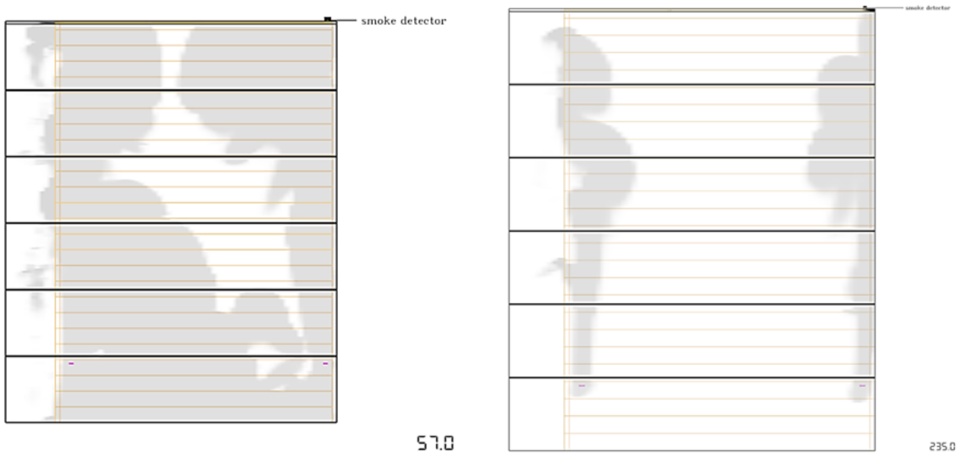

Figure 74: Smoke distribution for generic ship 3: Feeder at the time of minimum and maximum detection times. (Below deck).

These snaps were taken at the time of detection when the actual concentration of the smoke was enough to trigger the detector. Here, the smoke flow on the right-hand side reaches the detectors much quicker resulting in earlier detection at that side. This is due to the closed boundaries on that side, which is not the case on the other side. The open boundaries allow the smoke to dilute into the open atmosphere on the left-hand side of the container. Similar behaviours were observed for the cases of single island and twin island vessels as well. Similar snaps taken at the time of detection are shown below for single island vessels in Figure 75 and for twin islands vessels in Figure 76

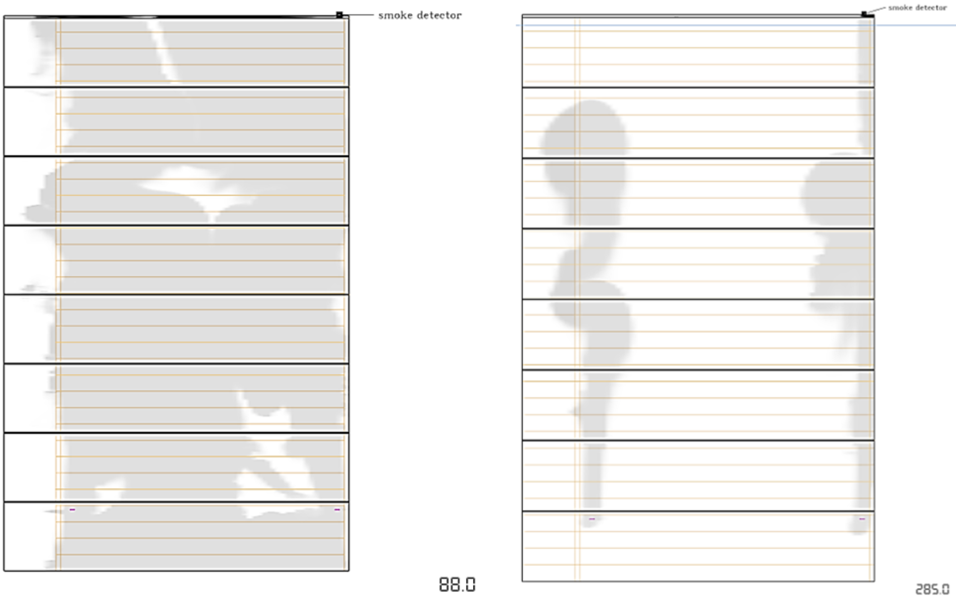

Figure 75: Smoke distribution for generic ship 2: single island at the time of minimum and maximum detection times. (Below deck).

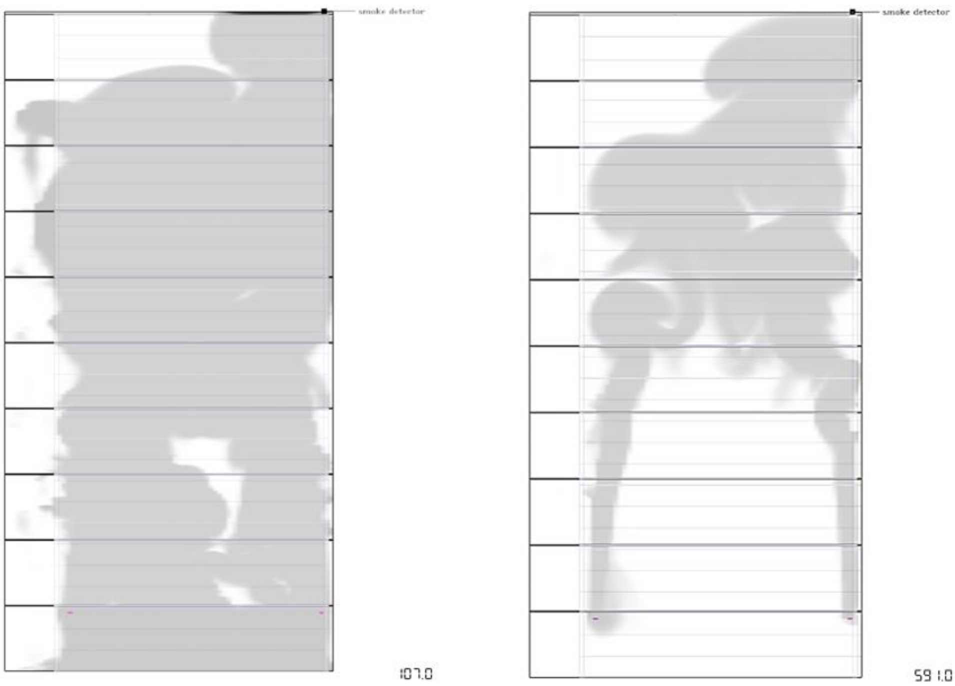

Figure 76: Smoke distribution for generic ship 1: twin islands at the time of minimum and maximum detection times. (Below deck).

In all the cases the detector placed on the closed side of the hold gives out the earliest detection times. The gap through which the smoke flows is almost 2 times larger for the twin island (generic ship 1) vessels which results in lower velocities thus increasing the travel times. Figure 77 shows the velocity profile of the gas phase for the smaller fire scenario throughout the whole vertical gap. Similar trends were observed for all vessel types.

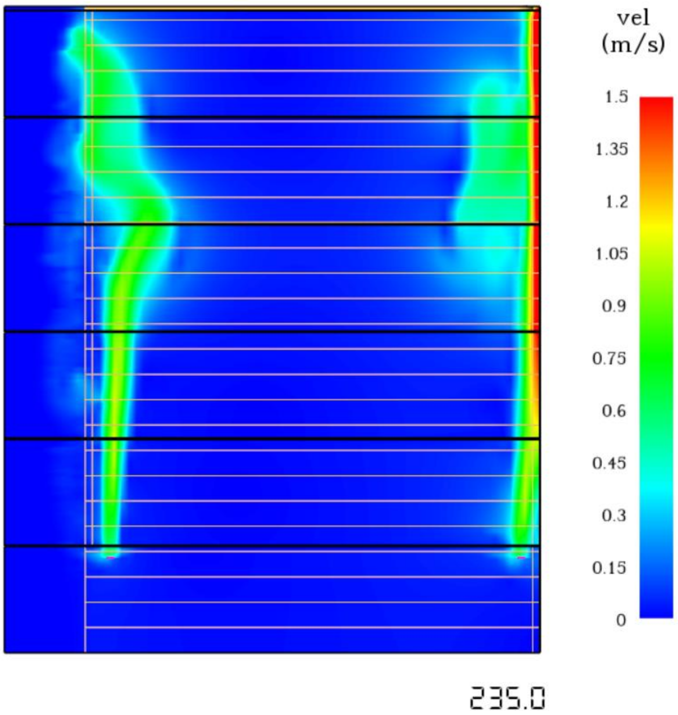

Figure 77: Velocity profile of the smoke flow in a feeder vessel. Higher velocities can be seen on the right-hand side of the hold where the boundary is closed.

Higher vertical velocities can be seen near the edge of the closed boundary for feeder and single island vessel (generic ship 3 and 2) while the velocities are considerably lower in the twin island vessel (generic ship 1). The lower velocities (vertical) results in a larger gap between the detection times of single island and twin islands vessel type even though the stack height difference is only 2 - 40 ft - high cube containers like the difference between feeder and single island vessel type.

III. Sampling point to detection unit

Assuming that a detectable amount of smoke is extracted through a single collection point at the cargo hold, it is essential that the extracted smoke reaches the main detector unit to raise an alarm indicating a potential fire. The collection points are connected to the main detector unit via a series of pipelines spanning across the entire cargo hold. Due to the lengths of these pipes in most cases being more than 100 m, a significant amount of time is required for the extracted smoke to reach the main detector unit. The current guidelines provided by the IMO[58], stated that:

"An alarm shall be received at the control unit in not more than 180 s for vehicle decks, and not more than 300 s for container and general cargo holds, after smoke is introduced at the most remote accumulator."

Therefore, the longest allowed travel time for the smoke to reach the detector unit is 300 s which can be considered as the upper limit representing the most unfavourable condition for detection. This value of 300 s is therefore used in the calculation of the overall detection time for all the cases.

IV. Smoke concentration build up

The detectors are sensitive enough they activate within fractions of a second once the smoke has reached the detector.

The final detection time was obtained by the sum of the different stages of the detection process. The alarm can only be triggered after the smoke has reached the collection point and then has travelled through the pipelines to the detector unit. As discussed, the travel path of the smoke was divided into two main portions:

[58] International Maritime Organization, International code for fire safety systems (FSS code), 2021

i. The time taken to reach the collection point at detectable levels t_1
ii. The time taken to reach the main detector unit from the collection point t_2

The first portion included CFD calculations whereas the second portion was taken as the worst-case scenario as per the IMO requirements for general cargo holds. This implies that the time taken for the smoke to reach alarm levels is equal to the sum of these two portions $(t_1 + t_2)$.

Table 43: Summary of total detection times (for each step) provides a comprehensive summary for the times taken for the smoke travel from the COO to the detector unit. The total sum provides an estimate for the range of potential detection time for each scenario.

Table 43: Summary of total detection times (for each step)

		Gen. ship 3 Feeder		Gen. ship 2 Single Island		Gen. ship 1 Twin Island	
		Fast	Slow	Fast	Slow	Fast	Slow
	Fire in container/smoke leakage rate [g/s]	80	5	80	5	80	5
i.	Fire in container/Smoke leakage from the container	25	0	25	0	25	0
ii.	Smoke travel time from COO to sampling points [s]	53	235	85	285	107	591
iii.	Travel time from sampling location, through pipes to detector unit [s]	300					
iv.	Time for smoke concentration to reach alarm levels	The detectors are sensitive enough they activate within fractions of a second once the smoke has reached the detector					
Total detection time estimate [s]		**378**	**535**	**410**	**585**	**432**	**891**

4.4.1.2 On deck: Visual observations

For cargo (shipping containers) stored on deck of container vessels, currently there exists no explicit means of detecting a container fire. The only means of detecting a fire is through visual observation by the officers or crew, either from the bridge or observations by crew during their other duties on board the vessel.

4.4.1.2.1IMO Requirements – Current system

SOLAS Convention specifies regulations for navigation bridge visibility in chapter V, regulation 22, ensuring that the view of the sea surface from the conning position shall not be obscured by more than two ship lengths, or 500 m, whichever is the less, forward of the bow to 10° on either side under all conditions of draught, trim and deck cargo taking conditions.

The main purpose of the regulation is to ensure that the watch keeping officer has as few blind spots as possible when from the bridge during his watch duty. No blind sectors shall exceed 10°, and the total arc of blind sectors shall not exceed 20°.

In addition to the requirements for a horizontal field of vision of not less than 225°, that is from right ahead to not less than 22.5° abaft the beam on either side of the ship, there is a requirement to ensure a horizontal field of vision aft.

From each bridge wing the horizontal field of vision shall extend over an arc at least 225° that is from at least 45° on the opposite bow through right ahead and then from right ahead to right astern through 180° on the same side of the ship, thereby ensuring that it must be possible to keep a lookout for any overtaking vessels.

From the bridge wing it must be possible to see the ship's side.

4.4.2 Risk Control Measures (RCMs)

RCM selection for detection followed the generic process described above. A list of potential RCMs was compiled from the HAZID, technical expert group, and core team research, and is presented in Table 44 below.

Table 44: Potential RCM from the HAZID workshop.

RCM No	RCM Description	OD or BD
1	Regular maintenance checks to verify integrity of wires and piping for the smoke sampling system.	BD
2	Change of sampling pipe material to avoid corrosion.	BD
3	Installation of sampling points inside the smoke sampling pipes to counter low airflow or insufficient number of sampling points.	BD
4	Make the holds more airtight and verify with regular maintenance checks and repairs	BD
5	New specification made for larger vessel types. New functional requirements (related to line 5).	BD
6	Portable gas sensors on crew.	OD/ BD
7	Portable IR camera for crew.	OD/ BD
8	IR cameras (installed at strategic locations). Coupled to a software solution to automate detection	OD
9	Heat detection looking at individual container temperature rise	OD/ BD
10	Individual container detectors (temp or smoke) (Local on ship, put on select units)	OD/ BD
11	Cameras/CCTV - AI - smoke detection	OD
12	Alternative smoke detection	BD
13	Drone detection technology	OD

4.4.3 Risk control options (RCOs)

For the RCO's listed in Table 44 a qualitative assessment with the core team and EMSA was performed. The aim was to further filter and group Table 4 and produce a smaller selection of RCOs deemed most viable for further assessment. The results of this assessment are presented in Table 45.

Table 45: List of RCOs for Detection.

RCO-D	RCO Title	OD or BD	Combination of RCMs
D1	Optimizing current system	BD	RCM 1-5
D2	Heat detection looking at individual container temperature rise	BD/OD	
D3	Fixed IR cameras (installed at strategic locations). Coupled to a software solution to automate detection	OD	
D4	CCTV - AI - smoke detection	OD	
D5	Portable IR cameras for crew to enhance manual detection - location of seat of fire, low smoke production, smouldering etc.	OD/BD	

4.4.3.1 RCO D1 – Optimizing current smoke detection system in cargo hold

This RCO is aimed at improving the current smoke detection system onboard container ships. The advantage of this being that it would not require any new systems to be added to the cargo hold.

Several potential improvements are examined in this section and are summarized in Table 46

Table 46: Suggested improvements for the current detection system.

Improvement	Details	Method of quantifying improvements
Additional sampling points	The addition of extra intermediate collection points will potentially reduce the detection times specially for the cases where the fire is in a container at the bottom of a stack.	CFD calculations were done similar to the smoke travel times calculation but including these additional collection points at different levels of the container stack
Change of sampling point locations	Collection points were placed at each level both in alignment with the vents and 4.2m away from the vents.	CFD calculations were done similar to the smoke travel times calculation with collection points included in different locations and at different levels of the stack.
Reducing of smoke travel time to the detector unit	Having the dedicated smoke detector unit on or at a closer location trims the travel time between the sampling point and the detector from the current 300s to a much lower value.	

- ***Additional sampling points or changing sampling point location – Time to reach the sampling points***

The smoke sampling points for the smoke detector are installed above the containers at the top of each hold. However, for an alarm to be triggered, the amount of smoke at the sampling point should reach alarm levels. It should also be noted that air/ smoke samples collected by two neighbouring holds are mixed inside the pipes resulting in dilution of whatever smoke was extracted from a sampling point.

Previously the travel times for the smoke assuming the fire origin as the lowest container on the stack were discussed. This represents a credible worst-case scenario. Having intermediate sampling point would decrease the total distance required to be travelled by the smoke thus, reducing the detection times.

Using the same geometry as discussed in the same section, additional simulations were performed looking into the detection times with extra sampling points installed at the ceiling level of each container on a stack. The detectors were placed in between the gaps denoted by d in Figure 70. The detectors were placed such that all the detectors were vertically aligned with the vents of each container as shown in Figure 78. Detectors were also placed 4.2 meters along the side wall from the end wall to compare the detection times of the several different detector placements.

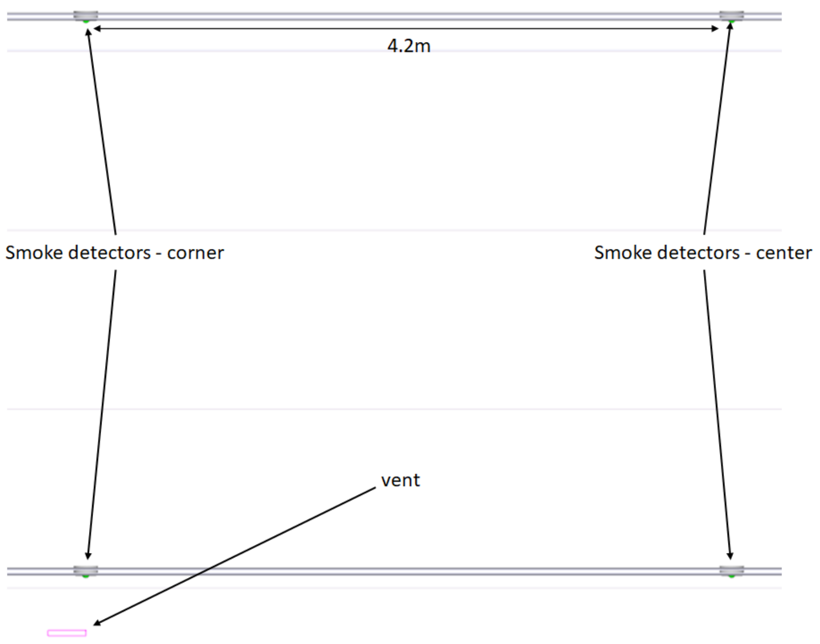

Figure 78: Placement of additional smoke collection points (modelled in FDS as smoke detectors).

All the below deck simulations were rerun with additional detectors in place in order obtain the different detection times at different levels in hold. The new smoke travel times for different levels are shown in Tables 47- 48 for feeder, single island, and twin island vessel type (Gen. ship 3, 2 and 1) for a rapidly growing fires and a slow growing fire respectively.

Table 47: Minimum smoke travel times from COO to additional collection points.

Tier	Minimum smoke travel times (s)					
	Gen. ship 3		Gen. ship 2		Gen. ship 1	
	Feeder		Single island		Twin islands	
	corner	centre	corner	centre	corner	centre
02	1	28	1	29	1	33
04	5	42	5	50	6	49
06	10	50	11	62	12	57
08	22	45	22	72	22	36
10	35	47	37	50	38	42
12	57	57	53	67	54	56
14			67	81	69	73
16			88	No activation	82	89
18					95	104
20					107	No activation
Current	57		88		107	

Table 48: Maximum smoke travel times from COO to each additional collection points.

Tier	Maximum smoke travel times (s)					
	Gen. ship 3		Gen. ship 2		Gen. ship 1	
	Feeder		Single island		Twin island	
	corner	centre	corner	centre	corner	centre
02	8	No activation	8	No activation	9	No activation
04	46	No activation	47	No activation	45	No activation
06	86	No activation	86	No activation	78	No activation
08	133	No activation	130	No activation	126	No activation
10	188	No activation	180	No activation	181	303
12	235	No activation	232	No activation	255	343
14			255	No activation	357	419
16			285	No activation	452	507
18					520	No activation
20					591	No activation
Current	235		285		591	

The values given in Tables 47 and 48 correspond to the smoke travel times from COO to the collection points and to get the total detection times (worst cases), 300s should be added on top of these values to allow for the smoke travel time through the pipelines leading to the detector unit.

The collection points placed aligned with the vents clearly are more effective with smaller detection times at all levels while the centrally placed collection points are ineffective especially around the level where the smoke leak is happening. Due to the size and the gap between the two corner vents, a collection point near the centre of the side wall proves to be ineffective at lower levels, however at higher levels detectors placed on central locations might be just as effective as the well aligned detectors for larger smoke flow rates. This is due to the entrainment of fresh air from the open spaces pushing the plume towards the centre as the plume rises. On the other hand, the centrally placed detectors are not ideal regardless of the levels for the detection of smaller smoke flow rates which are more applicable for a smaller fire or a slow growing fire. In conclusion, the detectors installed at lower levels could improve detection times if installed vertically aligned with the vents for any type of fire.

- ***Reducing of smoke travel time to the detector unit***

Based on the results presented in Table 43 one of the major contributors to the overall potential detection times is the component of travel time from sampling point location to detector unit. For this study, the IMO requirement of 300s was assumed. Although, this time will be dependent on the location of the cargo hold to the location of the detector unit, it still represents a potentially significant contributor to longer detection times.

For new builds, due to the requirements of the CO_2 system, the detection system can no longer take advantage of the of the piping infrastructure that is already in place for this system. Hence for new builds, a standard sampling system may not be the optimal choice. Thus, point detectors or similar that have no travel time for smoke to get to the detection point from the sampling point would result in a much-improved detection time.

Retrofit may be also possible but requires some additional costs.

4.4.3.2 RCO D2 – Heat detection system looking at rise of temperature of individual containers

Smoke detectors require smoke generation at the level of COO. However, self-heating events could occur inside container without the generation of smoke which can lead to a complete failure of the smoke detection system. Eventually these events could initiate a fire at some point but, the smoke detection systems are limited to detection of leaked smoke and therefore are ineffective during the course of the heating events. These heating events, at the earlier stages could conduct heat through the loaded cargo inside and eventually to the walls of the container. This results in the appearance of abnormal hotspots on the container walls. If these hotspots are identified as they appear on the container walls, this will potentially reduce the detection times by a huge margin and most importantly, in some scenarios even before flaming combustion has begun.

Another shortcoming of the current smoke detection system is the smoke travel times through the pipelines leading to the smoke detector unit. This implies at least 300 s (5 minutes) are required to trigger an alarm or a warning signal in the best possible scenario. However, using a system which relies on an electrical signal eliminates this portion from the time for detection. A heat detection system which works on an electrical signal which enables real time monitoring of container wall temperatures is described in this section followed by the estimated detection times of such a system which were calculated using CFD tools.

One major drawback of the current smoke detection systems installed in the cargo holds (below deck) is the very large smoke detection times due to the remote location of the collection points and the detector unit. Based on the size of the vessel, these times can be substantially large. This implies that even with the most sensitive detector, there will be a period which allows the fire to grow without detection. As pointed out earlier by the CFD calculations, these times can be around 500s and higher in some worst-case scenarios even for the smallest vessel type.

The cargo holds are a tricky location to install new additional devices due to the minimum space available for such devices and the potential damage during loading and unloading operations. Furthermore, optical detection systems such as thermal imaging cameras require an unobstructed view of all the containers which is not realistic a large cargo vessel with tight stacking arrangement. One other important factor is the continuous monitoring of the containers for a potential fire.

- ***Availability in current market***

Solutions which are optimized to the very specific environmental and operational challenges present in a cargo hold have been commercialized and are available in the market. The system in focus under this section is a linear heat detection system which is tailormade for cargo hold environments. These systems can monitor the temperatures of the container walls covering the whole cargo hold and the temperature readings are updated as frequently as every 5s. The devices are small and, complies with regulations such as ATmosphères EXplosives (ATEX) [59]. Due to the smaller size of the device, it is possible to install these devices throughout the hold. An attached sensor on a cargo hold is shown in Figure 79.

Figure 79: A container wall temperature monitoring sensor installation.

- ***Working principle***

The whole system can be considered as a linear heat detection system which monitors the temperatures of the containers in real time. An alarm is activated depending on the temperature gradient (both spatial and temporal) produced by the heatmap generated by the system. The devices should be installed within 20cm distance away from each container end wall as shown below in Figure 80. (a blue dot indicates a single device)

[59] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0034

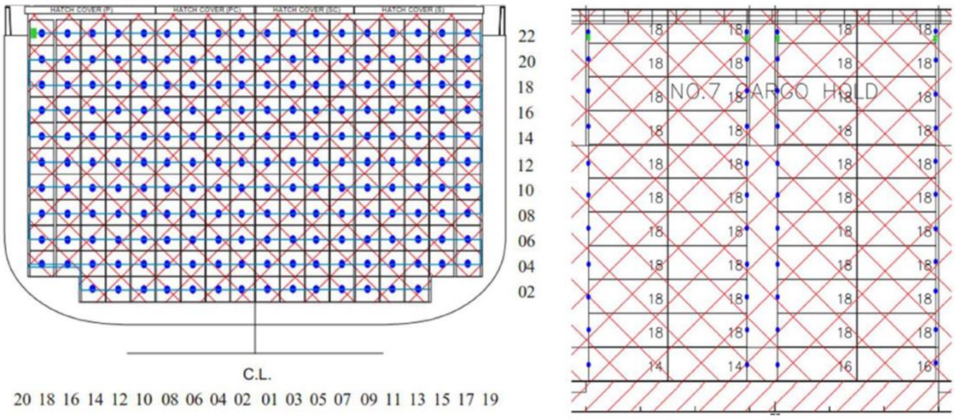

Figure 80: Sensor placement and layout for a full cargo hold source: [Radicos Technologies GmbH.]

All the nodes are addressable sensors which are integrated into a single cable. The temperature sensors have a precision of as low as ±0.025 ℃ and the sensor readings are updated every second on the output visual on the screen. The warning signals/ alarms can be set based on the absolute temperature of the container walls or the temporal gradient of temperature. The system has been designed to detect heating events/ abnormal hotspots, which require detection at extremely low temperature gradients in real time. Therefore, the system is capable of detection of temperature gradients of 0.01K/min (0.01℃/min).

Each sensor will monitor the container wall temperature and produce a heat (temperature) map which can be observed by personnel. The heat map provides information about hotspots which might appear suddenly in case of a fire or an internal heating event inside a single or multiple containers. An example heat map (normal conditions) generated by the devices on a cargo hold is shown below in Figure 81. This figure is then used to explain the working methodology behind the system.

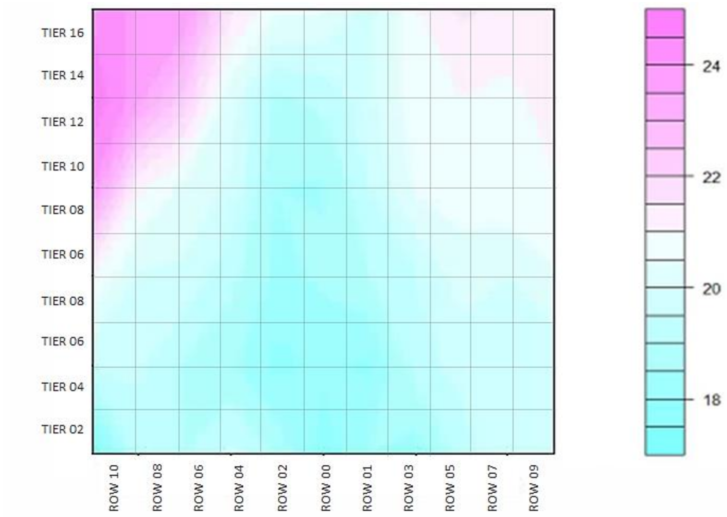

Figure 81: Heat map for a cargo hold under normal conditions source: [Radicos Technologies GmbH.]

The heat map, as expected, shows the temperature profile across all the container walls in the hold. The higher temperatures near the top corners are associated with external factors such as fuel tanks and radiation from the sun which can be assumed due to the heat flow direction (temperature gradient) is from the outside borders towards the interior of the hold. When a fire or self-heating incident occurs in a container the direction of temperature gradient will have the opposite direction as shown in Figure 82 (From the interior of the hold towards the outside) For the containers located at the boundary of the hold, extra temperature devices are required to detect a sudden temperature increase within those containers. These additional devices will track the temperature of the hull which is then used to distinguish a sudden temperature rise in the container located on the boundaries.

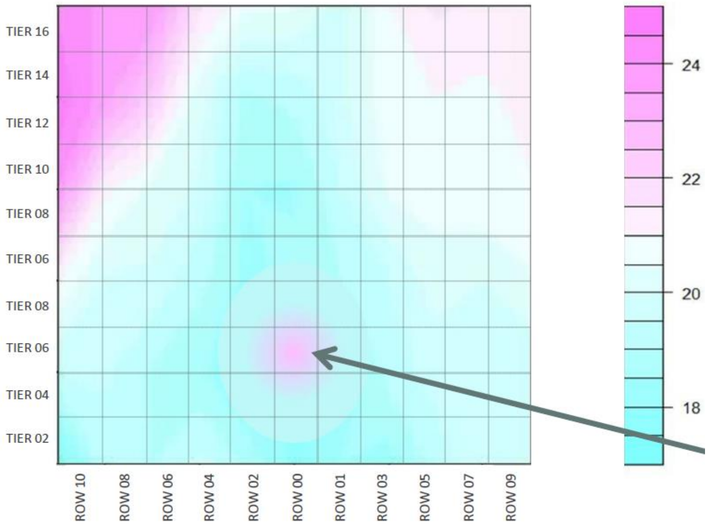

Figure 82: Heat map with a hotspot (indicated by the arrowhead) in a single container source: [Radicos Technologies GmbH].

The recorded hotspot shows an area on the heat map with an elevated temperature which suggests a potential fire or self-heating event. In addition, the temporal temperature variation of that specific container is monitored in combination with the spatial temperature distribution (i.e., heat map) to avoid false alarms. This heat map also provides an easier path to locate where the container of origin is located on the stack.

- **Limitations**

The system can monitor the temperatures of the whole stack below the deck. However, on the deck there is a limitation on how many levels it can track. This is due to the stacks above the deck are higher than the cell guide structure. Figure 83 shows the maximum levels the system can track above the deck highlighted in green. Thermal imaging cameras may be an option for the unreachable areas of the stack (i.e., combine with D-RCO3).

Risks associated with mechanical impact during loading and unloading also need to be considered.

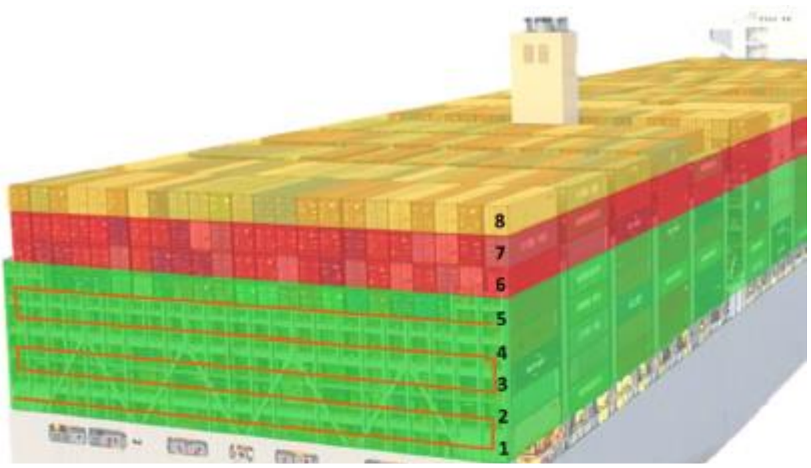

Figure 83: Limited use of container wall monitoring system above the deck (red and yellow regions are not reachable) source: [Radicos Technologies GmbH].

- **Risk reduction potential**

Improving the current system as suggested will lower the detection times. However, the risk reduction potential of such improvements was valued at 3.1% for slow growing fires and 2.7% for fast growing fires for all vessel types.

- **Simulations**

The detection times of this method will depend on the temperature variation with time (i.e., temperature gradient) of the container end walls. The simulations included single container configuration. The focus in these simulations is on the temperature evolution of the container end walls which relates directly to the detection times when this method is implemented. The temperatures of the solid boundaries can be directly monitored in FDS using the wall temperature measurements. This method of measurement will be used in the analysis presented below.

The temperature of the end walls in the event of a fire or self-heating event depends mostly on the heat transfer between the flames, smoke or any heated object within the container and these walls. Due to the uncertainty of the fire size and growth rate, 4 different sizes of fires were selected and placed in the centre of the container which was assumed to be the worst-case scenario due to the distance from each end wall to the fire being the highest in this configuration. Further details about the numerical set-up are presented in the next section.

- **Numerical set-up**
-

The geometry, the material properties, the computational domain were similar to the simulations of smoke leak from a single container. However, the size of the fire (HRR) was changed to account for the uncertainties involved. The area of the fire was set to be 0.96m × 0.64m and the heat release rate per unit area (HRRPUA) was adjusted such that the resulting HRR from the fire is capped at 100 kW, 200 kW, 500 kW, and 1000 kW using a propane fire. The different sizes of the fire provide a wide range of HRRs from a very small fire of only 100kW to a much larger fire of 2 MW.

The end wall temperature of the container was measured using boundary files on FDS which produces a visually similar figure to the one produced by the visual interface of these systems. The results of the simulations are presented below where the detections times of the system are derived from the wall temperature profiles generated in FDS.

- **Results**

As mentioned previously, the analysis focuses on the wall temperatures and the temporal temperature gradient of the end walls of the containers. To be more specific, the time taken to register and increment of +1ºC, +10ºC and +30ºC will be presented in this section for each different HRR. The system can be tuned accordingly to trigger a warning signal or an alarm at different temperature gradients (greater than 0.01ºC/min) as well as at desired absolute temperatures of the container walls (on the outer exposed face). The time taken to record these different temperature increments will be presented. The time taken to achieve this increment of temperature can only be taken as the detection time only if both the spatial and temporal sensitivity of the detector is high enough to capture the temperature field accurately. Otherwise, the detection times will be longer and considering this, the times taken for at least 50% of the area on the container wall is also given as the maximum possible detection time.

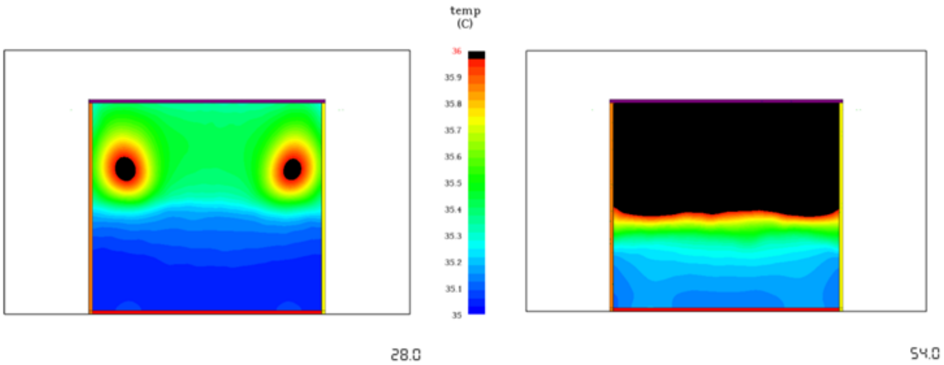

Figure 84: Minimum (left) and maximum (right) detection times for a 100kW with +1°C setting

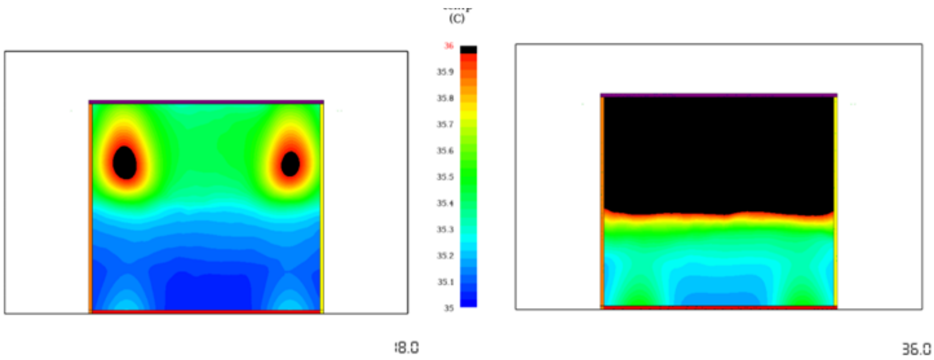

Figure 85: Minimum (left) and maximum (right) detection times for a 200 kW with +1 oC setting.

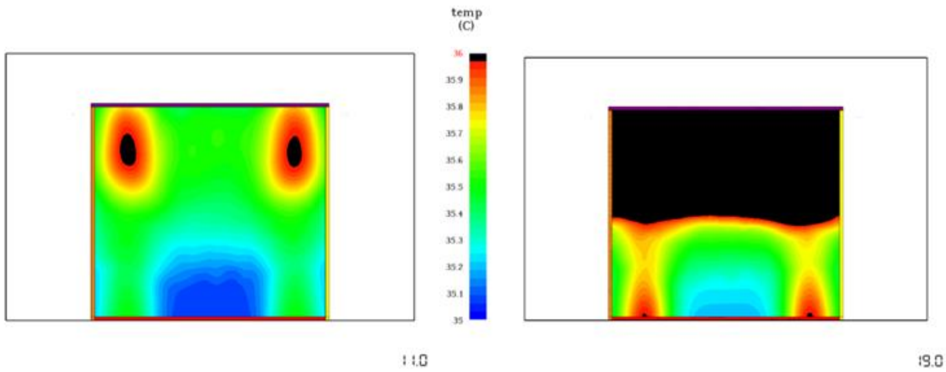

Figure 86: Minimum (left) and maximum (right) detection times for a 500kW with +1°C setting.

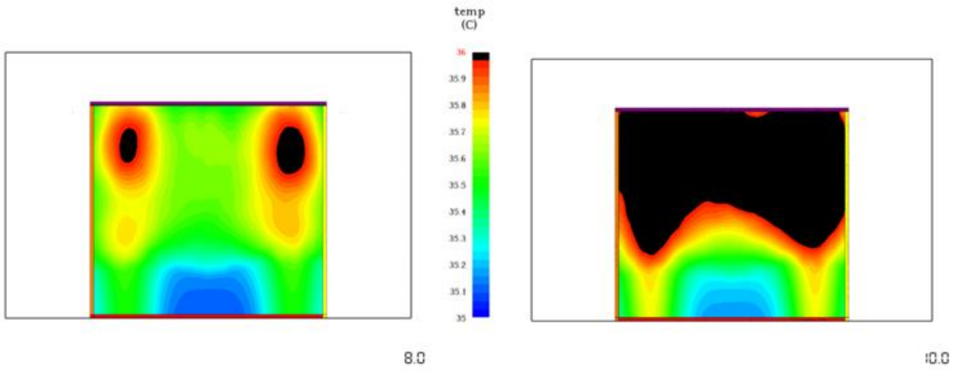

Figure 87: Minimum (left) and maximum (right) detection times for a 1000kW with +1°C setting.

The detection times associated with the smaller fires are, as expected, longer than the larger fires. In addition, the smaller fires only show an increment of temperature in a much smaller area which might make it more difficult to capture the smaller area with an increased temperature. The resolution of the heat map should be high enough to capture the smallest of areas with an increased temperature. For smaller fires, the time taken to heat up at least 50% of the container end wall above the alarm threshold is almost double the time taken for the initial appearance of the hotspot, which for larger fires is much less and the difference between the minimum and maximum times becomes negligible for stronger fire sizes. Similar trends were observed for the higher temperature increments of +10ºC and +30ºC as well but, due to the larger temperature increment required for alarm levels the gap between minimum and maximum detection times becomes larger for all the cases.

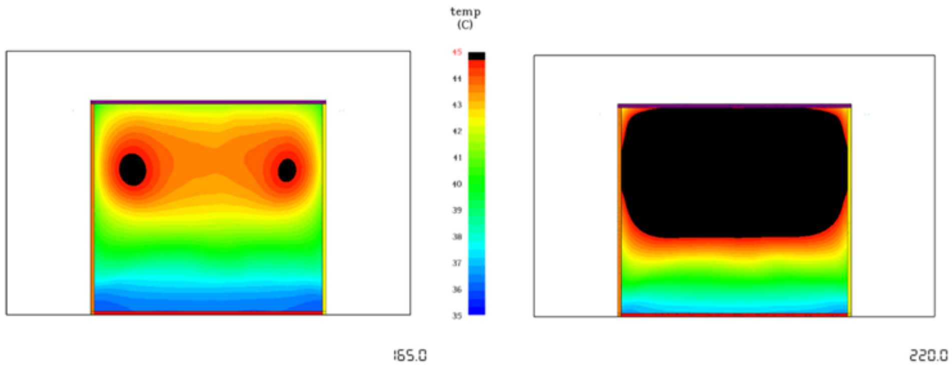

Figure 88: Minimum (left) and maximum (right) detection times for a 100kW with +10°C setting

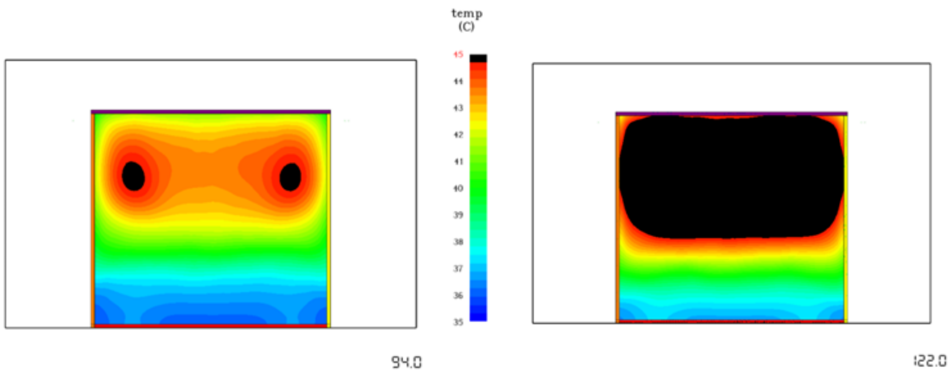

Figure 89: Minimum (left) and maximum (right) detection times for a 200kW with +10°C setting.

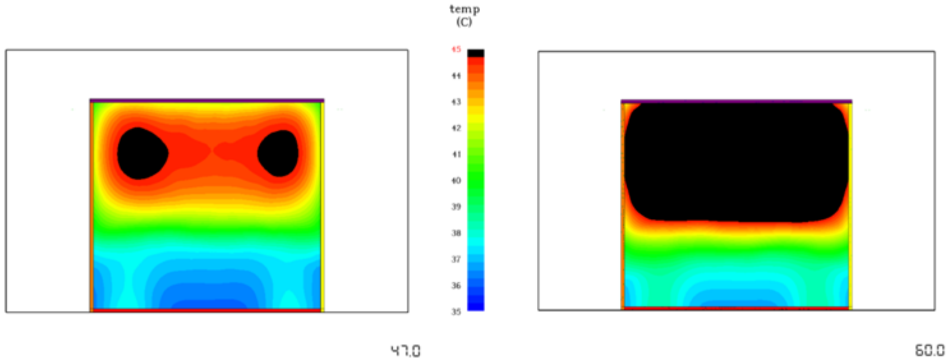

Figure 90: Minimum (left) and maximum (right) detection times for a 500kW with +10°C setting.

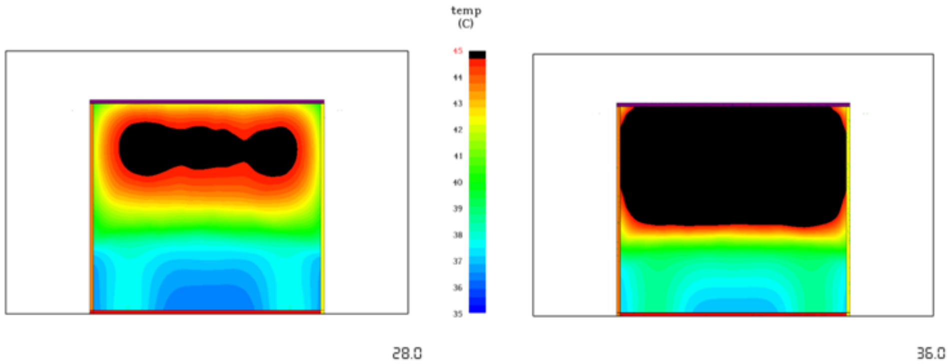

Figure 91: Minimum (left) and maximum (right) detection times for a 1000kW with +10°C setting.

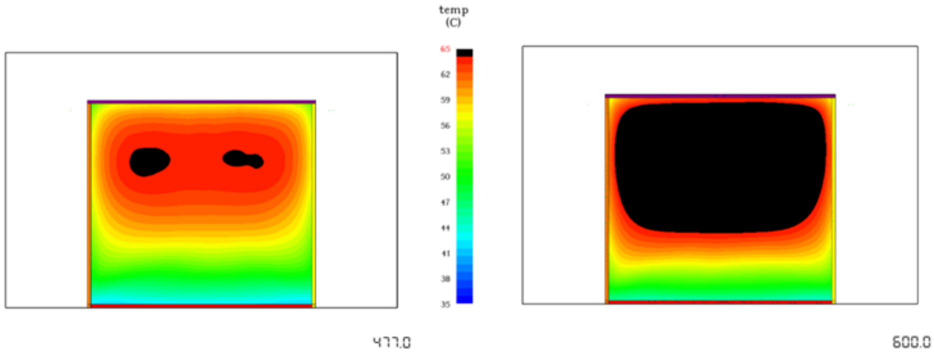

Figure 92: Minimum (left) and maximum (right) detection times for a 100kW with +30°C setting

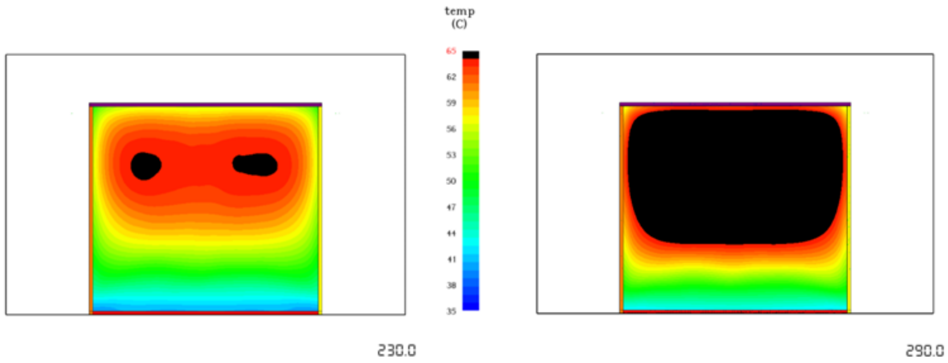

Figure 93: Minimum (left) and maximum (right) detection times for a 200kW with +30°C setting

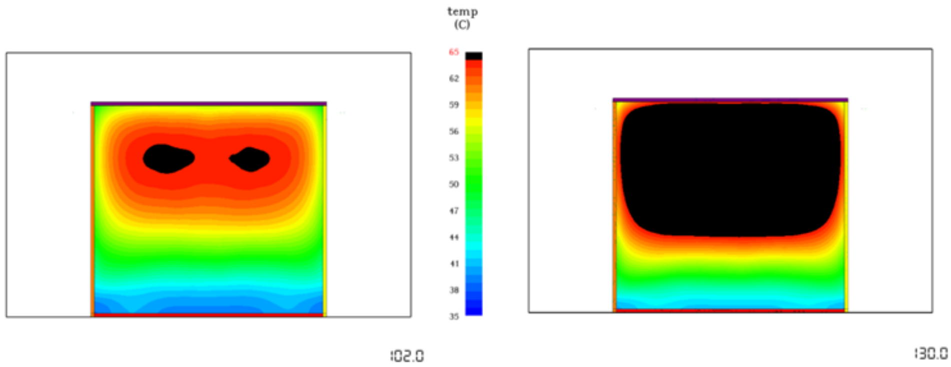

Figure 94: Minimum (left) and maximum (right) detection times for a 500kW with +30°C setting.

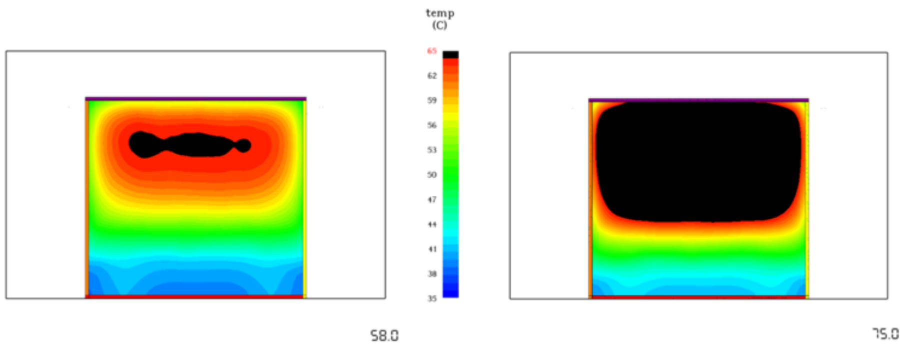

Figure 95: Minimum (left) and maximum (right) detection times for a 1000kW with +30°C setting.

When the temperature increment required for detection is set to a higher value (+10ºC or +30ºC) the detection times increase for all the cases. However, still for a larger fire around 1000kW from the beginning it only takes less than a minute to increase wall temperatures by 30ºC. In contrast, for smaller fires it takes over 2min before the end wall temperature is increased by just 10ºC.

The detection times recorded for each different HRR and for each adjusted sensitivity of the detection system is presented as a summary in Table 49

Table 49: Summary of detection times for each different setting for the temperature monitoring system (FDS results).

HRR [kW]	Temperature increment [s]					
	+1ºC		+10ºC		+30ºC	
	min	max	min	max	min	max
100	28	54	165	220	477	600
200	18	36	94	122	230	290
500	11	19	47	60	102	130
1000	8	10	28	36	58	75

Due to the adjustable alarm threshold of these types of systems, depending on the desired threshold set by the user, the detection times can vary from a few seconds to a few minutes before an alarm is triggered. The simulations performed have focused on 3 different settings which are based on the absolute temperature rise of the container wall. The alarm thresholds chosen for the analysis were +1ºC, +10ºC and +30ºC meaning an alarm can be triggered once such an increment in container wall temperature has been detected by the system. To account for the uncertainty of the fire size, different HRRs were chosen. The results show that the detection times depend greatly on the chosen fire size and the chosen alarm threshold. For smaller fires, the chosen alarm threshold has a greater effect on the detection times compared to the larger fires where the detection times do not vary as much.

− **Risk reduction potential**

Temperature monitoring of each individual container can improve the detection times for different heating events especially compared to the current system. This is evident in the relatively higher numbers for risk reduction potential scored by the system. On deck, for slow growing fires the risk reduction potential for feeder, single island and twin islands vessel type (Gen. ship 3, 2 and 1) are 3.1%, 3.6% and 3.1% respectively. For fast growing fires the potential is valued a bit higher for the three types of vessels at 9.1%, 9.2% and 7.0%. Below the deck, the system can provide full coverage on all the containers which increases its effectiveness for both slow and fast-growing fires. For feeder, single island and twin islands vessel type (Gen. ship 3, 2 and 1), the values are 8.8%, 9.7% and 7.9% for slow growing fires and for fast growing fires, the values are 8.8%, 20.2%and 15.2%.

4.4.3.3 RCO D3 – Fixed IR cameras

Currently, there is no detection system installed on the deck of the cargo ships. Therefore, the detection time relies solely on the crew. A fire can be spotted from the bridge or during the patrols. However, there are not specific fire detection patrols. The use of fixed IR cameras on deck, it is expected that the detection time will be reduced. Therefore, improving the probability of fighting the fire successfully.

− **Availability in current market**

A system developed by Alpha Marine has been tested on the Stena Scandinavica Ro-Ro passenger ship, and it was witnessed by Class Society Bureau Veritas Marine and Offshore and RISE Fire Research AS. The camera was tested on the weather deck, the maximum distance tested was 50 m, where an 80 kW fire was detected. Even when the gas burner was obstructed it detected a 300 kW fire in 3 minutes, and when half obstructed, an 80 kW in half a minute. Also, under simulated heavy rain conditions between the fire and the camera, a 400 kW fire was detected in four minutes. It has been proved then that fixed IR cameras can be used for fire detection on deck.

− **Working principle**

The system considered for this study has a field-of-view of 25° horizontal and 20° vertical, 25 mm lens, with high resolution. It can be set between -20°C and 200°C range. It can go up to 585 meters for temperature measurement and is made of stainless steel. The system should be integrated into the existing bridge computer system. It also could be connected to a stand-alone console or a high resolution, fully dimmable screen.

- **Limitations**

Since the cameras would be placed on deck, robustness to weather conditions becomes a challenge. However, current systems are being used on oil rigs for example and are sufficiently robust. This type of camera has been even tested under heavy rainy conditions. In addition, if the lens is exposed to ice or dirt, it has an internal system to protect against ice formation and to send a fault signal if the lens is contaminated. Another concern is the false alarm readings. The sensitivity of the camera can be adjusted to avoid faulty readings as much as possible. In one study, using this type of camera on board Ro-Ro passenger ships for a month, it was identified that during operations of loading and unloading, the system reported all the false alarms. Therefore, it can be calibrated to increase the sensitivity during this operation, or even to consider other systems as support.

- **Risk reduction potential**

Ideally there would be full coverage of the deck containers. The placement of the cameras is presented in the following images. To maximize the coverage, it is proposed that at least 6 cameras should be placed between the bays. Three of the cameras would be looking to the opposite bay. This aims to increase the camera field view.
For this situation, the detection node in FT goes from actual value to 75% efficiency. Assuming the system has a large coverage, still the reduced distance between bays challenges the cameras' field of view. Then the most likely risk reduction potentials for each ship type (Gen. ship 3, 2 and 1) are, for slow fire, 4.7%, 5.4% and 2.4%, for fast fire on deck, 10.5%. 13.8% and 6.9%.

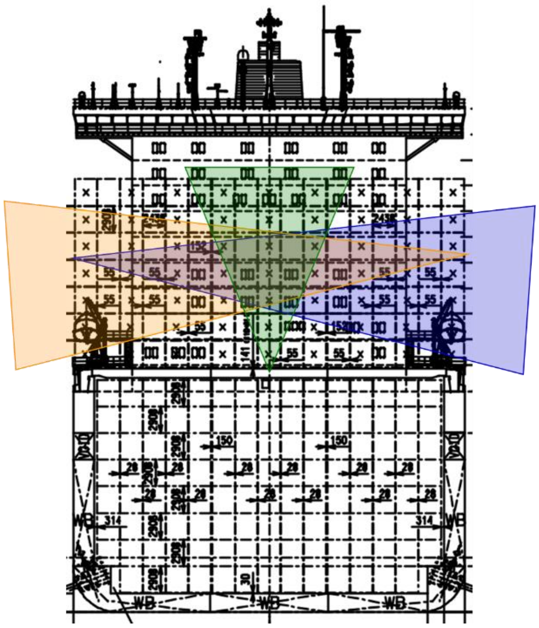

Figure 96: Fixed IR cameras on Single Island ship (Gen. ship 2) – Cross section view

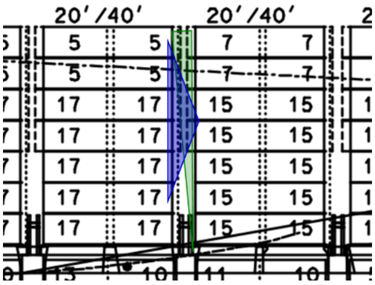

Figure 97: Fixed IR cameras on Single Island ship (Gen. ship 2) – Side view.

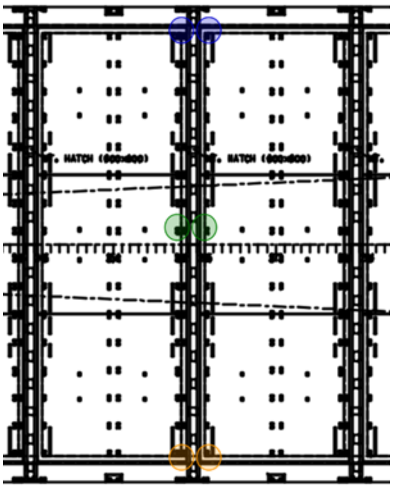

Figure 98: Fixed IR cameras on Single Island ship (Gen. ship 2) – Top view.

4.4.3.4 RCO D4 – CCTV and AI smoke detection

Smoke detection using CCTV and trained AI has been used in car parks, industrial warehouses, and different other scenarios. These systems are capable of 24/7 monitoring of the desired environment and the AI is trained to detect smoke coming out of an object in the field of view of the CCTV device. Although these systems have been proven to be effective in many scenarios, these are yet to reach the maritime industry as a potential smoke detection method.

- **Availability in current market**

AI based smoke detection systems have been developed for different industrial applications such as smoke detection in paper storage warehouses. Similar systems have been developed for smoke detection inside car parks where distinguishing between smoke from a fire is more challenging due to the general presence of exhaust gas. These systems work on the principle of a camera system and a trained AI for detection of smoke. These systems have been proven to be effective in tricky environments coupled with the need for as early as possible detection times to avoid large scale property damage.

- **Working principle**

[60]The system works on a trained AI and can distinguish between fire (flames) and smoke and trigger an alarm or a warning signal upon detection. Any existing CCTV cameras can also be included in the detection system if available

[60] https://highlightparking.co.uk/safe/

without the need for new cameras. The system, after detection, can be set up such that selected individuals receive personal alerts or trigger sound and visual alarms within a desired area. To avoid false alarms, the detected area is analysed by the AI 2 additional times before the activation of alarms and sending notifications out to personnel. Figure 99 shows a flow diagram indicating different steps in the process from the point of detection to the reception of a personal alarm on a smart system.
The system is equipped with 'smart' functions which require smart devices to be accessible. On board a cargo vessel, the smart functions will not be accessible, however it is still possible to trigger visual and auditory alarms and warning signal in case of detection. The requirement of coverage of larger area can only be dealt with an increased number of cameras fixed on the vessel.

Figure 99: AI based smoke detection system and its user interface

- **Limitations**

Shifting from an environment inside car parks to a cargo vessel is a considerable change in numerous ways. A fixed camera in a car park will be fixed to a stationary structure whereas a camera fixed on a moving vessel will have additional challenges with moving and different backgrounds, a larger area of coverage and changing weather conditions. Therefore, extra effort needs to be put towards training the AI to be optimized to the environment.

- **Risk reduction potential**

  - **Simulations**

The installed CCTV cameras can only detect the smoke coming out of a container only when the smoke has risen above the container stack. Therefore, the smoke travel time to reach the open atmosphere above stack at detectable concentrations can be considered as a key parameter when evaluating the effectiveness of having such systems installed on the vessel.

Two sets of simulations have been run looking into the smoke travel times above deck with two different weather conditions: one with the vessel moving in approximately 23 knots / 43km/h (12m/s) in still atmosphere and the other representing the bast case where the wind velocity matches the velocity of the vessel.

  - **Geometry**

The geometry in the above deck configurations shows minor differences from the below deck configurations. Apart from these minor differences the simulations only considered the smoke flow in the gap between two stacks similar to what was done in the below deck smoke flow simulations. The differences between the two simulations are discussed below.

The three types of vessels have three different stack heights with the feeder vessel having a stack height of 5 - 40 ft - high cube containers, the single island vessel and twin island vessel type (Gen. ship 1 and 2) having stacks of 7 and 9 - 40 ft - high cube containers respectively. Furthermore, the arrangements of stacks are also different compared to the below deck scenarios. However, above the deck all the three vessel types have similar stack arrangements.

Figure 100 shows a schematic of the stack configuration above the deck followed by Table 50 in which exact dimensions for each type of vessel are presented.

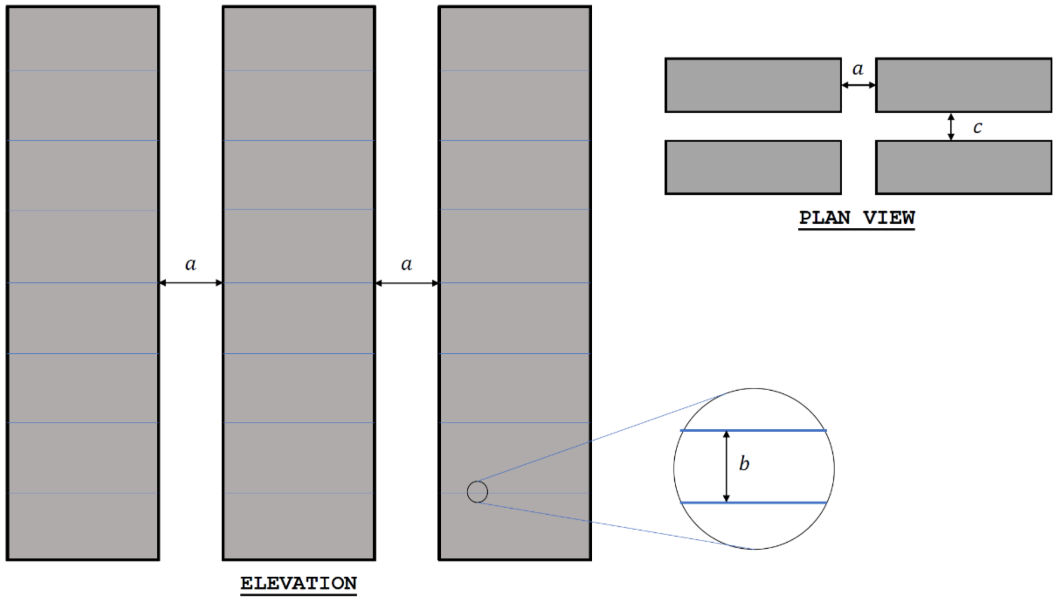

Figure 100: Stack configuration above the deck.

The gap between two end walls of two neighbouring stacks are given by a and b and c respectively indicate the vertical gap between two containers on a stack and the gap between two side walls of two neighbouring stacks respectively.

Table 50: Dimensions for each type of vessel.

Vessel type	*a*	*b*	*c*
Feeder (Gen. ship 3**)**	1980mm	30mm	55mm
Single island (Gen. ship 2**)**	1980mm	30mm	55mm
Twin islands (Gen. ship 1**)**	1980mm	30mm	55mm

- **Numerical set-up**

The simulations focused on the smoke travel times to reach the top container and disperse into the open atmosphere above in detectable concentrations assuming a smoke leak of 5g/s from the ISO vents of the bottom most container of the stack. Given that the stacks above the deck are exposed to the open atmosphere, the atmosphere around the stacks are affected by the relative movement between the moving vessel and the open air/ wind. The CFD calculations were done considering these effects which were already implemented in FDS.

The cell sizes for these simulations were also chosen considering the gaps sizes and having a minimum of 8 cells in the gas phase between the gap denoted by c in Figure 100. Table 51 below lists the chosen cell sizes for the simulations for each type of vessel.

Table 51: Cell sizes for the simulations.

Vessel type	Cell size [mm]
Feeder (Gen. ship 3**)**	200 × 6 × 6
Single island (Gen. ship 2**)**	200 × 6 × 6
Twin islands (Gen. ship 1**)**	200 × 6 × 6

As mentioned earlier the effect of weather conditions and the relative movement between were included in the simulations using activating the 'wall of wind' model in FDS[61]. This model applies a velocity field to the gas phase as per the user's input regarding both the magnitude and the direction of the wind velocity. This applies to the whole domain but with time the profile will adjust itself depending on the obstacles and other flow fields present in the domain such as a buoyant flow of hot smoke similar to this scenario. The model assumes a constant velocity wind profile which enters and leaves the domain from the open boundaries depending on the direction of the specified wind profile.

Two cases were chosen representing a 'best-case' scenario and the vessel moving at 23 knots (~12 m/s) in a still atmosphere. The 'best-case' scenario was the wind also blowing in the same direction of the vessel with the same speed as the vessel. This 'best-case' scenario does not affect the flow of the smoke and allows the smoke to rise up as it did in the below deck scenario. This allows the detection system to detect or see the smoke coming from the exact location where the fire/ heating event is going on making it easier to locate the fire. However, due to the wind velocities and the movement of the vessel in other cases might make locating the smoke leak less straightforward.

For the above deck scenarios, the computational domain was extended by 4m above the topmost container on the stack. This allows the smoke to disperse into the atmosphere more naturally and this region also allows the wind conditions to develop naturally above the container stack. It should be noted that these specific extended regions were meshed in a slightly different way due the computational limitations. The cell size chosen for these regions was 200 mm × 6 mm × 200 mm for all the simulations. The computational domain for the feeder vessel is shown below in Figure 101. The only difference between the domains for the vessel types is the stack heights.

[61] McGrattan, K., & Miles, S. (2016). Modeling Fires Using Computational Fluid Dynamics (CFD). In M. J. Hurley (Ed.), SFPE Handbook of Fire Protection Engineering (5th ed., pp. 1034–1065). Society of Fire Protection Engineers.

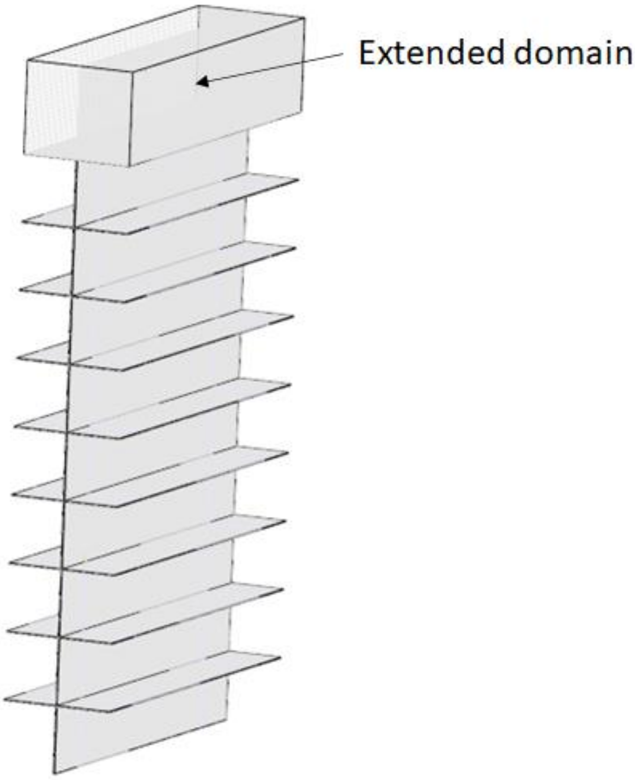

Figure 101: computational domain for the feeder vessel.

An assumption was made for the simulations with wind where it was assumed that the wind will only be present on the extended part of the domain. This was done by closing the boundaries below the extended part on the side where the wind would enter the domain from as shown in Figure 102. $\overleftarrow{V}_{wind}$ is the wind velocity.

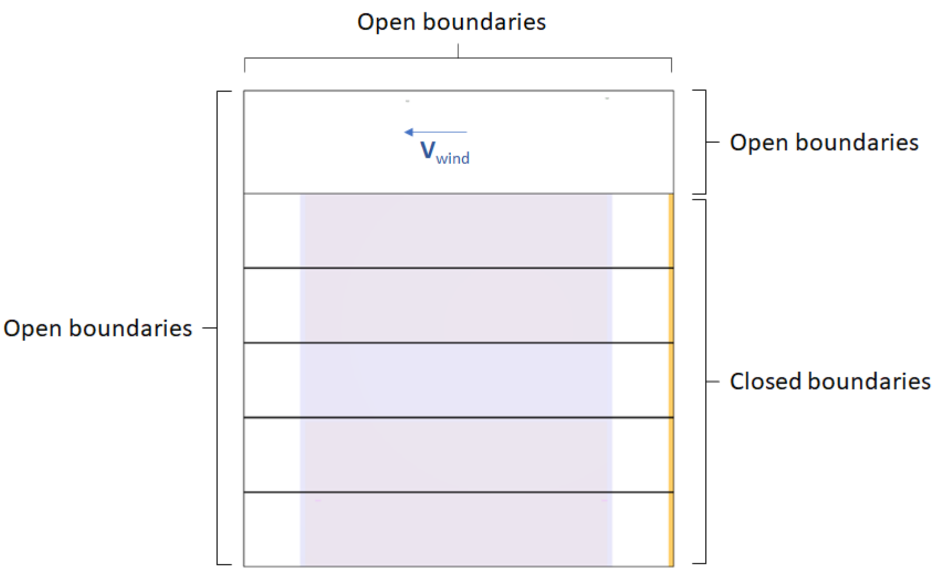

Figure 102: Domain boundaries.

The closed boundary on the headwind side used to represent the obstacles such as stacks present on that side which hinders the wind effect to a certain extent. The results from the simulations are presented in the upcoming section.

- **Results**

The vessel moving in a still atmosphere induces a relative movement between the atmosphere and the vessel similar to a wind profile in the opposite direction with the same magnitude. The effect of the said relative movement affects the trajectory of the leaked smoke. This could result in the smoke reaching the top of the stack in a different location compared to the initially leaked stack. Detection based on visual smoke detection above the stack are vulnerable in this scenario and could potentially lead to misleading information regarding the location of the initial leak.

As mentioned in the previous section simulations were run with different wind settings based on the velocity of the vessel. The wind speeds were changed from 12m/s, 2m/s and 0m/s representing vessel velocities of 23 knots in still atmosphere, 3.9 knots in still atmosphere and no relative movement between the vessel and the atmosphere.

The steady state wind profile is shown below in Figure 103 for $\overleftarrow{\boldsymbol{V}}_{\boldsymbol{wind}} = 12\ m/s$.

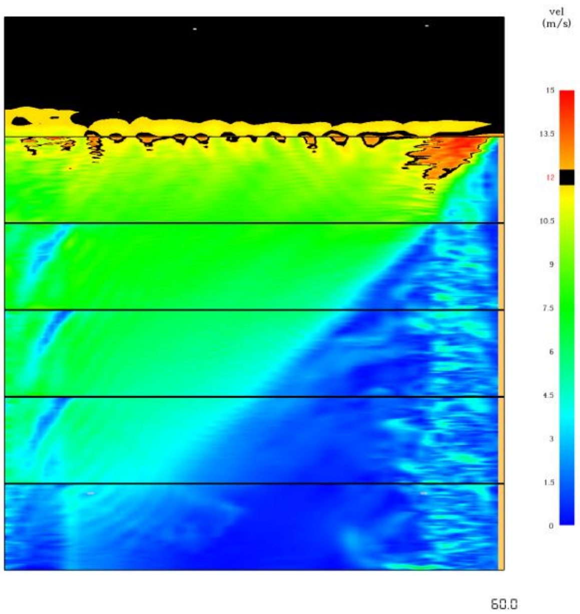

Figure 103: Steady state wind profile.

As per the velocity profile through the gap, it is evident that the wind effects are mostly likely to take the leaked smoke away from the stack with wind which was further confirmed while observing the smoke flow after letting the flow to develop over a considerable time (see Figure 104). This was true for all three vessel types which implies in all cases the smoke is very likely to reach the top of a stack in a completely different region due to the wind effects and the movement of the vessel. This will eliminate the capability of the CCTV detection method to locate the leak completely unless counter measures are implemented in AI with proper training.

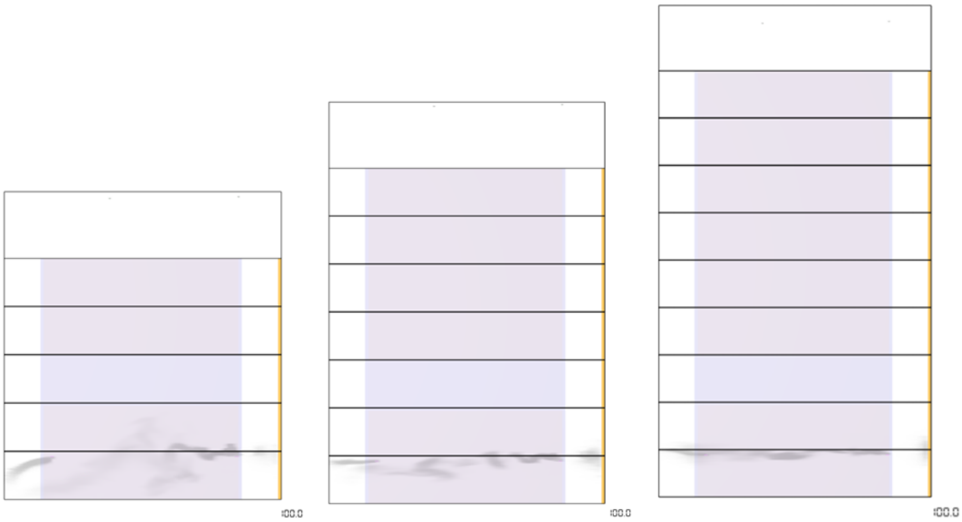

Figure 104: Smoke trajectory above deck with a wind speed of 12m/s.

As mentioned before, the effects of the relative motion between the vessel and the atmosphere do not allow the smoke to travel upwards which considerably reduces the effectiveness of detection methods which depends on visual observation. Furthermore, the smoke will be diluted heavily when the smoke reaches the gaps between two stacks making detection by visual observation even more difficult.

Upon observation of the smoke flow in the simulations above, the effect of wind (vessel movement) seems to be extremely high at this wind speed therefore, simulations with a relatively very low wind speed of 2 m/s (3.88 knots vessel speed in still atmosphere) were used as input in the simulations to further investigate the effects of the wind profile in a less extreme scenario. The steady state wind profile and the smoke flow after 500 s in Figure 105. Similar to the scenario with the relatively higher wind speed, the smoke did not reach the top of the stack within the stack of the COO which suggests that even with relatively lower wind speeds, detection via visual based systems will not be straightforward.

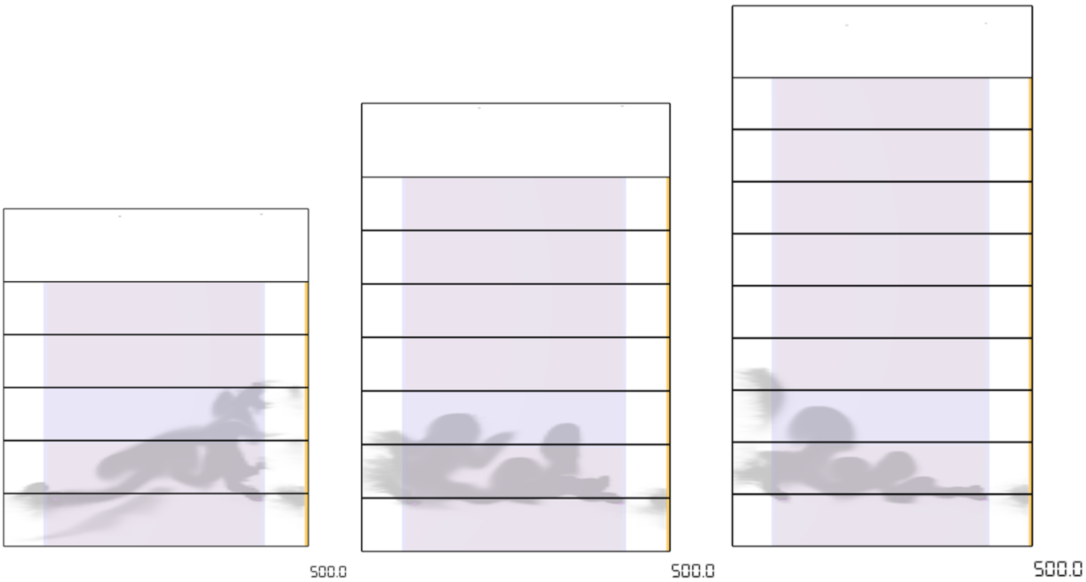

Figure 105: Smoke trajectory above deck with a wind speed of 2m/s.

The best-case scenario regardless of the vessels speed is when the wind velocity matches the vessel velocity. This is similar to a case where the smoke leak happening is still atmosphere when the vessel is not moving. To model this scenario in FDS, the 'wall of wind' model was deactivated before the simulations were run. The smoke travel times to reach the top of the stack are given below in Figure 106, the visibility of the smoke layer is provided with lower values corresponding to higher smoke concentrations and vice versa. The snaps were taken for all three vessel types when around half of the extended domain (2m above) was covered by the plume.

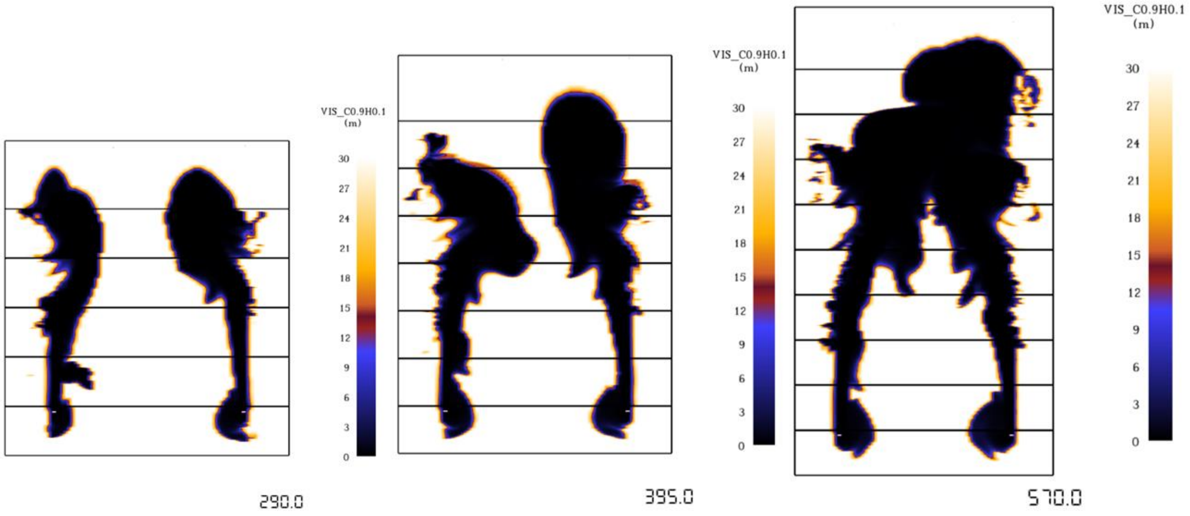

Figure 106: Smoke trajectory in above deck simulations without wind effects.

Table 52: Potential detection times of smoke with AI based CCTV cameras.

Vessel type	Time to reach 2m above the stack [s]
Feeder (Gen. ship 3**)**	290
Single island (Gen. ship 2**)**	395
Twin island (Gen. ship 1**)**	570

Without the presence of the wind effects, the smoke plume reaches the top of the stack for all three vessel types in detectable smoke concentrations. The visibility of the local regions where the smoke is present is on the lower side implying that visual detection is a possibility.

4.4.3.5 RCO D5 – Portable IR cameras for crew

A portable IR camera is a type of thermal camera (also known as thermal imager) that detects and measures the infrared radiation (also known as heat or thermal energy) of the object or the surrounding environment and displays it as an image or a color map. Compared with fixed thermal cameras, it has the characteristics of mobility, flexibility, and portability, which can be used for daily patrol of the workplace to discover hidden hot spots in time and enhance the safety of the workplace.

- **Availability in current market**

Depending on the performance and functionality there are different types of portable infrared cameras on the market that can measure temperatures from -50 °C to 2000 °C. Different quality cameras can be selected for different applications according to sensor resolution, thermal sensitivity, field of view and other properties. For example, a high-quality camera with a resolution of 1280 × 960 pixels, a detection sensitivity of 35mK (0.035 °C), and a temperature measurement range of -20 °C to 1000 °C can be used for hot spot detection.

- **Working principle**

The infrared radiation that cannot be observed by the naked eye is detected by a thermal sensor attached to the camera lens. The electronic components convert the data sent by the detector into an image or colour map with a temperature distribution and show it on the display. The surface temperature of the detected object is displayed in a coloured picture, which makes it easy for crew to find the abnormal point and take appropriate measures to prevent accidents.
To choose a portable thermal camera that can be used on board, because of the special conditions on a container ship, we need to consider the thermal imaging capability from multiple aspects.

- Temperature range

The temperature range is the entire span of temperatures for which the thermal camera is calibrated to and capable of measuring. Some cameras have multiple ranges for more accurate measurement of a wider range of temperatures. It is important that the device is calibrated correctly to match the temperature range which may be encountered in the application.

The purpose of daily inspections using portable thermal cameras on a container ship is to find the hot spots and heat sources. Many combustible materials can reach very high temperatures without producing flames and large amounts of smoke. For example, some substances can burn up to 300°C without producing large amounts of smoke, while some wood can burn at 400°C or higher before producing a flame. Therefore, in order to effectively find hot spots, it is recommended to choose a portable thermal imaging camera that has a maximum range of at least 400°C or higher.

- Sensor resolution

The resolution of the thermal camera is how many pixels the camera has on the scene. Sensors with a larger number of sensitive elements (pixels) can produce a more detailed image of an object. Higher resolution infrared cameras can measure smaller targets at a greater distance and create sharper thermal images for more accurate and reliable measurements. The sensor can come in a variety of pixel configurations from 80 × 60 to 1280 × 1024 pixels or more. The higher the resolution, the greater the detail and accuracy of the images, because the temperature to be measured could be relatively high (over 400 °C) to display the temperature distribution clearly, at least a 160 × 120 pixels resolution device is required.

- Thermal sensitivity

Thermal sensitivity (Noise Equivalent Temperature Difference, NETD) defines the minimum temperature difference a thermal camera can detect. In effect, the lower the NETD value, which is measured using millikelvin (mK), the better the sensor can register small temperature differences. Because the temperature of the hot spot we need to find out could be relatively high and the temperature span will be relatively large, so it is recommended that the sensitivity of the portable thermal camera can be selected from 150mK (which is 0.15 °C) or higher.

- Field of view

Field of View is determined by the camera lens and is the extent of a scene that the camera will see at any given moment. For work being done close-up, you need a lens with a wide angle FOV (45° or higher). For long distance work, you need a telephoto lens (12° or 6°). Because the distance between the containers on ship is relativity close-up, it is recommended to choose a FOV with around 45° x 35°, which the minimum focus distance is around 30cm.

- Focus

Cameras may have fixed focus, meaning they are always in focus; have manual focus, meaning the user adjusts the focus on the camera; or automatic focus, meaning the camera will autofocus based on what it can see for contrast on the scene. Because daily inspections need to detect multiple locations, if the device is manual focused, it will take more time to adjust the focus, it is recommended to use a device with automatic focus in order to get the detection results more efficiently.

- Ingress Protection

Dust and small particles will affect the accuracy and service life of the device, rain and sea water will often be encountered on board, so the portable thermal camera we choose for use on board must be both solid objects and liquids protection. The Intrusion Protection Range 5 is dust-proof according to IP ratings and standards, which means some dust may pass through, but not enough to damage the product. In terms of moisture protection, Range 4 is resistant to water splashes from any direction. Therefore, we recommend choosing a portable thermal camera with an IP rating of 54 or higher to use on board.

Beyond basic thermal imaging capabilities, you can find infrared cameras with a wide range of additional features that automate functions, allow voice annotation, enhance resolution, record and stream video of the images, and support analysis and reporting which can be selected according to need.

- **Limitations**

The portable IR camera is a good choice for daily patrols, but it has some limitations. First, due to the special conditions of the container ships (blew deck and on deck) and the number of patrol personnel, the application of portable IR cameras can only cover a certain number of containers. The other limitation portable IR cameras have is that surfaces that are reflective (shiny metals) will give inaccurate readings.

- **Risk reduction potential**

Without crew patrols, portable IR cameras can be used to locate the location of fires that have already been detected by other systems. For this situation, the “Poor location" (confirmation) node in FT goes from actual value to 0 in the best case. Then the most likely risk reduction potentials for each generic ship type (twin island, single island, feeder) are, for slow fire on deck, 2.8%, 2.1% and 0.8%, for fast fire on deck, 1.1%. 0.8% and 0.3%. For slow fire below deck ,2.0%, 1.5%, 0.8%, fast fire below deck, 0.8%, 0.6%, 0.3%.
If there are crew patrols (only for on deck), consider adding the probability of patrol detection based on the above. Considering the number of container layers that the crew can reach and the frequency of the patrol, the total risk reduction potentials for each ship are 3.7%, 2.9% and 1.5% for slow fire, 2.1%, 1.9%, and 1.2% for fast fire.

4.4.4 Effectiveness assessment

Table 53: Effectiveness assessment of detection RCOs.

D-RCO	RCO title	TRL	OD/ BD	RCO- side effects/ limitations
D1	Optimizing current system	9	BD	Retrofitting may not be possible in some cases. Then the RCO would be applicable only for new ships.
D2	Heat detection looking at individual container temperature rise	9	BD/OD	On the deck there is a limitation on how many levels it can track. Up to the lashing bridge. It requires mechanical protection of the system.
D3	Fixed IR cameras (installed at strategic locations). Coupled to a software solution to automate detection	8	OD	Susceptible to weather conditions. Requires several cameras to cover all the containers due to the small distance between the bays.
D4	CCTV - AI - smoke detection	7	OD	Required smoke to travel to the top. Not always happen due to the ship’s velocity.

D5	Portable IR cameras for crew to enhance manual detection - location of seat of fire, low smoke production, smouldering etc.	9	OD/BD	Mainly used to confirm a fire. When used as the main detection system on deck, it requires a standard procedure for crew patrols.

4.5 Firefighting

4.5.1 Current system evaluation

SOLAS Chapter II-2, chapter 10 dictates the requirements for firefighting equipment on board the three ship sizes. Ships shall be provided with fire pumps, fire mains, hydrants and hoses complying with the applicable requirements of this regulation.

Ships constructed on or after 1. January 2016, designed to carry containers on or above the weather deck have additional requirements as stipulated in SOLAS chapter II-2, regulation 10, sub paragraph 7.3.

Ships carrying dangerous goods on and below deck shall furthermore comply to SOLAS chapter II-2, regulation 19.

As this study is focusing on prevention, detection, firefighting, and containment for fires in containers on board container ships, the following will describe in general terms the requirements for firefighting equipment on deck and in cargo holds.

− **Purpose of the firefighting regulation**

The purpose of regulation is to suppress and swiftly extinguish a fire in the space of origin, except for paragraph 1.2. For this purpose, the following functional requirements shall be met:

- Fixed fire-extinguishing systems shall be installed having due regard to the fire growth potential of the protected spaces.
- Fire-extinguishing appliances shall be readily available.

For open-top container holds and on deck container stowage areas on ships designed to carry containers on or above the weather deck, constructed on or after 1 January 2016, fire protection arrangements shall be provided for the purpose of containing a fire in the space or area of origin and cooling adjacent areas to prevent fire spread and structural damage.

4.5.1.1 General equipment

− **Water supply**
−

Ships shall be provided with fire pumps, fire mains, hydrants and hoses complying with the applicable requirements of this regulation. The arrangements for the ready availability of water supply shall be to the satisfaction of the administration, and be readily available, either by remote starting of one of the main fire pumps with remote starting from the navigating bridge and fire control station, if any, or permanent pressurization of the fire main system by one of the main fire pumps.

− **Number and position of fire hydrants**

The number and position of hydrants shall be such that at least two jets of water not emanating from the same hydrant, one of which shall be from a single length of hose, may reach any part of the ship normally accessible to the passengers or crew while the ship is being navigated and any part of any cargo space when empty, any ro-ro space or any vehicle space in which latter case the two jets shall reach any part of the space, each from a single length of hose. Furthermore, such hydrants shall be positioned near the accesses to the protected spaces.

- **Fire pumps and capacity of pumps**

Each ship shall have at least 2 fire pumps, generating pressure at the hydrants of at least 0.27 N/ mm^2, not exceeding that at which the effective control of a fire hose can be demonstrated.

Each of the required fire pumps (other than any emergency pump required for cargo ships) shall have a capacity not less than 80% of the total required capacity divided by the minimum number of required fire pumps but in any case, not less than 25 m^3 /h and each such pump shall in any event be capable of delivering at least the two required jets of water.

These fire pumps shall be capable of supplying the fire main system under the required conditions. Where more pumps than the minimum of required pumps are installed, such additional pumps shall have a capacity of at least 25 m^3 /h and shall be capable of delivering at least the two jets of water required.

- **Fire hoses and nozzles**

Fire hoses shall be sufficient in length to project a jet of water to any of the spaces in which they may be required to be used. Each hose shall be provided with a nozzle and the necessary couplings. Hoses specified in this chapter as "fire hoses" shall, together with any necessary fittings and tools, be kept ready for use in conspicuous positions near the water service hydrants or connections.

Fire hoses shall have a length of at least 10 m, but not more than: 15 m in machinery spaces, 20 m in other spaces and open decks and 25 m for open decks on ships with a maximum breadth in excess of 30 m.

The number of fire hoses to be provided shall be one for each 30 m length of the ship and one spare but in no case less than five in all. Ships carrying dangerous goods in accordance with regulation 19 shall be provided with three hoses and nozzles, in addition to those required above.

Nozzles shall be of an approved dual-purpose type (i.e., spray/jet type) incorporating a shutoff.

4.5.1.2 Systems below deck

- **Fixed fire-extinguishing arrangements in cargo spaces**

Cargo spaces on cargo ships of 2,000 gross tonnage and upwards shall be protected by a fixed carbon dioxide or inert gas fire-extinguishing system complying with the provisions of the Fire Safety Systems Code, or by a fire-extinguishing system which gives equivalent protection.

Fixed gas fire-extinguishing systems for dangerous goods: A ship engaged in the carriage of dangerous goods in any cargo spaces shall be provided with a fixed carbon dioxide or inert gas fire-extinguishing system complying with the provisions of the Fire Safety Systems Code or with a fire-extinguishing system which, in the opinion of the Administration, gives equivalent protection for the cargoes carried.

- **Under deck cooling**

SOLAS chapter II-2, regulations 19, sub-paragraph 3 special requirements for ships carrying dangerous goods:

Means shall be provided for effectively cooling the designated underdeck cargo space by at least ***5 liters/min per square meter*** of the horizontal area of cargo spaces, either by a fixed arrangement of spraying nozzles or flooding the cargo space with water.

Hoses may be used for this purpose in small cargo spaces and in small areas of larger cargo spaces at the discretion of the Administration.

They will require additional drainage and pumping capacities, and arrangements shall be such as to prevent the build-up of free surfaces. The drainage system shall be sized to remove no less than 125% of the combined capacity of both the water spraying system pumps and the required number of fire hose nozzles. The drainage system valves shall be operable from outside the protected space at a position in the vicinity of the extinguishing system controls. Bilge wells shall be of sufficient holding capacity and shall be arranged at the side shell of the ship at a distance from each other of not more than 40 m in each watertight compartment. If this is not possible, the adverse effect upon stability of the added weight and free surface of water shall be considered to the extent deemed necessary by the Administration in its approval of the stability information.

4.5.1.3 Systems on deck

Firefighting for ships constructed on or after 1 January 2016 designed to carry containers on or above the weather deck, shall carry, in addition to the equipment and arrangements required, carry, at least one water mist lance.

The water mist lance shall consist of a tube with a piercing nozzle which is capable of penetrating a container wall and producing water mist inside a confined space (container, etc.) when connected to the fire main.

Ships designed to carry five or more tiers of containers on or above the weather deck shall carry, in addition to the requirements carry, mobile water monitors as follows:

- Ships with breadth less than 30 m: at least two mobile water monitors.
- Ships with breadth of 30 m or more: at least four mobile water monitors.

The mobile water monitors, all necessary hoses, fittings and required fixing hardware shall be kept ready for use in a location outside the cargo space area not likely to be cut-off in the event of a fire in the cargo spaces.

In addition to the required number of hydrants, a sufficient number of fire hydrants shall be provided such that:

- All provided mobile water monitors can be operated simultaneously for creating effective water barriers forward and aft of each container bay.
- Two jets of water as required can be supplied at the pressure required by paragraph 2.1.6; and each of the required mobile water monitors can be supplied by separate hydrants at the pressure necessary to reach the top tier of containers on deck.

The mobile water monitors may be supplied by the fire main, provided the capacity of fire pumps and fire main diameter are adequate to simultaneously operate the mobile water monitors and two jets of water from fire hoses at the required pressure values. If carrying dangerous goods, the capacity of fire pumps and fire main diameter shall also comply with the required needs with the regulation, as far as applicable to on-deck cargo areas.

4.5.2 Risk Control Measures (RCMs)

RCM selection for firefighting followed the same process. A list of potential RCMs was compiled from the HAZID, technical expert group, and core team research, and is presented in Table 54.

Table 54: Potential RCM from the HAZID workshop.

RCM No	RCM Description	OD or BD
1	Adding an additional sprinkler/ drencher system (or foam) would eliminate the need for crew to go in the hold. Would potentially reach more containers as well.	BD
2	PPE with gas detector to aid in determining ability to prolong FF effort.	
3	DYI clamps	OD
4	Increase awareness of crew about the importance of closing the vents	BD
5	Automated or remote closing of the vents	BD
6	Enhanced training regime in using the CO_2 system.	BD
7	Enhanced layout of CO_2 interface.	BD
8	More CO_2 onboard. Enough to provide more shots or fill the hold several times. Sustain suppression for longer.	BD
9	Recommend above 10 bar gauge just before the nozzle to have as much liquid CO_2 as possible in the pipe (vs. gaseous CO_2) in order to make the discharge efficient	BD
10	Crew and shore need a better understanding of the capabilities of the CO_2 system. Awareness c of crew and shore support. Additional FF layer to support CO_2, and/or more CO_2.	BD
11	FF tool which can reach the top of the stack.	OD
12	Lighter equipment to aid crew in carrying up ladders.	OD
13	Permanent fixed installation to avoid carrying gear.	OD
14	Equipment better suited to be used in highly constricted area.	OD/BD
15	Ability to fix nozzles in place where monitors are not available.	OD/BD
16	2D water spray between containers.	OD
17	Smart drones.	OD

18	Riser pipes to avoid carrying equipment on ladders.	OD
19	Permanent high-pressure installations (potentially with remote activation).	OD
20	Quick flooding system.	BD
21	Possibility to spray foam in hold.	BD
22	Smaller holds to allow for quick flooding.	BD
23	More/better water monitors	OD
24	improved methods for container breaching and flooding (performance requirement)	OD
25	Improved regulations for CO_2 installation	OD
26	Water mist turbines for on-deck	OD

4.5.3 Risk control options (RCOs)

From Table 54 a qualitative assessment with the core team and EMSA was performed. The aim of this was to filter and combine RCMs from Table 54 and produce a smaller selection of RCOs deemed most viable for further assessment. The results of this preliminary assessment are presented in Table 55.

Table 55: List of RCOs for Firefighting.

RCO-F	RCO Title	OD or BD	Combination of RCMs
F1	Increasing effectiveness of current CO_2 system	BD	4,5,6,7,8,9,10,25
F2	Improved manual firefighting tools, for individual container breaching and firefighting	BD/OD	12,13,14,24
F3	Manual firefighting tools that increase reach	OD	11,12,13,14
F4	Methods for unmanned firefighting	BD/OD	3,13,15,23
F5	Water mist turbine	OD	

4.5.3.1 RCO F1 – Increasing effectiveness of current CO_2 system

This RCO addresses the fixed fire protection systems on container ships for below-deck cargo holds. Specifically, the carbon dioxide total flooding (CO_2-TF) system is supplied by either a low-pressure carbon dioxide ($LPCO_2$) tank or a series of banks of high-pressure carbon dioxide ($HPCO_2$) cylinders. Per SOLAS Chapter II-2 regulation 10, the cargo holds of all container ships of 2000 gross tonnage and more, shall be protected by a fixed carbon dioxide or inert gas fire-extinguishing system, complying with the provisions of the Fire Safety System (FSS) Code, or by a fire-extinguishing system which gives equivalent protection. Basic system requirements for CO_2-TF systems are further detailed in chapter 5 of the FSS Code. The minimum required storage quantity of CO_2 shall be enough to provide 30% gross volume of the largest cargo hold. It is also stated that two thirds of the CO_2 shall be discharged into the hazard at most within 10 minutes. As for installation testing, there are only two required tests, (1) test the free flow of air in the piping network and nozzles and (2) a functional test of the fire alarm equipment. Additional specific installation requirements are detailed within the FSS Code for CO_2-TF systems and fire alarm systems which can be referenced for a supplementary study.

Through the analysis performed in this study, the current CO_2-TF systems have a number of limitations:

1. *Compartment conditions*: A CO_2-TF system operates assuming the protected compartment is well sealed. Compartment leakage, if it is expected, can be compensated for by (1) improving the boundary conditions of the cargo hold and/or (2) increasing the quantity of discharged CO_2.
2. *Fire Type*: Another limitation of this fire protection system is the range of fires it is effective against. Inertization of the atmosphere is effective for many fires but this method of firefighting is ineffective with oxidizer fuels (nitric acid, nitrogen tetroxide, etc.), low ignition temperature fuels (refined hydrocarbons), deep-set smoldering fires (coal, biofuels, etc.), and lithium-ion batteries. For these types of fire hazards the ideal method of firefighting is to absorb as much heat energy from the combusting fuels. Unfortunately, the CO_2-TF system provides a negligible cooling effect.
3. *Quantity of* CO_2: The current requirements found in the FSS Code only demand enough CO_2 storage to provide minimum fire protection criteria for the largest cargo hold or the engine room. Once the system is used, it cannot be used again until refilled when docked. This limitation prevents extended protection capabilities while at sea which can be potentially catastrophic.
4. *Commissioning Test*: There is a lack of test requirements to commission an CO_2-TF system onboard a container ship. The only two tests mentioned in the FSS Code are (1) test the free flow of air in the piping network and nozzles and (2) a functional test of the fire alarm equipment. These two commissioning tests do not provide assurances that the required minimum concentration of 30% is reached for the respective cargo hold nor the minimum discharge time of 10 mins for two thirds of the shot. A widespread practice for commissioning land-based CO_2-TF installations is to ensure these requirements by doing a discharge test while measuring for these requirements. Without a discharge test there remains uncertainty of the performance of the installation. In confidential communication with ship owners, this uncertainty is shared by many.

To improve the effectiveness of the CO_2-TF system, the above limitations need to be addressed. Some suggestions are given below:

- *Compartment conditions*: Inspection of the cargo hold should be completed to ensure a well-sealed compartment. Should any permanent leakage be found, it should be accounted for by (1) improving the boundary conditions of the cargo hold and/or (2) increasing the quantity of discharged CO_2.
- *Fire Type*: Little can be done to improve the effectiveness of a carbon dioxide total flooding system against the mentioned fuel types: oxidizers, low ignition temperature fuels, smoldering fires, and lithium-ion batteries. Instead, it is recommended that these hazards should be labeled and stored on-deck for more effective firefighting methods.
- *Quantity of* CO_2: It is recommended to increase the minimum quantity of stored CO_2 to accommodate two discharges into the largest cargo hold or the engine room, whichever is largest. This would provide assurances that if the first discharge was not effective a second discharge is available as back up. Also, this would provide extended protection for the other cargo holds after discharging into the first cargo hold of origin.
- *Commissioning Test*: During the commissioning of an $LPCO_2$ system installed for the protection of a cargo hold, a discharge test should be completed on the largest hold. The minimum CO_2 concentration and flow rates will need to be measured to conclude effective engineering and design. This additional test during commissioning removes uncertainty on providing the minimum protection criteria per SOLAS II-2 and the FSS Code.

For the purposes of further analysis, the following sections concentrate on increasing the amount of CO_2 on board as a means of increasing the effectiveness.

- **Availability in Current Market**

The CO_2 used with this system can be provided by either a bank of $HPCO_2$ cylinders or a large $LPCO_2$ tank. The amount of minimum CO_2 required can be more than 12 metric tons. The $HPCO_2$ cylinders generally come charged with 45 kg of CO_2, meaning storage and operating space for +250 individual cylinders. Alternatively, a single $LPCO_2$ tank can be used with similar trim components (pilot cabinets, isolation valves, bleeder valves, etc.) to provide the same level of protection with the benefit of easier inspection and maintenance. The simplest method of increasing the amount of CO_2 is to add more tanks, to increase the number of "shots" the system can provide to the cargo holds.

Another method is to look at systems that can produce CO_2 (or other inert gases such as N2 may also be an option) continuously. These rather than having a bank/tank system, simply produce CO_2 continuously, thus in theory can keep a cargo hold inerted (i.e., low in oxygen), indefinitely (assuming power and their system requirements are provided for e.g., fuel).

- **Working Principle**

Adding more CO_2 works in the same manner as intended by the original system, however it aims to extend the time in which the cargo hold is in a reduced oxygen state, which makes the system more effective at extinguishing fires by simply increasing this time period, allowing for further cooling of fire area, and may also allow greater penetration into the containers of fire origin.

- **Limitations**

Adding additional tanks to increase the amount of CO_2 on board will take more room on the ship, thus less cargo may be carried for the same size ship. The cargo capacity loss has to be accounted for over the ship's lifespan. Additionally, more tanks will mean further maintenance requirements and other associated costs. Systems that can provide continuous CO_2 will require a significant re-design of how the CO_2 is injected into the cargo holds, thus is likely only relevant for new builds. Further, some of the current systems on the market that can provide continuous CO_2 are designed on fuel driven turbines, thus additional fuel will be required for these systems and regular system performance checks may need to be carried out (due to higher complexity in the overall system).

- **Risk Reduction Potential**

Data provided by EMSA, and other sources, have been filtered to determine certain failure rates. Specific to this RCO, a failure is qualified as the inability to keep a fire originating in a below deck cargo hold within that specific hold. The mode of failure is one of three modes: slow fire, fast fire, or explosion scenario. Additionally, consideration was given to the size of the container ship: generic ship 3, 2 and 1. The determined respective failure rates are 58.6%, 60.7%, and 71.3% for slow fires, 79.2%, 80.2%, and 88.8% for fast fires, and 80.0%, 80.0%, and 81.0% for explosions.

During internal discussions it was determined that ship size may not have a significant impact on the risk reduction potential for this RCO. Instead, the failure mode (slow, fast, explosion) has a direct impact on risk reduction potential. For all slow fires a max risk reduction potential of 20% was determined assuming that all limitations are addressed. For all fast fires the max risk reduction potential was a lower value of 5% due to the likelihood of decision delay and fire growth rate. Finally, the max potential risk reduction potential for an explosion is the lowest at 2.5% due to potential damage to the fire protection system and surrounding infrastructure. The likely risk reduction potential of the mentioned max values is halved based on expert judgement. This halving is to account for uncertainty.

4.5.3.2 RCO F2 – Improved manual firefighting tools for individual container breaching and firefighting

According to the requirements in SOLAS regulation II-2/10.7.3., firefighting for ships constructed on or after 1 January 2016 designed to carry containers on or above the weather deck, shall carry, in addition to the equipment and arrangements required, at least one water mist lance. The water mist lance shall consist of a tube with a piercing nozzle which can penetrate a container wall and producing water mist inside a confined space (container, etc.) when connected to the fire main.

As the SOLAS requirements are a bit vague on the performance requirements for the water mist lance and tube with a piercing nozzle, various systems have been taking into use.

Manual firefighting tools currently used on board rely on hard objects to impact and penetrate the container and then extinguish the fire. Commonly it takes at least two people or more to use the various systems, often using a hammer to force the water mist lance into a container or impact tools to breach the container surface, and often in combination.

This approach adds risk of misuse, and brings the operators in harm's way, particularly when firefighting at a height or entering a cargo hold. Furthermore, this approach is only effective when the containers are within reach, i.e., the systems will not be able to reach higher than the operator can reach, in case of container fires on deck. Alternatively, any firefighting crew would have to arrange for ladders or other ways to access higher positioned containers.

- **Availability in current market**

Improving penetration efficiency can be considered from two aspects, one is to consider the application of power tools such as drills and hole cutters and a combination of water mist lance, the second is to consider the use of cold cutting tools that use the water pressure to directly penetrate the container and extinguish the fire.

There are many types of drills and hole cutters available in the market, and the appropriate power tool can be selected according to the diameter of the water mist lance.
Cold cutting tools can also be divided into two types. One of them is hand-held high pressure water jet lance, which can be held by a crew to penetrate the container and produce water mist to extinguish the fire. The other can be directly hung on ISO standard containers, combined penetration, and fire extinguishing device, able to penetrate standard steel containers and spray water/foam/CO_2 into the container in case of fire.

- **Working principle**

After determining which container is on fire, manual fire extinguishing tools can be used to effectively extinguish the container. The power tool for manual firefighting consists of a drill, hole cutter and water mist lance. After cutting a hole in the door of the burning container, the water mist lance connected to a fire hose is inserted into the hole to start firefighting, as shown in Figure 107.

Figure 107: Power tool with water mist lance

The hand-held cold cutting tool is mainly made of stainless steel, with a high IP rating and a shockproof design that allows exposure to harsh environments shown in Figure 108. The tool is designed for integration with the existing water supply system on board and is equipped with a high-pressure pump that can be connected to a fire hose to provide sufficient pressure for the water jets. There is also the option to add a portable Additive Pump. The high-pressure water jet in combination with abrasive pierces quickly through all known construction materials including container walls. Its water jet cutting technology is also a highly effective fire suppression system. As the water jet penetrates the obstacle, the water jet transforms into water vapor. This process consumes a significant amount of energy derived from the heat of the fire. The environment around the fire is cooled down and oxygen is consumed, resulting in the fire being extinguished.

Figure 108: Hand-held cold cutting tool.

The hanging cold cutting tool is specifically designed for container firefighting able to penetrate standard steel containers and spray water/foam/CO_2 into the container in case of fire. It only uses water pressure from the fire main system to operate. This tool consists of 3 main parts. The drilling unit is a firefighting device capable of extinguishing fires inside containers. The unit can penetrate container structures and change function to water spraying mode inside the enclosed space. The drilling unit of this device consists of a hydrodynamic turbine and a hole saw and it is mounted on the aluminum mount specified for container firefighting. The lock unit is an add-on device, which makes the drilling unit able to be mounted on reachable containers without using the Telescopic Lift system. The telescopic lift system enables the tool to reach stacked containers up to a certain height, which will be discussed in 5.4.3.3. RCO F3 – Manual firefighting tools that increase reach.

When the device is mounted on the container's locking bar, crew members can walk out of a potentially hazardous area. When water is supplied, the penetration mode is automatically activated. Water pressure flows into the hydrodynamic turbine, which rotates and initiates the automatic drilling process. A hole saw at the end of the tool will penetrate the container. Once the hole saw enters the container, the tool will automatically change mode, shutting off the water supply to the turbine and instead directing the water through the hole saw/nozzle and spraying it inside the burning container as shown in Figure 109.

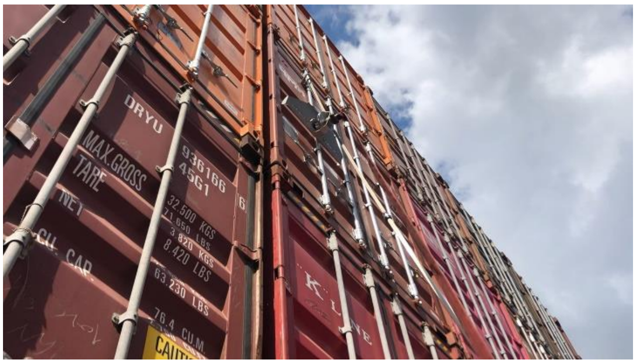

Figure 109: The hanging cold cutting tool.

- **Limitations**

For power tools and water mist lance, it may produce sparks or cause the local temperature to increase when drilling a hole in the container wall, so using this method to penetrate a container without determining what kind of cargo is burning in the container may adversely affect firefighting. Therefore, this tool should only be used for the identified container fires.

For cold cutting tools, there must be sufficient water pressure for maximum efficiency and if the water pressure is not enough, it may take longer to drill or may not penetrate the container. For hanging cold cutting tools, it can only be used on the ISO standard containers with free hanging locking bars and indentations, for some older types of containers with hidden locking bars or other locking systems, this tool is not suitable. Furthermore, this tool cannot be mounted on twenty-foot containers when the doors are facing each other, that is when two twenty-foot containers are loaded on deck, and their doors are facing each other.

- **Risk reduction potential**

From the data provided by EMSA and other sources, the failure rates of Detection & Local first response on COO of the three generic ship types (twin island, single island, feeder), 60.8%, 48.2%, and 46.2% for slow fire, 84.7%, 79.3%, and 78.6% for fast fire, the failure rate for the explosion leading to fire is 100% for all ship types. In the fault tree, taking failure of detection & local first response on COO as the top event, for RCO F2, under the best-case scenario considering that the failure rate of manual firefighting for individual container breaching and firefighting is 0. The maximum risk reduction potential rates of 3 ship types are, for slow fire 12,5%, 23,4%, 24,3% respectively, for fast fire 5.8%, 9.2%, 9.4% respectively, for explosion leading to fire, this RCO has no effect. Considering the most likely risk reduction potential, halving the maximum give values of 6.2%, 11.7%, and 12.15% for the slow fire and 2.9%, 4.6%, and 4.7% for the fast fire.

4.5.3.3 RCO F3 – Manual firefighting tools that increase reach

A limitation of the current manual firefighting tools used on board is the restricted height they can access. The penetration hammer and water mist lance, for example, can only access the first tier of containers above the lashing bridge. For higher tiers container firefighting issues, the currently on-board tools are not efficient, so it is necessary to consider applying other tools to increase reach to improve the efficiency of manual firefighting.

- **Availability in current market**

The hanging tool mentioned in 4.5.3.2. RCO F2 – Improved manual firefighting tools for individual container breaching and firefighting, when attached to a telescopic pole system, it can extinguish fires at height directly in burning containers. This combination tool can be purchased directly from the market and can effectively cover firefighting in high containers.

- **Working principle**

The hanging manual firefighting tool that can penetrate the container at heights consists of 3 different parts, the first two parts mentioned in 4.5.3.2. RCO F2 are about penetrating and extinguishing the burning container. The third part, telescopic lift system, as shown in Figure 110, enables the equipment to reach stacked containers up to a height of 12.5m (equivalent to the top of 5 tiers of standard ISO containers). It is a telescopic pole with a winch at the bottom and a hook with a block wheel at the top. An internal wire passes through the block wheel and returns to the bottom with a carabiner that connects to the equipment. Once the tool is connected, the winch is used to hoist the equipment to the top of the Telescopic Lift. This equipment enables firefighting without contacting the affected container, effectively improving the safety of personnel.

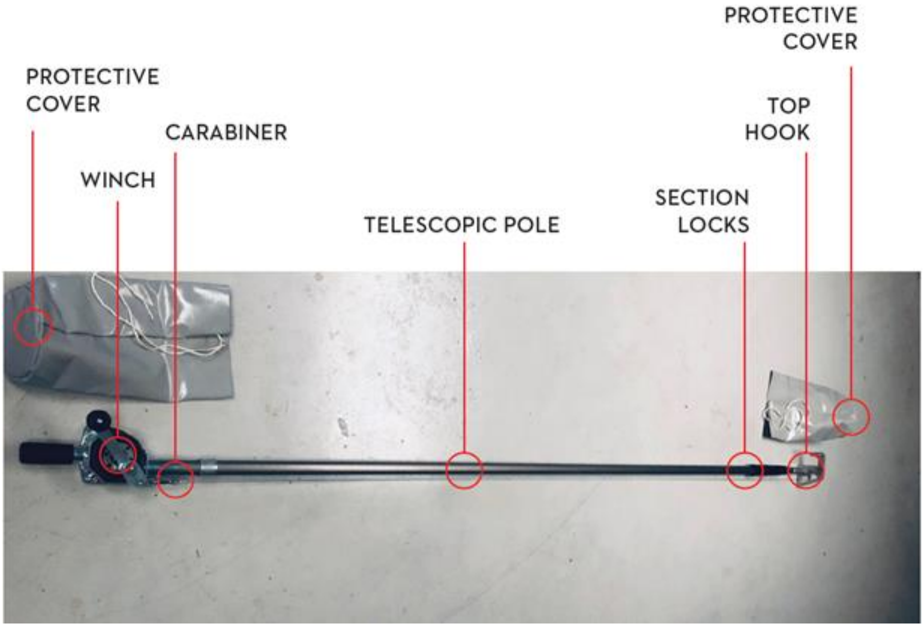

Figure 110: Telescopic lift system of hanging cold cutting tool.

- **Limitations**

The hanging height reaching firefighting equipment has requirement for the pressure of the supplied water, the normal working pressure is about 4 bars. If the water pressure is not enough, it may take longer to drill or may not penetrate the container. In addition, after every use with saltwater, flush the unit thoroughly with fresh water to slow down the corrosion of seawater to the equipment.

- **Risk reduction potential**

As with RCO F2, in the best-case scenario, the probability of COO out of reach is considered to be 0. Bringing it into the fault tree and halving the obtained maximum values, the most likely risk reduction potential rates for RCO F3 are obtained as 20.9%, 18.4%, and 19.3% for slow fire and 8.3%, 6.3%, and 6.5% for fast fire.

4.5.3.4 RCO F4 – Methods for unmanned fire fighting

According to the requirements in SOLAS regulation II-2/10.7.3. Ships constructed on or after 1 January 2016 designed to carry five or more tiers of containers on or above the weather deck shall carry mobile water monitors. Ships with breadth less than 30 m, at least two mobile water monitors; Ships with breadth of 30 m or more, at least four mobile water monitors. In addition to this required equipment, it is proposed to include a fixation system to allow the unmanned operation of the mobile water monitors.
In addition to above specific requirements, the mobile water monitors, all necessary hoses, fittings and required fixing hardware shall be kept ready for use in a location outside the cargo space area not likely to be cut-off in the event of a fire in the cargo spaces.

As specified in SOLAS regulation II/2/10.7.3.2.2. A sufficient number of fire hydrants shall be provided such that:

1. All provided mobile water monitors can be operated simultaneously for creating effective water barriers forward and aft of each container bay;
2. The two jets of water required by paragraph 2.1.5.1 can be supplied at the pressure required by paragraph 2.1.6; and
3. Each of the required mobile water monitors can be supplied by separate hydrants at the pressure necessary to reach the top tier of containers on deck.

SOLAS regulation II-2/10.7.3.2.3 specifies that the mobile water monitors may be supplied by the fire main, provided the capacity of fire pumps and fire main diameter are adequate to simultaneously operate the mobile water monitors and two jets of water from fire hoses at the required pressure values.
The operational performance of each mobile water monitor shall be tested during the initial survey on board the ship to the satisfaction of the Administration.
The test shall verify that:

- 1. The mobile water monitor can be securely fixed to the ship structure ensuring safe and effective operation; and
- 2. The mobile water monitor jet reaches the top tier of containers with all required monitors and water jets from fire hoses operated simultaneously.

Need to be equipped with different numbers and functions of water monitors on the container ship according to SOLAS requirements.

- **Availability in current market**

The mobile water monitor can be selected according to different parameters. The body material, which is related to the total weight, the nozzle type which can be jet, spray, or dual purpose, as well as the working pressure, jet flow rate, jet length, rotation range, etc. There are various models of equipment available on the market. In addition, the water monitors or nozzles can be customized and placed according to the structure and configuration of the ship, which have the high flow rate, long jet range and can cover the whole ship including the place where the crew hard to reach. Furthermore, DIY modification for fire hoses or water monitors can be designed on the lashing bridges in Figure 111, so that when an accident occurs, the fire hoses and monitors can be temporarily installed on the modifications to extinguish the fire.

Figure 111: DIY modification for fire hoses.

- **Working principle**

For the mobile water monitor, due to the need to facilitate the crew to carry to the lashing bridge, it is recommended to choose the overall weight of the lighter equipment, such as aluminum alloy. Because of the structure of the container ship and the relative position between container stack and lashing bridge, the mobile water monitor with fixing device and have a nozzle rotation range at least 0˚- 90˚ can be selected as shown in Figure 112 which can be temporarily fixed on the railings or ladders to start firefighting when the container is on fire. The monitor is connected to the fire mains with a standard fire hose, this starts operating as soon as the hydrant valve is opened. The angle of the water jet is easily adjusted by a turning wheel, and the direction is set by turning the monitor. The monitor stays stable by itself and can operate if it is needed.

Figure 112: Mobile water monitor with fixing device.

The monitors can be manually operated. They can be very flexible and have fully customized features. The nozzle can be brought to x, y, z position by command, then, once the nozzle is in position, the valve can be opened to start the water flow, the nozzle can also switch between spray or jet mode.

Figure 113: Remote-control water monitor.

- **Limitations**

The required water pressure and the quantity of extinguishing water must be provided. The main problem with mobile monitors is that with high container stacks, there can be a very steep angle between the possible position of the monitor and the top tiers. This can lead to difficulties in applying the extinguishing agent directly to the front of the container or indirectly between the containers.

The corrosion of seawater and the slat crystallization can affect the monitors, to minimize the influence of seawater and extend the life of the equipment, it is better to flush with fresh water after each use.

For those monitors mounted on the top of the superstructure, the water jet they shoot out at certain angles will be blocked by the container stacks if the ship is fully loaded, so in this case they can only partially cover the container.

- **Risk reduction potential**

Considering the best-case scenario, the RCO can reduce the probability of "container boundary cooling not effective" node and "human element" node in the fault tree to 50% of the original values, assuming the crew would be less exhausted when performing the firefighting activities. However, the most likely risk reduction potential rates for RCO F4 are obtained as 3.5%, 6.7%, and 7% for slow fire and 1.7%, 2.7%, 2.8% for fast fire. The risk reduction potential rates for explosion leading to fire of this RCO considered the same as fast fire.

4.5.3.5 RCO F5 – Water mist turbine

This RCO addresses the lack of a fixed on-deck firefighting device to protect the surrounding container stacks. Currently there is no requirement for such a device within SOLAS II-2 Regulation 10 or the FSS code. A fire protection device that can offer additional fire protection to on-deck container stacks is a water mist turbine like the one shown in Figure 114. A water mist turbine is a remotely controlled water turret that can project a range of spray patterns ranging from a wide water mist cloud to a narrow water stream. Currently, the primary industries that water mist turbines are used in are the power sector (high voltage transformers), waste management (whole waste processing facilities), and chemical storage plants (large storage tanks). When implemented with an intelligent fire detector network the water mist turbine could automatically position and project water directly to the source of fire.

Figure 114: Water mist turbine

Figure 115: Water mist turbine performance test.

- **Availability in Current Market**

This is a newer firefighting apparatus and therefore there is a limited number of manufacturers. However, there are at least 3 manufacturers offering solutions within this concept field. To install this turbine aboard a container ship would require significant engineering adjustments by the manufacturer.

- **Working Principle**

There are turbines which are sold as a turnkey product that only need to be connected to a water supply of 10 bar and wired to a 400v panel.

The proposed mounting location for the water mist turbine is on top of the superstructure(s) to provide remote firefighting capabilities. The recommended infrared detector, although great for land-based installations, is not a recommended detection option for on-deck detections. Therefore, the turbine water spray/stream will need to be manually directed towards the fire via a fixed control panel and/or a remote control. The fixed control panel should be installed on the bridge and portable remote controls should be available as a backup.

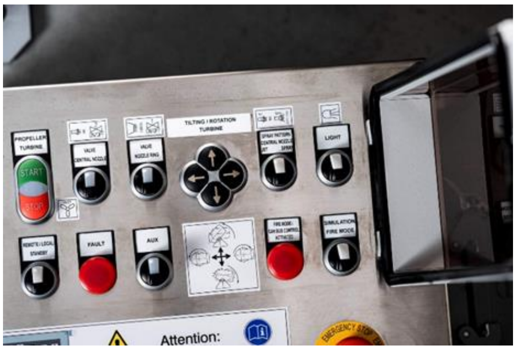

Figure 116: Fixed control panel.

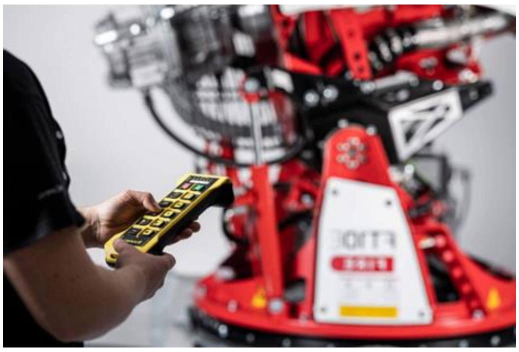

Figure 117:Portable remote control.

The likely order of operations would be (1) a fire is detected on deck, (2) fire is confirmed with visual observation, (3) an operator is assigned to attend the control panel (4) system start up procedure for the water mist turbine begins, (5) turbine is manually adjusted towards the fire, (6) ship orientation may need to be adjusted depending on wind direction, and (7) the turbine water stream pattern and orientation are adjusted to apply water directly onto the fire hazard. Depending on the conditions of the fire scenario an automatic spray pattern can be initiated to free up the operator for other emergency tasks. Adjustments can be made from the control panel and remote control to better direct water application during firefighting operations.

The gradient spray patterns from a narrow nozzle pattern to a large water mist cloud offer a wider range of effective firefighting methods. For fire's originating further from the superstructure(s) a narrow nozzle provides reach and a focused application of a cooling water stream. Alternatively, fire closer to the superstructure(s) would best be attacked with a large water mist cloud. A natural gradient exists between these distances and spray patterns.

- **Limitations**

This is a newer firefighting appliance when it comes to container ships. Therefore, there are several limitations that are anticipated:

1. *Blind angles/shadow effects*: The angle of attack from the top of the superstructure(s) means that fires originating from the far side of a container stack of origin or lower containers on the stack cannot have water applied directly to the affected container. Instead, this system will provide secondary cooling to surrounding containers.
2. *Maintenance*: This is an advanced piece of technology that needs to be maintained regularly to ensure that it remains operable. Without a regular maintenance schedule, the turbine may fall into disrepair and reduce performance.
3. *Pressure requirements*: The recommended pressure rating for the turbine is 10 bar. This minimum rating may be difficult to achieve since the turbine is on top of the superstructure(s). Without the minimum pressure and flow rates the range of protection will be significantly decreased.
4. *Range of water spray/stream*: The max distance the turbine can reach with a narrow water stream is roughly 150m. This limits the number of on-deck container stacks that can be protected. The single island container ship (generic ship 2) have the worst coverage compared to the feeder and twin styles.
5. *Sea water corrosion*: Sea water can be used during firefighting operations. However, if left alone after firefighting operations salt crystals will form and corrode the internal piping and fittings. This will compromise the performance for the next time it is used.
6. *New Apparatus Delay*: This is a new firefighting apparatus, and it will require moderate training to learn how to use and maintain. Without regular training, an inexperienced operator may delay water application on a fire or be unable to properly operate the turbine.
7. *Visibility*: From the bridge, there is limited visibility of the whole container ship, which can hinder accurate targeting of the system.
8. *Sea effects*: In rough waters the container ship may transversely rock back and forth. This movement can cause the point of contact from the water stream to shift laterally and cause indirect cooling of the fire.
9. *Weather deterioration*: Currently, there is no weatherproof option for this firefighting appliance. Therefore, without additional protection from the elements, it is estimated that an unprotected turbine will be significantly compromised after only a year of use.
10. *Wind effects*: When circumstances require long distance firefighting the wind can have significant effects on the water spray/stream. Depending on the direction of the wind it can improve or diminish the distance the length of throw or shift the contact point to the left or right.

- **Risk Reduction Potential**

To improve the effectiveness of the water mist turbine the limitations have been identified and investigated. Now they need to be improved and implemented:

1. *Blind angles/shadow effects*: To improve the angle of attack and allow direct application to the container of origin the turbine can be placed on an articulating arm. This arm may provide elevation or extension over the container stacks. Note that this is an expensive solution to this limitation.
2. *Maintenance*: A maintenance schedule shall be generated, likely by the manufacturer, and enforced by the respective ship command. This will protect the turbine from abuse and general weathering.

3. *Pressure requirements*: If the current minimum pressure and flow rate is too low a secondary booster pump may need to be added. This booster will need to be designed to maintain the minimum pressure and flow requirements.
4. *Range of water spray/stream*: To extend the range, the water pressure and flow rate can be increased. This increase in flow characteristics is dependent on the existing pump and piping configuration. Engineering and design may be required to update piping and have a booster pump with adjustable flow characteristics. It should be noted that for the EmiControls and Minimax turbine, the max rated operating pressure is 16 bar.
5. *Sea water corrosion:* To reduce the risk of internal corrosion, the system should be flushed with fresh water after each use. This will extend the operating life of the turbine. Turbine manufacturers are actively working on sea water rated turbines, but they are not currently available on the market.
6. *New apparatus delay*: After installation, a training seminar should be held to educate operators on how to operate and maintain the turbine. In-person training is offered by the respective manufacturers.
7. *Visibility*: The existing visibility cannot be improved from the bridge. Instead, an operator can assist from on-deck using a wireless remote control. A portable radio should be taken as well, as a redundancy, to communicate with the operator on the bridge to adjust the turbine accordingly.
8. *Sea effects*: To counteract the effects of transverse rocking, hydraulic stabilizer can be used to stabilize the platform the turbine is mounted to. Note that this is an expensive solution.
9. *Weather deterioration*: Currently there is no weatherproof turbine offered by the manufacturers. They are, however, working on a stainless-steel version which would provide protection from the elements. For immediate purposes, a retractable weatherproof structure or tarp can be placed around the turbine during disuse only to be removed when needed.
10. *Wind effects*: Wind effects are beyond the control of our human domain. Instead, the ship orientation can be adjusted to provide a relative tailwind blowing from the turbine towards the respective fire. This adjustment of the ship's orientation can assist with projecting the water towards the respective fire.

If all the limitations are addressed a best-case scenario will be achieved. Data provided by EMSA, and other sources, have been filtered to determine certain failure rates. Specific to this RCO, a failure is qualified as the inability to keep a fire originating in container stack to the original container stack of origin. The mode of failure is one of three modes: slow fire, fast fire, or explosion scenario. Additionally, consideration was given to the size of the container ship: feeder, single island, and twin island container ship (generic ship 3, 2 and 1). Their respective failure rates are 46.2%, 48.2%, and 60.8% for slow fires, 78.6%, 79.4%, and 84.7% for fast fires, and 100% for all explosion scenarios.

Implementing this RCO has a direct impact on the fault tree. Specifically, this RCO provides efficient boundary cooling for the container stack of origin. In turn the respective max risk reduction potential for slow fires on feeder, single island, and twin island container ships types (generic ship 3, 2 and 1) are 34.5%, 32.7%, and 39.9% respectively. As for fast fires and explosion scenarios, no difference was determined to impact the calculated max risk reduction potential. The respective max risk reduction potential for fast fires and explosions on feeder, single island, and twin island container ships type (generic ship 3, 2 and 1) are 13.2%, 12.7%, and 17.4% respectively. The likely risk reduction potential of the mentioned max values is quartered based on expert judgement. This significant reduction of risk reduction potential is to account for the significant range of uncertainty.

4.5.4 Effectiveness assessment

Table 56: Effectiveness assessment of firefighting RCOs.

F-RCO	RCO title	TRL	OD/BD	RCO- side effects/ limitations
F1	Increasing effectiveness of current CO_2 system	9	BD	Performance dependent on the cargo hold being well sealed and quantity of stored CO_2. A total flooding CO_2 system is not effective for smouldering fires, lithium-ion battery fires, and fuels with low-ignition temperatures or

				classified as an oxidizer. Without a discharge test during commissioning the performance cannot be ensured.
F2	Improved manual firefighting tools, for individual container breaching and firefighting	9	BD/OD	For power tools, the drilling process may generate heat or produce sparks. For cold cutting tools there must be sufficient water pressure and the hanging cutting tools can only be used on ISO standard containers.
F3	Manual firefighting tools that increase reach	9	OD	Occupational safety of personal when crew stands on the lifting equipment.
F4	Methods for unmanned firefighting	8	BD/OD	Minimum pressure and flow rates, mounting locations, steep angles, obstructions.
F5	Water mist turbine	7	OD	This RCO is a novel solution that has not been implemented aboard container ships. The determined limitations for this option are blind angles due to visibility and angle of attack, lack of training and maintenance, minimum pressure requirements, limited accurate range due to wind, weather, and sea effects, and sea water/weather corrosion.

4.6 Containment

4.6.1 Risk Control Measures (RCMs)

A list of potential RCMs was compiled from the HAZID, technical expert group, and core team research, and is presented in Table 57 below.

Table 57: Potential RCM from the HAZID workshop.

RCM No	RCM Description	OD or BD
1	Container to be designed with a soft/weak spot(s)	BD/ OD
2	Change of material for container flooring.	
3	Adding foam insulation to the container floor.	
4	Strengthening of container structure, - pillars in each corner.	
5	Passive protection on hatch covers to protect from fire spread towards the deck.	BD
6	Active protection underneath hatch covers to protect from fire spread towards the deck.	BD
7	Auto-seawater system.	

8	Floodable ballast tanks to create insulation between holds on demand.	BD
9	Stack splitters between containers to prevent structural collapse of stacks.	BD
10	water sprinklers to stop spread between stacks	OD
11	Fire rating of construction (superstructure...)	BD
12	Ventilation (superstructure)	OD
15	Flooding	BD

4.6.2 Risk control options (RCOs)

From Table 44, a qualitative assessment with the core team and EMSA was performed. The aim of this was to filter and combine RCMs from Table 44 and produce a smaller selection of RCOs deemed most viable for further assessment. The results of this preliminary assessment are presented in Table 58

Table 58: List of RCOs for Containment.

RCO-C	RCO Title	OD or BD	Combination of RCMs
C1	Active protection (e.g., sprinklers) underneath hatch covers to protect from fire spread towards the deck.	BD	
C2	Passive protection to protect from fire spread towards the deck.	BD	5,8,11
C3	On-deck container stack cooling/containment system (e.g., water sprinklers and water monitors)	OD	
C4	Flooding cargo hold to a limited degree (up to a limited height)	BD	

4.6.2.1 RCO C1 – Active protection underneath hatch covers to protect from fire spread towards the deck.

The water spray system is required in case of carriage of dangerous goods and is then assumed to be designed in conformity to SOLAS II-2/19.3.1.3:

3.1.3 Means shall be provided for effectively cooling the designated underdeck cargo space by at least 5 l/min per square meter of the horizontal area of cargo spaces, either by a fixed arrangement of spraying nozzles or flooding the cargo space with water. Hoses may be used for this purpose in small cargo spaces and in small areas of larger cargo spaces at the discretion of the Administration. However, the drainage and pumping arrangements shall be such as to prevent the build-up of free surfaces. The drainage system shall be sized to remove no less than 125% of the combined capacity of both the water spraying system pumps and the required number of fire hose nozzles. The drainage system valves shall be operable from outside the protected space at a position in the vicinity of the *extinguishing system controls. Bilge wells shall be of sufficient holding capacity and shall be arranged at the side shell of the ship at a distance from each other of not more than 40 m in each watertight compartment. If this is not possible, the adverse effect upon stability of the added weight and free surface of water shall be taken into account to the extent deemed necessary by the Administration in its approval of the stability information.*

To comply with BV's additional class notation ECFP-2, some other criteria need to be fulfilled (for instance a more important flow of 20L/min per square meter).

- **Availability in current market**

Due to the fact that this system is already required in some cases (e.g. when dangerous goods are carried), this technology is currently available in the market.

- **Working principle**

The system installed on board a ship must comply with rules defined by the corresponding class society. For instance, in order for the ship to be certified ECFP-2 by BV, the water spray below hatch cover must fulfill some criteria:

- The system must be able to deliver at least 20L/min per square meter.
- The capacity of the system water supply is to be sufficient to feed the water-spray in any one cargo hold.
- The drainage system is to be sized to remove no less than 125% of the combined capacity of both the water-spraying system pumps and the required number of fire hose nozzles.
- Etc.[62]

It should be noted that these are BV requirements and does not necessarily exactly match the rules of the other classification societies.

- **Limitations**

The ship must be equipped to be able to satisfy the different requirements of SOLAS in terms of water flow capacity, both for the spraying and the draining of the water. Moreover, the system only works for in-hold fires, and, due to the location of the water release (below the hatch cover) is way more efficient to avoid above propagation when the fire is in the lower tiers of the hold.

The drenchers are fixed under mobile hatches: it implies that they can be disconnected/re-connected, creating a risk of quicker degradation for the connection components.

- **Risk reduction potential**

A fire in the hold uncontrolled by water spray or any other means of firefighting shall propagate on the deck. Based on BV data, this propagation can be avoided with a water spray if it is activated early, or in case of late activation, if the fire is not located in the first seven containers below the deck. Hence, the following event tree was used:

[62] All the requirements can be found in "*NR467 – Rules for Steel Ships Pt F, Ch 11, Sec 30., 3.6. Water-spray system below hatch cover*"

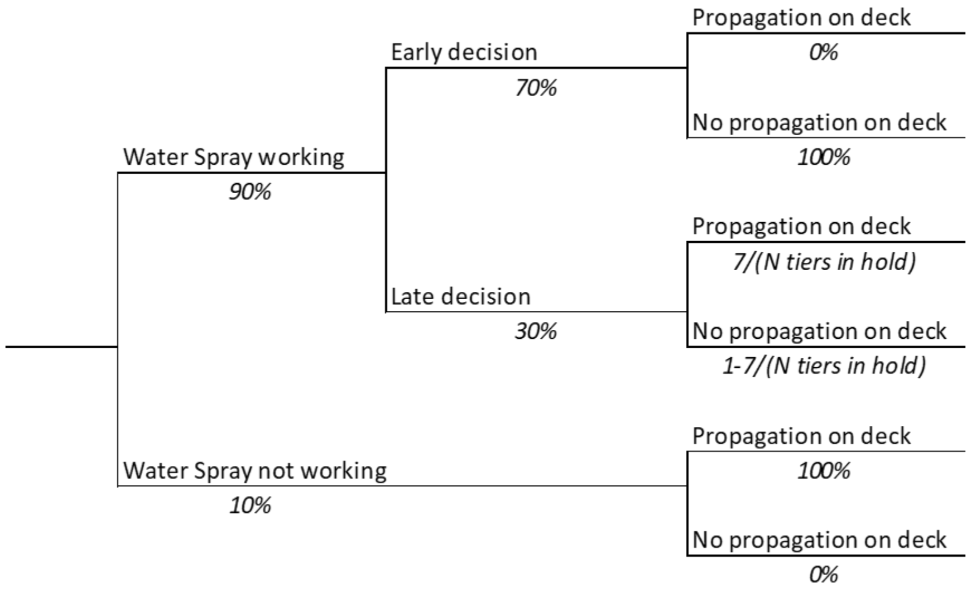

Figure 118: Event tree used to compute the probability of fire propagation with water spray.

The k-factor for this RCO was then the probability of no propagation, based on this event tree (because without the RCO, there is 100% chance of propagation). For fast fires, the 70%/30% early/late decision was turned into 30%/70%, and in the case of an explosion, 0%/100%.

4.6.2.2 RCO C2 – Passive protection to protect from fire spread towards the deck.

Some passive protection measures can be taken to prevent the spread of fire in cargo hold. Consider adding floodable ballast tanks between adjacent cargo holds to create insulation or consider changing the fire rating of construction to improve passive fire protection capabilities. In addition, measures can be taken to make the hatch covers "Class A-60 division" fireproof to protect the fire in the cargo hold from spreading to the deck.
"Class A-60 division" means a division formed by a bulkhead or deck that is:

1. Constructed of steel or an equivalent material and suitably stiffened,
2. Constructed to prevent the passage of smoke and flame after 60 minutes of exposure to a standard fire test, and
3. Insulated with non-combustible materials so that, if either side is exposed to a standard fire test, after 60 minutes the average temperature on the unexposed face will not increase by more than 139°C above the initial temperature and the temperature at any point on the unexposed face, including any joint, will not increase by more than 180°C above the initial temperature.

- **Availability in current market**

There are a variety of passive protection that would be applicable to provide the required class A-60 protection. The passive protection used for this RCO can either be sourced as bulk insulation or an intumescent paint spray. Both types of passive protection can be readily sourced using suppliers such as Rockwool or Sherwin-Williams. The bulk insulation option would likely be made of mineral wool, fiberglass, or equivalent roll of A-60 rated material. The intumescent paint spray would be made of a proprietary compound which also provides the minimum A-60 fire rating.

- **Working principle**

Fiberglass shown in Figure 119 is the most used insulating material in modern times. Because of the way it is manufactured, by effectively weaving fine glass filaments into the insulation, fiberglass minimizes heat transfer and is an excellent non-flammable insulating material with an R-value per inch ranging from R-2.9 to R-3.8.

Figure 119: Fiberglass.

Mineral wool as shown in Figure 120 refers to several different types of insulation materials. First, it may refer to glass wool, which is a glass fiber made from recycled glass. Second, it may refer to rock wool, which is an insulating material made from basalt. Finally, it may refer to slag wool, which is produced from steel mill slag. Mineral wool is non-combustible. When used in conjunction with other more fire-resistant insulation materials, mineral wool is an effective way to insulate large areas. The R-value of mineral wool varies from R-2.8 to R-3.5.

Figure 120: Mineral wool.

Intumescent paint for steel is one of the most used and cost-effective solutions in a passive fire protection project. Intumescent substances expand when exposed to heat and fire. When used as paint coatings or fire sprays, they form a protective layer on the surface. When exposed to fire or overheating, the protective layer resists and absorbs heat, thus protecting structural members from damage or deformation. Volume expansion and density reduction occur when the temperature begins to rise. The organic materials used to make intumescent coatings are inert at low temperatures, but when they come into contact with heat or fire, they expand instantly. The Figure 121 shows the intumescent paint before and after heating.

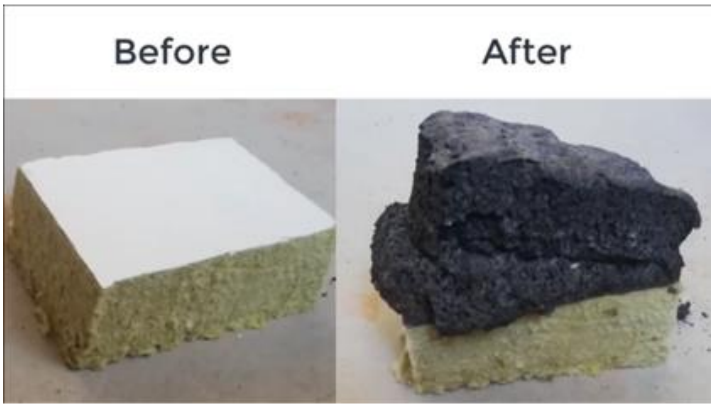

Figure 121: Intumescent paint before and after heating.

- **Limitations**

The main downside of glass fibers and mineral wool is that they can cause skin and lung irritation if inhaled. The fine fibers are made of glass and stone and can therefore be embedded in the skin or can damage the lungs if inhaled. However, this problem can be effectively avoided if proper safety equipment is used.
The intumescent paint is highly sensitive to environmental exposure at the time of application. Therefore, timely maintenance and inspection or re-painting is needed.

- **Risk reduction potential**

The application of passive protection option can effectively prolong the time for the fire to spread towards the deck or the adjacent cargo hold. For slow fire, a maximum risk reduction rate of 25% was chosen, which represents low efficiency. For fast fire choose the maximum risk reduction rate of 50% which represents medium efficiency. Halve the maximum value to get the most likely risk reduction rate 12.5% for slow fire and 25% for fast fire. Explosion may cause damage to passive protection, so the percentage of the top two tiers of containers in the cargo hold of different ship types is subtracted from the fast fire reduction rate to obtain 20.45%, 18.75% and 16.67%, respectively.

4.6.2.3 RCO C3 – On-deck container stack cooling/containment system

This RCO addresses capabilities to contain a fire within the container stack of origin. In review of SOLAS II-2 Regulation 10, the on-deck firefighting equipment requirements aboard container ships are modest or non-existent. Currently, the available options for on-deck container ship firefighting are portable fire extinguishers, hoselines, mobile water monitors, and water mist lances. In addition, mobile water monitors and water mist lances are only required for ships constructed on or after January 1st, 2016. Thus, many container ships only have hoselines and portable fire extinguishers available for on-deck firefighting operations.

Figure 122: An example of portable fire extinguishers and hoselines available onboard a container ship.

Regarding this specific RCO the concept of a fixed water-based fire containment options were investigated. Between each container stack a lashing bridge is located. The primary purpose of this bridge is meant as a lashing point for the lower rows of containers on-deck. The containers can be stacked several rows higher than the lashing bridge but due to impact on loading/off-loading processes no permanent extension of the lashing bridge structure can be considered. Therefore, the space between container stacks is split into two zones: the hatch cover to the top of the lashing bridge and the top of the lashing bridge to the top of the highest container row. This two-zone method of containment allows investigation into distinctly different fixed water-based containment methods. The investigated protection system for the lower zone, we will refer to as the lashing bridge zone (LBZ), is a fixed water sprinkler system. This containment system projects a wall of water between the container stack of origin and the lashing bridge. This option provides shielding for the neighbouring container stack and a limited cooling effect on the container stack of origin within the LBZ. The investigated protection system for the higher zone, we will refer to as the container spacing zone (CSZ), are both fixed and mobile water monitors. The water monitors will need to be configured to project a curtain of water above the LBZ in between the container stacks. This water projection has the same effect as the LBZ water sprinkler system with an improved cooling effect if the monitor can be transitioned into firefighting operations.

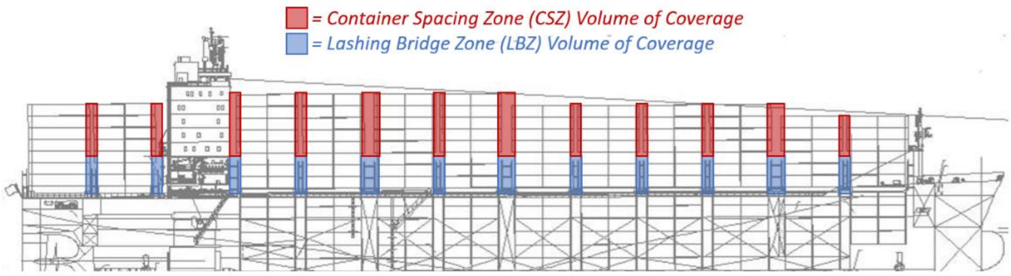

Figure 123: Containment zones for on-deck protection systems.

- **Availability in Current Market**

There are a variety of possible containment options for the LBZ. Such as, low-pressure water mist systems, high-pressure water mist systems, and water curtain systems. It should be noted that high-pressure systems will require high pressure pump stations. In addition, the low-pressure and water curtain systems may still require additional pumping power to compensate for the sprinkler system.

Figure 124: An example of a water spray curtain system.

The containment options for the CSZ are divided into two types of water monitors: mobile and fixed. The mobile water monitors can be sourced and requires a limited amount of effort in implementing them aboard a container ship. The fixed water monitors are available from a range of manufacturers, but they do require a considerable amount of effort in implementation. Other than reducing the time for activation, fixed water monitors can come with remote control features. This feature allows remote operation of a water monitor and even preprogramed patterns that can be activated prior to on-scene intervention.

Figure 125: Mobile water monitor.

Figure 126: Fixed water monitor.

- ***Working Principle***

The LBZ is protected with one of the fixed sprinkler systems: low and high-pressure water mist and water curtain system. Regardless of the chosen sprinkler system the same working principle remains. Water is projected from the nozzles to form a uniform water spray curtain in between the lashing bridge and the container stack. This water spray curtain serves two key functions (1) shield the lashing bridge and neighbouring container stack from radiant heat energy emitted from the container stack of origin and (2) provide limited cooling effects to surface of the container stack of origin. A helpful visual of this working principle is shown in Figure 127. It should be noted that this system is not an active firefighting system but rather a supplemental fire protection system. There is a lack of fire testing on container stacks with fixed water sprinkler systems so there is not currently an ideal sprinkler type to provide the greatest performance.

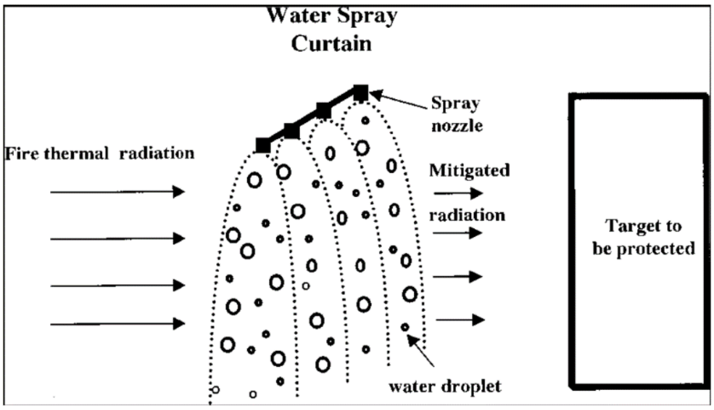

Figure 127: Working principle of a water spray curtain

As opposed to the fixed sprinkler systems in the LBZ, the water monitors meant for the CSZ have a little more flexibility. Per SOLAS II Regulation 10, container ships built on or after January 1st, 2016, will need to be equipped with mobile water monitors. For container ships with a breadth of less than 30 m they are required to carry two mobile monitors and four mobile monitors for ships with a breadth of 30 m or more. Additionally, flow testing is to be completed to ensure that all mobile monitors can be operated simultaneously and reach the topmost container row. After a fire scenario is confirmed and the fire crews have been dispatched the water monitors can be deployed.

The general operating procedure after this point is to (1) retrieve the monitors from an easily accessible weatherproof container on deck, (2) travel promptly towards the fire event, (3) mount the monitor to the ships frame as shown in Figure 112 (4) connect to an on-deck water connection, and (5) begin firefighting operations.

Note that this order of operations is a generalization, and each shipping line would have their own detailed standard operating procedures. During a firefighting operation, and with access to multiple mobile water monitors, a containment procedure can be implemented. This containment procedure would mean projecting a water curtain spray within the CSZ using the spare mobile monitor and if necessary, applying a surface cooling spray onto the opposite facing container stack. Water monitors fixed to the lashing bridge will reduce the time for firefighting and containment operations. An additional advancement in the overall safety of operating this apparatus would be the implementation of remote controls. Increasing the distance fire crews are from a fire event while still performing their duties should always be pursued when feasible. A possible configuration using remote controlled fixed water monitors would be to place a monitor on each side of the lashing bridge half of the way towards the centerline of the ship as shown in Figure 128 Figure 128.

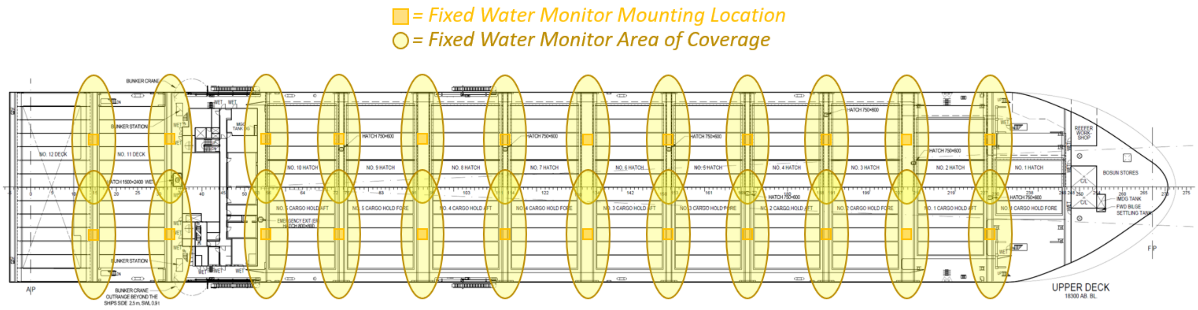

Figure 128: Plan view of a feeder style container ship with a fixed water monitor mounting arrangement.

Mounting above the lashing bridge is not possible so an additional feature that would be required is to have the fixed monitors folded into the bridge until a fire event is detected and confirmed. During a fire event the monitors would unfold and, if chosen as an option, begin a preprogramed with a spray pattern to protect the CSZ until manually or remotely controlled by the responding fire crew. An example of the unfolding of a fixed water monitor is shown in Figure 129 below for reference.

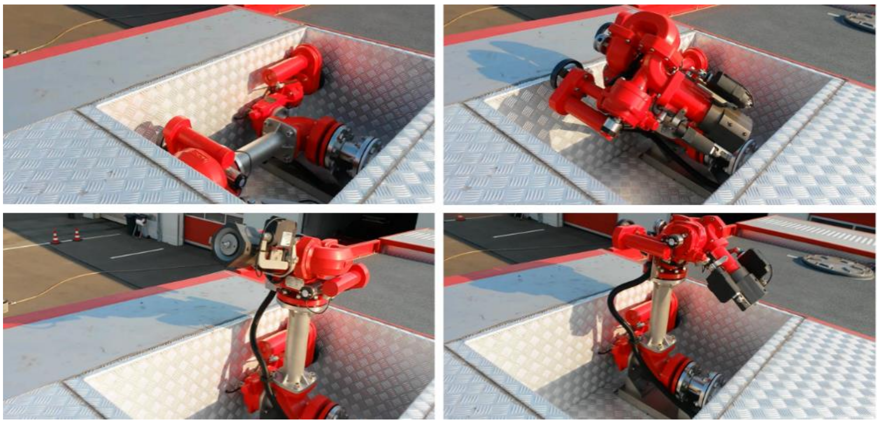

Figure 129: The unfolding steps of a fixed water monitor (starting in the upper left picture rotating clockwise).

Remote control of the fixed water monitors would be possible from two locations. First from the bridge which would have a control panel that could initiate the preprogrammed spray pattern until the responding fire crew arrives. After arrival of the fire crew, a weatherproof control box would be located at either end of the lashing bridge that contains a pin connector for a wired controller.

- **Limitations**

Although there are the two zones of coverage, the LBZ and CSZ, the limitations for this fire containment RCO are generally synonyms between the zones unless specified:

1. *Quantity of monitors [CSZ only]:* Unless the ship is built after 2016, water monitors are not expected aboard. For ships that do require mobile water monitors, the quantity aboard will either be two (ships with breadth less than 30 m) or four (ships with breadth of 30 m or more). This limited or non-existent monitors mean that firefighting and fire containment operations are limited to manual hose lines and reduced efficiency.
2. *New apparatus delay*: This RCO means implementing an on-deck fire protection system that is not industry standard. Moderate training would be necessary to learn how to use and maintain these systems. Without regular training, an inexperienced operator may delay water application on a fire or be unable to properly operate the systems.
3. *Obstructions [LBZ only]*: For the water spray curtain system installed in the LBZ, any physical obstructions such as the lashing rods, extralong containers, and the lashing bridge itself may obstruct the regular flow of the water. These obstructions can directly impact the performance of the system.
4. *Pressure requirements*: Adding additional water demanding devices on-deck may strain the existing fire protection water network. If minimum pressures are not provided when all devices are flowing, then the performance may be hindered or halted.
5. *Reach of water spray [CSZ only]*: This limitation is closely related to the minimum pressure requirements. If the water system is not designed for operating the water spray curtain system and the water monitors simultaneously then the spray patterns may not provide protection for the whole area between the container stacks.
6. *Sea Water Corrosion*: All mentioned fire containment apparatus in this RCO is supplied by sea water. The water monitors are designed to be used with sea water, but certain water spray curtain nozzles are not. If the nozzles are not designed for sea water, then the system may need to be flushed with fresh water after discharge.
7. *Weather deterioration*: General deterioration can occur while at sea which can compromise the performance of the system.
8. *Wind effects*: Whether the wind is blowing transversely or lengthwise across the ship, the wind will have a direct impact on the water sprays. This impacts both the fixed water spray curtain system and the water monitors.

– **Risk Reduction Potential**

To improve the effectiveness of the water monitors and water spray curtain system the limitations have been identified and investigated. Now they need to be improved and implemented:

1. *Quantity of monitors [CSZ only]:* Regardless of ship breath or age, adding a minimum of 4 water monitors would be advantageous for both containment and on-deck firefighting. Additionally, the use of fixed and remote-controlled water monitors greatly increases the risk reduction potential.
2. *New apparatus delay*: After installation, a training seminar should be held to educate operators on how to operate and maintain both the water spray curtain system and the water monitors. Training will decrease delay of use and increase the effectiveness of the system.
3. *Obstructions [LBZ only]*: Little can be done to prevent obstruction from the lashing rods without changing the lashing procedure and connection points. Instead, care should be taken during installation to avoid obstruction caused by the lashing bridge itself. Coordination with ship builders and the respective able seamen will assist with avoiding these obstructions.
4. *Pressure requirements*: To ensure the minimum pressure requirements are reached a fire scenario should be simulated. This can be done by simultaneously activating the water spray curtain on either side of a container stack and four water monitors. For the water spray curtain system, a visual observation of full coverage would be a minimum assurance of the performance of the system. The water monitors can be tested the same as the existing standard of reaching the topmost row of containers.
5. *Reach of water spray [CSZ only]*: The risk reduction potential for this limitation is the same as the pressure requirements.
6. *Sea Water Corrosion*: Care needs to be made during procurement to ensure that all aspects of the system are compatible with sea water.
7. *Weather deterioration*: Care needs to be taken during procurement to ensure that all aspects of the system are weatherproof and marine approved/listed.
8. *Wind effects*: Wind effects are beyond the control of our human domain. Without field testing it is unclear if changing the ship's orientation with respect to the wind will have an impact on the performance of this RCO.

If all the limitations are addressed a best-case scenario will be achieved. Data provided by EMSA, and other sources, have been filtered to determine certain failure rates. Specific to this RCO, a failure is qualified as the inability to keep a fire originating in container stack to the original container stack of origin. The mode of failure is one of three modes: slow fire, fast fire, or explosion scenario. Additionally, consideration was given to the size of the container ship: feeder, single island, and twin island container ship (generic ship 3, 2 and 1). Their respective failure rates are 8.3%, 12.2%, and 11.5% for slow fires, 72.7%, 73.1%, and 66.6% for fast fires, and 88.9%, 88.4%, and 83.4 for explosion scenarios.

The max risk reduction potential for this RCO during slow fire scenarios was determined to be very high, 90%, for the lower container rows up until the second container row above the lashing bridge. This means a max 90% risk reduction potential for the whole of the LBZ and the lowest portion of the CSZ. The ratio of on-deck container rows to lashing bridge height varied between container ship sizes. The determined max risk reduction potential for small fires on feeder, single island, and twin island container ship types (generic ship 3, 2 and 1) are 51%, 64%, and 45% respectively. Additional reductions were necessary for the fast fire and explosion scenarios. Fast fire scenarios would likely have delayed activation of the RCO. Thus, the max risk reduction potential was determined to be half of the slow fire values. The max risk reduction potential for fast fires were 26%, 32%, and 23% respectively. The explosion scenarios are valued at half of the fast scenarios to account for damage to the fire protection system and surrounding infrastructure. This reduction results in values of 13%, 16%, and 11% respectively for explosion scenarios. The likely risk reduction potential of the mentioned max values is halved based on expert judgement and to account for uncertainty.

4.6.2.4 RCO C4 – Flooding cargo hold to limited degree

This RCO addresses the capability to contain a fire within a below deck cargo hold. In review of SOLAS II-2, the only mention of a cargo hold flooding system is in Regulation 19 regarding the carriage of dangerous goods. This section specifies the following minimum requirements for a cargo hold flooding system:

- A minimum flow of 5 liters of water / minute / m² of the horizontal area of the cargo hold.
- The pumping system shall be sized to handle 125% of the discharged water. Both the flooding system and the dewatering system.
- All drainage valves shall be operable from outside the protected space and located near the system controls.
- Bilge wells that are arranged at the side shell of the ship shall not be more than 40 m from each other.
  - If this spacing is not possible, the potential for ship instability shall be accounted for by the Administration during approvals.

In addition to this regulation, several class societies (such as: DNV GL[63], BV[64], and ABS[65]) have developed their own class notations. These class societies provide specific requirements for their cargo hold flooding system with consideration for controls, water supply, flooding procedure, dewatering procedure, structural member strength, and ship stability.

- **Availability in current market**

Each cargo hold filling system is built on a case-by-case basis and no universal solution is applicable. However, the filling of a cargo hold is possible from multiple routes, such as: temporary systems, permanent systems, or combination systems. A temporary cargo hold filling system refers to the use of manual hose-lines or equivalent systems to fill the respective cargo hold from the main deck through closeable openings. A permanent cargo hold filling system refers to the use of the ballast, fire main, and/or dedicated pumps in conjunction with a fixed piping network to fill the respective cargo hold. Additionally, gravity filling may be applicable for a permanent system on a case-by-case basis. A combination cargo hold filling system consists of a system that can use both a temporary and permanent system.

- **Working principle**

Cargo hold flooding is considered a last resort when addressing a fire within the cargo hold. The working principle is that if a fire within the cargo hold has developed past the capabilities of all other firefighting operations the hold can be flooded to attempt to regain control of the situation. Regardless of the type of cargo filling system installed, the final installation complies with the corresponding class society (DNV GL, BV, and ABS). In addition to consideration for the filling procedure there may be class society specific requirements on the general control, water level, dewatering, and ventilation systems. Additionally, there is consideration for the dangers of progressive flooding, water reactive goods, flammable liquid goods, ship trim and stability, and structural integrity.

For instance, for the ship to be certified ECFP-2 by BV, the flooding system must fulfill the following criteria:

- Indication of the sea water level in the cargo holds is to be available at the continuously manned central control station.
- The permeability of the container cargo holds when flooded is to be taken equal to 0,7.
- The permissible still water vertical bending moment and vertical shear force for cargo hold flooding at any longitudinal position need to respect some conditions.
- Each cargo hold is to be served by one or several isolation valves which are to be in a safe location outside of the protected hold.
- Etc.[66]

[63] DNV GL. "6.7 Fire-Fighting in Container Holds by Hold Flooding - FCS(HF)." In Rules for Classification: Ships - Pt.6, Ch.5 Equipment and Design Features, July 2022., 341–344. DNV GL, n.d.
[64] Bureau Veritas. "Ch.13, Sec.2, 3.7 Flooding System for the Cargo Holds." In NR467 Rules for the Classification of Steel Ships - Part F Additional Class Notations, July 2022., 439–441. Bureau Veritas, n.d.
[65] ABS. "Section 7: CHF Notation." In ABS Guide for Fire-fighting Systems for Cargo Areas of Container Carriers, 2022., 46-49. ABS, n.d.
[66] All the requirements can be found in "BV *NR467 – Rules for Steel Ships Pt F, Ch 13, Sec 2., 3.7. Flooding system for the cargo hold*"

It should be noted that these are BV requirements, and do not necessarily exactly match the rules of the other classification societies.

− **Limitations**

This technology is newer and lacks industry acceptance thus it has some limitations:

1. *Dangerous Goods*: Activating a cargo hold flooding system would fill a respective cargo hold to a maximum fill level. All containers at or below this maximum fill level can be compromised with water impingement. The risk level can increase if the impinged container is a refer container or contains dangerous goods such as flammable liquids, class 4.3 goods, or lithium-ion batteries.
2. *Instability*: This containment tool can raise some issues regarding the stability of the ship due to a large free surface of water. Moreover, the bending and shear stress applied to the hold when filled must be considered during the building of the ship. ABS provides strength formulas for boundary structure[67] and longitudinal strength[68].
3. *New Construction vs Retrofit*: Implementation of a cargo hold flooding system to an existing container ship requires installation of a significant piping network, central control station, and integration of many system components. This type of system would be easier to integrate into new construction container ships rather than retrofit.

− **Risk reduction potential**

Since the maximum flooding level is to be determined by the owner or the designer and is not imposed by the regulation, it was assumed that the flooding system could flood the bottom five tiers of containers. Based on BV values, the following tree was used for slow fires to compute the risk reduction brought by the RCO:

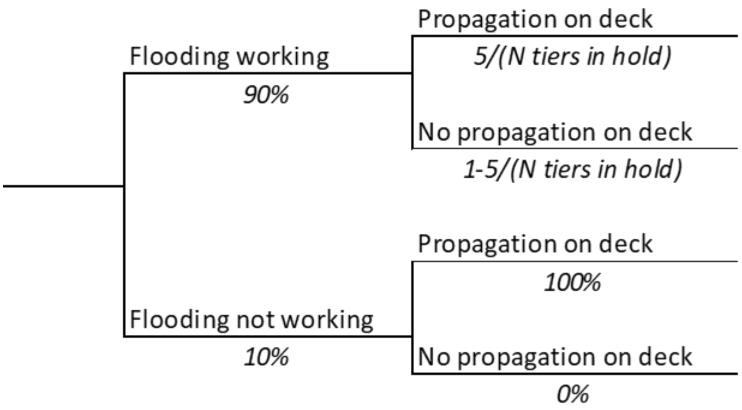

Figure 130: Event tree used to compute the probability of propagation with flooding.

Therefore, with a maximum of 90% effectiveness for slow fires the deciding factor for each ship size was the number of tiers of containers. The feeder type container ship has 6 tiers while the single and twin container ship have 8 and 10 tiers, respectively. Thus, the maximum k-factor for "slow" fires aboard for all container ship types are 75%, 56%, and 45%, respectively.

For "fast" fires, a reduction of 33% of the k-factor for "slow" was applied, to consider the increase of the fire propagation speed while the water flooding remains the same. Thus, the maximum k-factor for "fast" fires aboard for all container ship types are 50%, 37%, and 30%, respectively. For "explosions", a reduction of 66% of the k-factor

[67] ABS. "Appendix 1: Boundary Structure of Flooded Container Cargo Holds." In ABS Guide for Fire-fighting Systems for Cargo Areas of Container Carriers, 2022., 53-57. ABS, n.d.
[68] ABS. "Appendix 2: Longitudinal Strength of Container Carriers in Flooded Condition." In ABS Guide for Fire-fighting Systems for Cargo Areas of Container Carriers, 2022., 58-60. ABS, n.d.

was applied to the "slow" k-factor for the same reason. Thus, the maximum k-factor for "explosions" for all container ship types are 25%, 19%, and 15%, respectively. Note that the k-factor values mentioned in this section are maximum values. The likely k-factor values are half of the maximum k-factor values, and the minimum k-factor values are half of the likely k-factor values.

4.6.3 Effectiveness assessment

Table 59: Effectiveness assessment of containment RCOs.

C-RCO	RCO title	TRL	OD/ BD	RCO-side effects/ limitations
C1	Active protection (e.g., sprinklers) underneath hatch covers to protect from fire spread towards the deck.	9	BD	Minimum water pressure and flow rate, installation obstructions, only contain fire spread originating from the below deck hold.
C2	Passive protection to protect from fire spread towards the deck.	8	BD	Lung inhalation risk during installation, timely maintenance is needed.
C3	On-deck container stack cooling/containment system (e.g., water sprinklers and water monitors)	7	OD	Due to the limited or lack of monitors aboard current effectiveness is low. Additional limitations are minimum pressure requirements, the reach of water spray, weather deterioration of equipment, and negative wind effects.
C4	Flooding cargo hold to limited degree (to limited height)	3	BD	Shear and bending stresses on cargo hold/ballast tanks, need for separate water circuit and water removal pumps, secondary risks for refer containers.

4.7 Risk reduction evaluation

4.7.1 Compilation of RCOs' risk reduction potential

Table 60 presents the most likely risk reduction potential of each of the RCOs. The justification for the numbers is discussed through each of the previous RCOs' descriptions. The risk reduction potential vary with the fire growth rates and the generic ship types. Some of the RCOs can be implemented both on deck and below deck. In this situation the value is presented for both cases.

The risk reduction potential evaluated here is highly subjective, since not all proposed solutions have been assessed under realistic scenarios. In addition to the most likely potential, it was also proposing a maximum and minimum value. Later, they are used to carry out an uncertainty analysis for the risk reduction evaluation. The complete evaluation of risk reduction potential can be found in Annex M. Using a probability distribution for uncertain inputs like the risk reduction potential, allows to present the different possible losses, along with their likelihood of occurrence.

Table 60: RCO effectiveness capabilities.

Module	RCO ID	Name	OD/BD	Tier	Node	K-factor [%]		
						Twin Island	Single Island	Feeder
						18000 TEU	7500 TEU	3500 TEU
Prevention	P1	Container screening tool	OD/BD	Fire/TEU.year	NA	3.1%		
	P4	Improved control of lashing	OD	Fire/TEU.year	NA	0.8%		
Detection	D1	Optimizing current smoke detection system	BD	Smoke detection & CO_2 system	Slow	3.1%	3.1%	3.1%
					Fast	2.7%	2.7%	2.7%
	D2	Heat detection looking at individual container temperature rise	OD	Detection & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	3.1%	3.6%	3.1%
					Fast	7.0%	9.2%	9.1%
			BD	Detection (manual/random) & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	7.9%	9.7%	8.8%
					Fast	15.2%	20.2%	8.8%
				Smoke detection & CO_2 system	Slow	5.0%	5.0%	5.0%
					Fast	2.5%	2.5%	2.5%
	D3	Fixed IR cameras	OD	Detection & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	4.7%	5.4%	2.4%
					Fast	10.5%	13.8%	6.9%
	D4	CCTV - AI - smoke detection	OD	Detection & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	1.4%	1.6%	0.7%
					Fast	3.1%	4.1%	1.4%
	D5	Portable IR cameras for crew to enhance manual detection	OD	Detection & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	2.8%	2.1%	0.8%
					Fast	1.1%	0.8%	0.3%
			BD	Detection (manual/random) & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	2.0%	1.5%	0.8%
					Fast	0.8%	0.6%	0.3%

European Maritime Safety Agency

Firefighting	F1	Increasing effectiveness of current CO_2 system	BD	Smoke detection & CO_2 system	Slow	10.0%	10.0%	10.0%
					Fast	2.5%	2.5%	2.5%
					Explosion	1.3%	1.3%	1.3%
	F2	Improved manual firefighting tools for individual container breaching and firefighting	OD	Detection & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	6.2%	11.7%	12.1%
					Fast	2.9%	4.6%	4.7%
					Explosion	0.0%	0.0%	0.0%
	F3	Manual firefighting tools that increase reach	OD	Detection & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	20.9%	18.4%	19.3%
					Fast	8.4%	6.3%	6.5%
					Explosion	0.0%	0.0%	0.0%
	F4	Methods for unmanned fire fighting	OD	Detection & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	3.5%	6.7%	7.0%
					Fast	1.7%	2.7%	2.8%
					Explosion	1.7%	2.7%	2.8%
	F5	Water mist turbine	OD	Detection & Local first response on COO (including accessibility, MFF and local BND cooling)	Slow	10.0%	8.2%	8.6%
					Fast	4.3%	3.2%	3.3%
					Explosion	4.3%	3.2%	3.3%
Containment	C1	Active protection underneath hatch covers to protect from fire spread towards the deck	BD	Firefighting / Containment in HOO	Slow	37.0%	33%	32%
					Fast	26.5%	17%	14%
					Explosion	18.5%	6%	0%
	C2	Passive protection to protect from fire spread towards the deck	BD	Firefighting / Containment in HOO	Slow	12.5%	12.5%	12.5%
					Fast	25.0%	25.0%	25.0%
					Explosion	20.5%	18.8%	16.7%
	C3	On-deck container stack cooling/ containment system	OD	Firefighting / 1st bay boundary cooling	Slow	22.5%	32.1%	25.7%
					Fast	11.3%	16.1%	12.9%
					Explosion	5.6%	8.0%	6.4%
	C4	Flooding cargo hold to limited degree	BD	Firefighting / Containment in HOO	Slow	23%	28%	38%
					Fast	15%	19%	25%
					Explosion	7%	9%	12%

4.7.2 Risk reduction quantification

The risk reduction evaluation was performed using the event trees. A new failure probability was assumed depending on the RCO implemented. The values used are presented in Table 60 and Annex M In cases where more than one node on the event tree was affected, all the involved new probabilities were changed at the same time. For example, D2 – Heat detection system, is assumed to be installed on the deck and below the deck, therefore, both event trees were changed to the new failure probability at the same time, correspondingly.

There is a high uncertainty on the risk reduction potential, therefore, the evaluation of the new risk was performed using a Monte Carlo simulation. Each of the RCOs was assigned a minimum, maximum and most likely value of potential effectiveness. Then a triangular probability distribution was used as the potential new probability. The simulation was performed one time for each RCO, with 10000 iterations. The final result is a range or distribution of possible risks. This simulation allows us to calculate the probabilities of different outcomes. It means presenting a range of possible risk reductions with a confidence interval of 95%. Finally, this difference between the baseline risk and the new risk is calculated and denoted as delta loss.

Table 61 presents the mean results of the delta risk reduction in terms of Total Potential Loss (TPL) and Potential Loss of Life (PLL). The present results are going to be used to evaluate if the implementation of each of the RCOs is cost beneficial. In addition, Annex N shows the complete distribution of possible risk with a 95% confidence interval.

Table 61: Effectiveness in reducing risk for each of the RCOs.

RCO ID	Description	Mean Δ TPL			Mean Δ PLL		
		Twin Island	Single Island	Feeder	Twin Island	Single Island	Feeder
		Gen sh 1	Gen sh 2	Gen sh 3	Gen sh 1	Gen sh 2	Gen sh 3
P1	Container screening tool	€ 61,153	€ 9,773	€ 1,755	2.0E-04	6.7E-05	1.9E-05
P4	Improved control of lashing	€ 16,103	€ 2,573	€ 462	5.2E-05	1.8E-05	5.1E-06
D1	Optimizing current smoke detection system	€ 22,908	€ 3,204	€ 464	1.1E-04	3.3E-05	7.7E-06
D2	Heat detection looking at individual container temperature rise	€ 103,635	€ 18,087	€ 3,001	4.0E-04	1.3E-04	3.0E-05
D3	Fixed IR cameras (installed at strategic locations). Coupled to a software solution to automate detection	€ 14,371	€ 3,544	€ 740	1.6E-05	8.3E-06	2.8E-06
D4	CCTV - AI - smoke detection	€ 4,311	€ 1,063	€ 151	4.7E-06	2.5E-06	5.8E-07
D5	Portable IR cameras for crew to enhance manual detection	€ 20,274	€ 2,231	€ 115	7.9E-05	1.8E-05	1.0E-06
F1	Increasing effectiveness of current CO_2 system	€ 40,590	€ 5,668	€ 858	2.2E-04	6.2E-05	1.4E-05
F2	Improved manual firefighting tools for individual container breaching and firefighting	€ 5,160	€ 1,545	€ 442	5.4E-06	3.5E-06	1.6E-06
F3	Manual firefighting tools that increase reach	€ 15,449	€ 2,207	€ 634	1.6E-05	5.0E-06	2.2E-06
F4	Methods for unmanned fire fighting	€ 6,589	€ 1,951	€ 542	1.0E-05	6.6E-06	3.2E-06
F5	Water mist turbine	€ 25,175	€ 3,517	€ 972	3.8E-05	1.2E-05	5.7E-06
C1	Active protection underneath hatch covers to protect from fire spread towards the deck	€ 331,135	€ 25,466	€ 1,798	1.3E-03	2.6E-04	3.7E-05
C2	Passive protection to protect from fire spread towards the deck	€ 306,064	€ 43,868	€ 5,012	1.0E-03	3.3E-04	7.4E-05
C3	On-deck container stack cooling/containment system	€ 23,793	€ 6,401	€ 1,273	2.6E-05	1.6E-05	5.7E-06
C4	Flooding cargo hold to limited degree	€ 166,999	€ 29,765	€ 4,683	7.3E-04	2.7E-04	7.7E-05

4.7.1 Uncertainty analysis

The Monte Carlo simulation allows us to account for uncertainty propagation. It inputs the uncertainty distribution of the RCO risk reduction potential on the event tree, to calculate the potential loss. This calculation was performed 10000 times where random effectiveness was drawn from the input distribution. After many random trials, a value is calculated with an embedded uncertainty distribution. The possible risk reduction with its confidence interval is presented in Annex N.

4.8 Interdependencies

Table 62 shows a summary of the identified interdependencies. To read the table, use these questions: Will the horizontal RCO (e.g., P3) ***positively*** affect the vertical RCO (e.g., P5)? Then by how much will one affect the other?
The interdependencies was ranked by using level 1 (no), 2 (weak) and 3 (high).
It is assumed that any high-ranking interdependency will therefore result in a higher risk reduction for the combined solution.

- **Prevention:**

Based on the analysis illustrated in Table 62, RCO - P3 shows a clear interdependency with P4 and P5 within the prevention category.

RCO - P3 Risk-based stowage planning tool is the only RCO which upon implementation, is expected to have an interdependency with other identified RCOs in Detection, Firefighting and Containment. Since this RCO only has an impact on the severity, i.e., only relevant for declared DG, the rest of the FTs (cf. 3.6.1.3) remain unaffected. P3 works very well when implemented in combination with other fire tiers such as Detection (D2, D3, D4), Firefighting (F3, F4, F5) and Containment (C3) rather than Prevention alone. This means that the risk of any severe incident or accident such as explosion arising from a high-risk cargo can be mitigated when this RCO is implemented in conjunction with other RCOs from the Event Tree (ET), i.e., the Consequence Model. In isolation (stand-alone), RCO - P3 has limited or no effect on reducing the probability of ignition. In other words, this RCO only affects the severity when implemented with other RCOs from other fire tiers from the ET side of the Global Risk Model.

- **Detection:**

Detection RCOs show a clear interdependency with the firefighting RCOs, this is illustrated in Table 62 with the strongest grouping of level 3 (strong) dependencies between D2, D3, D5 and F2, F3 and F4. This makes sense, as earlier detection (detection RCOs provide) clearly will influence the effectiveness of the manual firefighting RCOs as an earlier detection leads to manual firefighting intervention being both more likely and more effective.

The interdependency scores between detection and firefighting RCOs suggest that some combinations between these RCOs may have a much higher impact, especially on deck (OD) within the detection and manual first response event tree node.

- **Firefighting:**

Besides the detection RCOs as discussed above, firefighting RCOs F2 and F3 show a strong interdependency due to their combination giving both increased efficiency in penetrating the COO (F2) and greater reach (F3) meaning more containers are easily accessible. Which will have a strong effect on the performance of any manual firefighting attempts.

F4 and F5 also show a strong interdependency with the containment RCO C3. This is due to C3 acting as an active containment for OD fire scenarios, which will also affect the other firefighting RCOs to also be more effective due to higher loads of water.

- **Containment:**

The containment RCOs C1 and C3 are also affected by the detection RCOs as they are active protection systems, they are also reliant on the fire being detected to effective, hence earlier detection will strongly influence the effectiveness. C1 and F1 are also interdependent due to them both activating in case of a cargo hold fire. CO_2 (F1) + water (C1) will have a greater suppression effect than separately.

Table 62: RCOs Interdependencies.

		P1	P2	P3	P4	P5	D1	D2	D3	D4	D5	F1	F2	F3	F4	F5	C1	C2	C3	C4
Container screening tool	**P1**																			
Common database for rejected screening cargo	**P2**	1																		
Stowage planning tool	**P3**	1	1																	
Improved control of lashing	**P4**	1	1	2																
Improve test methods for self-heating cargo	**P5**	1	1	3	1															
Optimizing current smoke detection system	**D1**	1	1	1	1	1														
Heat detection looking at individual container temperature rise	**D2**	1	1	2	1	1	1													
Fixed IR cameras	**D3**	1	1	2	1	1	1	1												
CCTV - AI - smoke detection	**D4**	1	1	2	1	1	1	1	1											
Portable IR cameras for crew to enhance manual detection	**D5**	1	1	1	1	1	2	2	2	3										
Increasing effectiveness of current CO_2 system	**F1**	1	1	1	1	1	3	3	1	1	2									
Improved manual firefighting tools for individual container breaching and firefighting	**F2**	1	1	1	1	1	2	3	3	2	3	1								
Manual firefighting tools that increase reach	**F3**	1	1	2	1	1	1	3	3	2	3	1	3							
Methods for unmanned fire fighting	**F4**	1	1	3	1	1	1	3	3	2	3	1	1	2						
Water mist turbine	**F5**	1	1	3	1	1	1	3	3	2	3	1	1	1	2					
Active protection underneath hatch covers to protect from fire spread towards the deck	**C1**	1	1	1	1	1	3	3	1	1	2	3	1	1	2	2				
Passive protection to protect from fire spread towards the deck	**C2**	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	3			
On-deck container stack cooling/containment system	**C3**	1	1	3	1	1	1	3	3	2	2	1	1	1	3	3	1	1		
Flooding cargo hold to limited degree	**C4**	1	1	1	1	1	2	2	1	1	1	2	1	1	1	1	2	1	1	

Does one affect the other performance?

No	1
Weak	2
Strong	3

4.8.1 Effectiveness assessment

Different RCOs were combined to assess the effectiveness of RCO combinations, including all combinations with strong interdependence rank and most combinations with weak interdependence rank. Depending on the situation, the effectiveness of the RCO combination can be assessed in two different ways. If the two RCOs each affect a different node in the ET, the effectiveness of each of the two nodes can be subsequently assessed separately.
If the two RCOs affect the same node in the ET, then the best scenario after applying both RCOs is considered in the FT and the probability of the node is derived, and the effectiveness of the combined RCOs is calculated using the risk reduction effectiveness method mentioned in Section 4.2.4.1. Effectiveness in reducing risk. For example, RCO F2 Improved manual firefighting tools for individual container breaching and firefighting and RCO F3 Manual firefighting tools that increase reach have a strong interdependence rank. They both affect the node Detection & Local first response on COO (including accessibility, MFF and local BND cooling). In the FT, under the best-case scenario considering that the failure rate of manual firefighting for individual container and COO out of reach nodes as 0. For twin island container ship (generic ship 1), the probability of Failure of Detection & Local first response on COO (including accessibility, MFF and local BND cooling) was then obtained as 28.38% and 62.30% for the slow fire and fast fire, respectively. Then the two probabilities are brought into the formula to obtain the effectiveness of the combined RCOs of 57,9% and 25,2% respectively. The effectiveness of all combined RCOs is available in Annex O.

4.8.2 Risk reduction quantification

The risk reduction quantification of the combination of RCO was assessed using the same procedure described in section 4.7.2. The quantification was performed only for the generic ship 1: Twin Island, knowing that it has the larger budget for implementing RCOs. Therefore, the implementation of two RCO becomes feasible. The final results are presented in Annex P. It is noted that the risk reduction for some of the combinations is much higher than the sum of the single RCOs. This is because of the assumption that the effectiveness of the combined RCOs is stronger than individual implemented RCOS's. For example, having early detection combined with local firefighting is expected to have a better result than these RCO's applied individually.

5. COST EFFECTIVENESS ASSESSMENT

The objective of task 4 is to estimate the cost effectiveness of the selected RCOs from Task 3. This is done by calculating one value and three metrics which are:

- Gross Cost of Averting a Fatality (GCAF)
- Net Cost of Averting a Fatality (NCAF)
- Net Present Value (NPV)
- Benefit-Cost Ratio (BCR)

Calculation of these values and metrics for the three ship types as well as both new building and retro fit solution scenarios, make it possible to rank the different RCOs from a cost-effective perspective and support proposed recommendations of Task 5.

5.1 GCAF & NCAF calculation method

Formulas and definitions to calculate the GCAF & NCAF are extracted from the FSA Guidelines (IMO, 2018), and shown below:

- GCAF (Gross Cost of Averting a Fatality): A cost-effectiveness measure in terms of ratio of marginal (additional) cost of the risk control option to the reduction in risk to personnel in terms of the fatalities averted.

$$GCAF = \Delta Cost / \Delta Risk$$

- NCAF (Net Cost of Averting a Fatality): A cost-effectiveness measure in terms of ratio of marginal (additional) cost, accounting for the economic benefits of the risk control option to of the risk control option to the reduction in risk to personnel in terms of the fatalities averted.

$$NCAF = \frac{\Delta Cost - \Delta EconomicBenefit}{\Delta Risk}$$

The GCAF is used to investigate if a RCO's impact on fatalities is efficient from a cost perspective alone or not. The NCAF includes additional economic benefits for the industry and society from implementing the RCO into the investigation. In this study it has been chosen to include benefits gained from reduction in likelihood of cargo and ship loss, as well as salvage and environmental costs. ΔCost and ΔEconomicBenefits are estimated using discounting methods as explained in next section.

RCOs can be ranked according to their GCAF, which are, by definition, always positive. Then for NCAF a ranking only makes sense in case of positive values. One should be careful when ranking RCOs with negative NCAF, as a highly negative NCAF can be caused by either a high ΔEconomicBenefit, or a very low ΔRisk.

5.2 Cost, Net Present Value and Benefit-Cost Ratio Calculation method

For each RCO, the costs and benefits of implementation have been assessed and calculated individually from a life cycle perspective as basis for GCAF and NCAF calculations, but also calculations of Net Present Value and Benefit Cost Ratios. Implementation of an RCO incur costs via the initial investment in the solution which typically covers expenses for hardware, software, commissioning, installation, training etc. However, there will often also be regular annual running cost coupled to implementation, as for example costs for electricity, maintenance, repair / replacement, inspection, and testing, changed work procedures etc. over the RCO lifetime. Benefits include annual economic savings due to reduced potential for cargo loss, ship damage, salvage, and environmental loss. In principle annual expected monetary savings from reduction in fatalities, injuries of crew etc. could also be considered as an economic benefit but has, in line with the FSA guidelines, not been included here. A future used / scrapped value of the solution at the end of its lifetime onboard the vessel, has been included as a benefit for relevant RCOs.

To calculate both GCAF and NCAF, the actual monetary value of costs and benefits, the Net Present Value (NPV) method has been applied. The NPV method assesses the present value of an investment taking into account but also discounting all future annual costs and benefits in the asset lifetime. The annual discount factor is determined using the risk-free return rate and / or the inflation rate. The formulae to calculate the discount factor is as shown below:

$$DiscountFactor_{year} = (1 + RiskFreeReturnRate)^{-\Delta Year}$$

Where Δ Year is referring to the number of years in the future.

This discount factor essentially reduces the value of annual running costs and benefits considering that the investor could place an identical sum of money into assets with risk free return as US Government Treasury bonds as they globally are perceived as one of the safest investments and previously used in similar studies. While doing calculations, a US treasury bond offered 3.16 % return per year, and therefore the discount rate is set to 3.16 %. The annual value of for example the benefits is calculated using this discount factor like so:

$$Benefit_{year} = \Delta TPL \times DiscountFactor_{year}$$

Where the ΔTPL, which are “Total potential losses” are referring to the Potential Loss of Ship and Cargo, Salvage and Environmental costs identified as part of task 3 for each RCO.

When calculating GCAF, NCAF (estimating ΔCost and ΔBenefit across RCO lifetime) and not at least the NPV of the RCOs in the aforementioned ways, a complete list containing the initial investment and all annual running costs and benefits related to each RCO is thus required for all three ship types and both the new building and retrofit scenarios. For CARGOSAFE, the expected lifetime of a vessel has been set at 25 years for which costs and benefits are considered, and this assumption is applied for both new building and retrofit scenarios[69]. For every RCO investment and running cost items have been estimated based on mainly information and estimates from vendors supported by assessments made by industry expert judgement and study authors. A positive NPV value indicates that the individual RCO will have a positive economic impact on industry and society across the vessels lifetime compared to a negative value, which indicates an opposite potential negative impact.

In addition to the NPV calculations, CARGOSAFE also includes calculations of a Benefit-Cost ratio. The Benefit-Cost ratio (BCR) has been calculated for every RCO by first calculating the difference between accumulated discounted benefits versus the initial year zero investment plus accumulated discounted cost over the 25 years, see below:

$$BCR = \frac{Sum\ of\ Benefit_{years}(25\ years)}{Initial\ RCO\ Investment\ + Sum\ of\ Discounted\ Annual\ Costs\ (25\ years)}$$

A BCR above 1, indicates that the individual RCO will have a positive economic impact on industry and society over a lifetime of 25 years compared to a BCR below 1 which in contrast indicates a potential negative impact.

5.3 Cost of averting a fatality (CAF) as Criteria for selection of RCOs

The Cost of averting a Fatality is estimated in order to set a monetary value for the Potential Loss of Life. There are several methods to estimate this cost:

1. The first method consists in using a former cost and applying a 5% interest rate for each years passing to calculate today’s value. According to the FAS guidelines, the value of preventing a Fatality was set 3 million USD in 1998. This amount is converted to Euro using statistics of the average exchange rate of USD to € over the past 24 years. This gives a 1998 value of 2.55 million Euro, which results in a 2022 value of 8.22 M€ taking interest rates into account. This method was referenced as relevant in the FIRESAFE II study.

2. The second method is based on a formula developed by Skjong and Ronold[70], which takes into several indicators for OECD countries, at the considered year. This method was used in the FIRESAFE study.
   This formula is:

[69] A 25-year life expectancy was kept for both new builds and retrofits. If a reduced life expectancy were to be used for retrofits, this would have a decremental impact on the cost-effectiveness of the RCOs for this scenario.
[70] Skjong & Ronold, *“So much for safety”*, Det Norske Veritas, 2002.

$$CAF\ criterion = \frac{1}{n}\sum_{k=1}^{n}\frac{g_k e_k}{4} * \frac{1-w_k}{w_k}$$

With:

- n the number of OECD countries.
- g_k the gross domestic product per capita for country k (Statistics from world bank used).
- e_k the life expectancy at birth for country k (statistics from CIA fact-book used),
- w_k the portion of life spent in economic production for country k (statistics from OECD used).

Using this formula, a CAF criterion of 8.67 M€ was computed.

To be as accurate as possible, the second method was used, and the CAF criterion to be applied for CARGOSAFE should be 8.7 M€. This criterion can be compared to completed GCAF and NCAF calculations for all RCOs. If the calculated GCAF for each RCO is above this criterion, then alone from a loss of life perspective, the RCO should be recommended for implementation.

5.4 RCO Cost Estimates

This section presents an overview of RCOs from task 3, required investments and annual running costs for the three ship types and newbuilding vs retrofit scenarios. As mentioned earlier, the tables 63-80 below included both the initial investment in acquiring and installing the RCO as well as running costs. The following sections will include a short description of some of the main investment and running cost items for each RCO per generic vessel type size and new building vs retrofit scenario (in total 6 vessel categories).

5.4.1 Prevention

5.4.1.1 P1 - Container screening tool

This RCO requires installation of an X-ray scanner of a size to fit a complete container of different types and sizes through, which has a cost of app. 3.5 M€. Such a scanner is estimated to consume 48KWh/hr of electricity, making the cost a significant annual cost. The investment and annual costs have been calculated based on assumptions around amount of TEUs scanned annually per vessel category.

Table 63: P1 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	938,967 €	938,967 €	14,099 €
Single island: Gen. ship 2	391,389 €	391,389 €	5,877 €
Feeder: Gen. ship 3	184,417 €	184,417 €	2,769 €

5.4.1.2 P2 - Common database for rejected cargo

There is no initial investment, but a fee for using the database would enquire a cost of around 0.0295 € per TEU checked. Similar to P1, the calculations are based on the number of containers checked annually per ship category. However, cost-effectiveness calculations were not performed for this RCO as ΔPLL and ΔTPL were not quantified in task 3.

Table 64: P2 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	0 €	0 €	2,764 €
Single island: Gen. ship 2	0 €	0 €	1,443 €
Feeder: Gen. ship 3	0 €	0 €	944 €

5.4.1.3 P3 – Risk based stowage planning tool

The initial cost of risk-based stowage planning includes the time spent in training the stowage planners and cargo stowage officers to apply this new methodology. Therefore, this and additional annual (re)training costs are set identical for all vessel categories, however cost-effectiveness calculations were not performed for this RCO as ΔPLL and ΔTPL were not quantified in task 3.

Table 65: P3 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	1,000 €	1,000 €	1,000 €
Single island: Gen. ship 2	1,000 €	1,000 €	1,000 €
Feeder: Gen. ship 3	1,000 €	1,000 €	1,000 €

An argument can be made that the new methodology of stowage could lead to an increase in time for stowage planning and cargo operations and related expenses. It is however difficult to validate this as the effect could be either small or large depending on the stowage plan and the type and amount of dangerous goods for a specific service or vessel voyage.

5.4.1.4 P4 - Improved control of lashing

This RCO mostly covers additional regular work hours for regular checks by the crew onboard the vessels and no additional asset investments. Therefore, the price has been set based on the additional work time crew will spend on patrols, to check the lashings.

Table 66: P4 cost estimation.

	Retrofit	Newbuilding	Annual Cost
Twin island: Gen. ship 1	0 €	0 €	7,360 €
Single island: Gen. ship 2	0 €	0 €	4,987 €
Feeder: Gen. ship 3	0 €	0 €	1,680 €

Time spent on control of lashings will be decided by the Master. Often lashing will be checked during the cargo operation following the Cargo Securing Manual for that specific vessel. This check will ensure that the cargo is properly secured and lashed before departure, as no vessels should leave port with cargo not properly secured and lashed. More frequent control for a larger pool of containers would thus be business as usual for some crews, while others will experience a big increase in workload during the year. Average assumptions on number of extra lashing checks annually as well as time spent have thus been set for each of the three ship categories.

5.4.1.5 P5 - Improved test method for self-heating cargo

This RCO would require additional research, development, and regulatory effort to be completed in order to create a new the improved test method for self-heating cargo. The current self-heating test costs around 1,850 € per test. But it has been estimated that implementing a new testing method, will increase slightly the annual costs. Prices differ per vessel category due to TEU size and testing needs.

Table 67: P5 cost estimation.

	Annual cost
Twin island: Gen. ship 1	26,280 €
Single island: Gen. ship 2	10,950 €
Feeder: Gen. ship 3	5,156 €

5.4.2 Detection

5.4.2.1 D1 - Optimizing current smoke detection system in cargo hold

Prices were acquired for newbuilding and retrofitting system solutions for a twin island vessel type. The single island and feeder type prices have been set via reducing the price equivalent to the TEU ratio of the vessel categories. No additional annual costs are assumed to be incurred compared to how it is currently.

Table 68: D1 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	4,365,400 €	540,400 €	0 €
Single island: Gen. ship 2	1,818,917 €	225,167 €	0 €
Feeder: Gen. ship 3	856,588 €	106,038 €	0 €

5.4.2.2 D2 - Heat detection system

The pricing for this system was given as per TEU. Since there would be significant difficulties in reaching containers above deck which are stacked higher than the lashing bridges, the prices have been estimated based on the number of reachable containers. Both container slots below deck combined with the containers above deck which are up to the same height as the lashing bridges are covered.

Table 69: D2 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	458,240 €	458,240 €	2,500 €
Single island: Gen. ship 2	170,320 €	170,320 €	2,500 €
Feeder: Gen. ship 3	85,440 €	85,440 €	2,500 €

5.4.2.3 D3 – Fixed IR cameras

The price provided for this system was the price of six cameras for each bay as their “simplest” solution. Without any installation, engineering or “murphy’s law” cost included. The yearly cost was assumed based on the price of the system compared to the other camera solution and the respective running costs for that scenario.

Table 70: D3 cost estimation.

	Retrofit	Newbuilding	Yearly cost
Twin island: Gen. ship 1	3,600,000 €	3,600,000 €	36,000 €
Single island: Gen. ship 2	3,300,000 €	3,300,000 €	33,000 €
Feeder: Gen. ship 3	1,800,000 €	1,800,000 €	18,000 €

5.4.2.4 D4 – CCTV and AI smoke detection

For AI smoke detection, a complete pricelist was given for the feeder vessel size with a monthly running cost. The yearly cost mostly consisted of constant training of the AI model. Therefore, an assumption is made that the cost will be significantly lower for an increased number of ships, as they most likely would be able to share costs for model upgrades.

Table 71: D4 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	363,899 €	363,899 €	6,560 €
Single island: Gen. ship 2	151,624 €	151,624 €	6,560 €
Feeder: Gen. ship 3	71,405 €	71,405 €	6,560 €

5.4.2.5 D5 – Portable IR cameras for crew to enhance manual detection

The camera required for this RCO comes with a free training course on how to use it. The price was provided per camera, but information from a company that currently utilizes this system, makes it clear that two cameras would be sufficient. That gives one camera for the fire patrol to use at any given time, and a second one for redundancy. The expected lifetime of these cameras might be short in the harsh environment they are used in, so it is assumed that a replacement with new cameras is need every five years. The price of these replacements is averaged out as a part of the yearly cost.

Table 72: D5 cost estimation

	Retrofit	Newbuilding	Yearly cost
Twin island: Gen. ship 1	1,520 €	1,520 €	243 €
Single island: Gen. ship 2	1,520 €	1,520 €	243 €
Feeder: Gen. ship 3	1,520 €	1,520 €	243 €

5.4.3 Firefighting

5.4.3.1 F1 - Increasing effectiveness of current CO_2 System

It was proposed to increase the current CO_2 system's effectiveness by increasing its capacity. Two different methods were proposed, either to increase the number of CO_2 storage tanks or to install a continuous CO_2 production system. Both alternatives have limitations previously discussed. Only the latter option was assessed as part of the Cost Effectiveness Assessment (CEA). It is assumed that a continuous system has a slightly higher risk reduction potential because it also improves the boundary conditions of the cargo hold. Moreover, the cargo capacity loss over the ship's lifespan adds a high yearly cost to this RCO. Therefore, installing the continuous system would create a better business case.

One example of the installation of a continuous CO_2 system which may provide the highest risk reduction within this category has an estimated cost of approximately 500,000 €. Full maintenance was estimated to 15,000 €. Travel costs of technicians were estimated at 5,000 € annually. The system will require a replacement of some electrical components after around 10 years at a cost of 25,000 €, which have been split into a yearly maintenance cost of 2,500 €.

Table 73: F1 cost estimation

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	500,000 €	500,000 €	22,500 €
Single island: Gen. ship 2	500,000 €	500,000 €	22,500 €
Feeder: Gen. ship 3	500,000 €	500,000 €	22,500 €

5.4.3.2 F2 - Improved manual firefighting tools for individual container breaching and firefighting

The costs related to this RCO are mainly various hardware items which can be useful for onboard crew in a firefighting scenario set at 15,000 € for all vessel categories.

Table 74: F2 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	15,000 €	15,000 €	0 €
Single island: Gen. ship 2	15,000 €	15,000 €	0 €
Feeder: Gen. ship 3	15,000 €	15,000 €	0 €

5.4.3.3 F3 - Manual firefighting tools that increase reach

The costs related to this RCO are mainly various hardware that could be useful to the crew for easy reach a fire that is difficult to get to.

Table 75: F3 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	15,000 €	15,000 €	0 €
Single island: Gen. ship 2	15,000 €	15,000 €	0 €
Feeder: Gen. ship 3	15,000 €	15,000 €	0 €

5.4.3.4 F4 - Methods for unmanned firefighting

The costs associated with this RCO can be divided in 2 cases according to the SOLAS regulation. For container ships built after 2016, SOLAS requires this system to be available, so all relevant equipment is already on the container ship, and what is proposed is to make unmanned operation of it possible. For container ships built before 2016, the total cost of this RCO will include the cost of materials, including seawater pumps, filters, values, piping and mobile water monitors, the cost of operations system and installation cost. For case 2 vessels, investments depend on ship size, and for case 1 vessels there is assumed a fixed price for enabling unmanned operations. Annual costs are set to zero.

Table 76: F4 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	1,037,284 €	10,000 €	0 €
Single island: Gen. ship 2	490,535 €	10,000 €	0 €
Feeder: Gen. ship 3	283,916 €	10,000 €	0 €

5.4.3.5 F5 – Water mist turbine

The installation of a turbine-driven water mist canon has been estimated at a cost of 525,000 €. The maintenance and repair costs would otherwise be similar to RCO F1, with service technicians traveling around to the vessels and a 10-year replacement of key electronic components.

Table 77: F5 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	525,000 €	525,000 €	22,500 €
Single island: Gen. ship 2	525,000 €	525,000 €	22,500 €
Feeder: Gen. ship 3	525,000 €	525,000 €	22,500 €

5.4.4 Containment

5.4.4.1 C1 - Active protection underneath hatch covers to protect from fire spread towards the deck

For this RCO a quote of 70,000 € per two holds and 2,500 € of annual maintenance costs per hold, were used as basis for calculating costs per vessel category.

Table 78: C1 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	805,000 €	805,000 €	57,500 €
Single island: Gen. ship 2	735,000 €	735,000 €	52,500 €
Feeder: Gen. ship 3	350,000 €	350,000 €	25,000 €

5.4.4.2 C2 - Passive protection to protect from fire spread towards the deck

Passive protection requires installation of insulation on the hatch covers. The cost per vessel category has been estimated based on a price of 25 € per m² of surface. The twin island ship has a hatch cover dimension of app. 9,7 x 13,1 meters, and a total of 112 hatches. The insulation also has to cover the vertical surfaces on the hatch covers, and the area is thus doubled per hatch cover. This gives an area of 28.450 m² on the twin island. The single island has a hatch dimension of 12,2 x 13,1 meters, with 60 hatches total. This gives a total doubled surface of 19.200 m². The feeder has a hatch dimension of 9,7 x 13,1 meters, with a total of 29 hatches. This gives a doubled total of 7,400 m².

Table 79: C2 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	711,200 €	711,200 €	0 €
Single island: Gen. ship 2	480,000 €	480,000 €	0 €
Feeder: Gen. ship 3	184,150 €	184,150 €	0 €

5.4.4.3 C3 – On-deck container stack cooling/containment system

RCO C3 has been assessed based on a quote per lashing bridge price of 44,640 € for a twin island vessel. For single island vessels, 31,248 € and 26,784 € for the feeder vessel. The total amount of lashing bridges with containers or structure on either side per vessel category formed the basis for estimating the initial investment. Maintenance, operations, and service is estimated to 10% of the initial investment cost.

Table 80:C3 cost estimation.

	Retrofit	Newbuilding	Annual cost
Twin island: Gen. ship 1	1,116,000 €	1,116,000 €	11,160 €
Single island: Gen. ship 2	687,456 €	687,456 €	6,875 €
Feeder: Gen. ship 3	321,408 €	321,408 €	3,214 €

5.4.4.4 C4 – Flooding cargo hold to limited degree

A quantitative cost-effective assessment will not be completed for this RCO. The filling process requires dedicated systems, described above and in BV's Rule Notes (NR) for instance, as well as extensive calculations. However, the shipyard cooperating with this project is unfamiliar with this type of solution. It was thus not possible to make an accurate and appropriate cost assessment for vessel categories.

5.5 Results of RCO Cost Effectiveness assessment

Having determined the costs of close to all the RCOs for each vessel category, it is now possible to perform the cost-effectiveness calculations for the relevant values and metrics: GCAF, NCAF, NPV and BCR.

Table 81 shows the Cost effectiveness and fire safety impact for the Twin Island (generic ship 1). It should be noticed that cost-effectiveness of prevention RCOs as part of task 3 was determined using a different methodology compared to the rest of the RCO's.

Table 81: CEA for the Twin Island (generic ship 1). All values are in € expect BCR and ΔPLL.

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
P1	938 967 €	14 099 €	-108 591 €	0.909	1.101	1.97E-04	241.6E+6	22.1E+6
P4	0 €	7 360 €	154 273 €	2.188	0.457	5.18E-05	100.3E+6	-119.2E+6
D1	540 400 €	0 €	-136 153 €	0.748	1.337	1.10E-04	196.6E+6	49.5E+6
D1R	4 365 400 €	0 €	-3 961 153 €	0.093	10.799	1.10E-04	1.6E+9	1.4E+9
D2	458 240 €	2 500 €	1 326 521 €	3.641	0.275	3.95E-04	50.8E+6	-134.2E+6
D3	3 600 000 €	36 000 €	-3 981 711 €	0.060	16.701	1.56E-05	10.9E+9	10.2E+9
D4	363 899 €	6 560 €	-403 588 €	0.159	6.305	4.68E-06	4.1E+9	3.4E+9
D5	1 520 €	243 €	351 973 €	61.598	0.016	7.93E-05	2.9E+6	-177.6E+6
F1	500 000 €	22 500 €	-180 760 €	0.798	1.252	2.20E-04	163.0E+6	32.8E+6
F2	15 000 €	0 €	76 060 €	6.071	0.165	5.43E-06	110.5E+6	-560.5E+6
F3	15 000 €	0 €	257 633 €	18.176	0.055	1.62E-05	37.1E+6	-637.4E+6
F4	10 000 €	0 €	106 278 €	11.628	0.086	1.01E-05	39.7E+6	-421.7E+6
F4R	1 037 284 €	0 €	-921 006 €	0.112	8.921	1.01E-05	4.1E+9	3.7E+9
F5	525 000 €	22 500 €	-477 776 €	0.482	2.075	3.82E-05	964.4E+6	499.7E+6
C1	805 000 €	57 500 €	4 023 921 €	3.211	0.311	1.34E-03	54.2E+6	-119.8E+6
C2	711 200 €	0 €	4 690 006 €	7.594	0.132	1.02E-03	27.8E+6	-183.4E+6
C3	1 116 000 €	11 160 €	-893 062 €	0.320	3.127	2.62E-05	2.0E+9	1.4E+9

For most of these RCOs, there are no price differences between solutions for newbuilding vs vessels to be retrofitted. The only exception is D1 with € 4,365,000 for the retrofitted Twin Island version, however for this RCO the cheaper newbuilding solution is already too expensive compared to its effectiveness and benefits. For the Single Island RCOs, the cost effectiveness calculation results are presented in Table 82.

Table 82: CEA for the Single Island (generic ship 2). All values are in € except BCR and ΔPLL.

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
P1	391 389 €	5 877 €	-322 635 €	0.348	2.871	6.66E-05	297.3E+6	193.7E+6
P4	0 €	4 987 €	-42 601 €	0.516	1.938	1.75E-05	200.7E+6	97.1E+6
D1	225 167 €	0 €	-168 625 €	0.251	3.982	3.30E-05	272.6E+6	204.2E+6
D1R	1 818 917 €	0 €	-1 762 375 €	0.031	32.169	3.30E-05	2.2E+9	2.1E+9
D2	170 320 €	2 500 €	104 749 €	1.488	0.672	1.30E-04	65.9E+6	-32.2E+6
D3	3 300 000 €	33 000 €	-3 819 819 €	0.016	62.076	8.34E-06	18.6E+9	18.3E+9
D4	151 624 €	6 560 €	-248 614 €	0.070	14.241	2.50E-06	4.3E+9	4.0E+9
D5	1 520 €	243 €	33 563 €	6.778	0.148	1.81E-05	12.9E+6	-74.3E+6
F1	500 000 €	22 500 €	-797 039 €	0.112	8.968	6.22E-05	577.0E+6	512.7E+6
F2	15 000 €	0 €	12 265 €	1.818	0.550	3.51E-06	170.9E+6	-139.8E+6
F3	15 000 €	0 €	23 930 €	2.595	0.385	4.99E-06	120.2E+6	-191.8E+6
F4	10 000 €	0 €	24 430 €	3.443	0.290	6.59E-06	60.7E+6	-148.3E+6
F4R	490 535 €	0 €	-456 105 €	0.070	14.247	6.59E-06	3.0E+9	2.8E+9
F5	525 000 €	22 500 €	-859 981 €	0.067	14.852	1.19E-05	3.1E+9	2.9E+9
C1	735 000 €	52 500 €	-1 212 095 €	0.270	3.697	2.61E-04	254.7E+6	185.8E+6
C2	480 000 €	0 €	294 152 €	1.613	0.620	3.28E-04	58.5E+6	-35.9E+6
C3	687 456 €	6 875 €	-695 838 €	0.140	7.161	1.59E-05	2.0E+9	1.8E+9

For the feeder (generic ship 3), results are presented in Table 83.

Table 83: CEA for the Feeder (generic ship 3). All values are in € except BCR.

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
P1	184 417 €	2 769 €	-202 294 €	0.133	7.528	1.93E-05	483.8E+6	419.5E+6
P4	0 €	1 680 €	-21 477 €	0.276	3.629	5.08E-06	233.5E+6	169.1E+6
D1	106 038 €	0 €	-97 850 €	0.077	12.950	7.73E-06	548.5E+6	506.2E+6
D1R	856 588 €	0 €	-848 400 €	0.010	104.611	7.73E-06	4.4E+9	4.4E+9
D2	85 440 €	2 500 €	-76 599 €	0.409	2.446	3.03E-05	170.8E+6	101.0E+6
D3	1 800 000 €	18 000 €	-2 104 593 €	0.006	162.160	2.84E-06	29.9E+9	29.7E+9
D4	71 405 €	6 560 €	-184 489 €	0.014	69.778	5.77E-07	13.0E+9	12.8E+9
D5	1 520 €	243 €	-3 779 €	0.349	2.862	9.96E-07	233.1E+6	151.7E+6
F1	500 000 €	22 500 €	-881 905 €	0.017	59.177	1.35E-05	2.7E+9	2.6E+9
F2	15 000 €	0 €	-7 200 €	0.520	1.923	1.57E-06	382.5E+6	183.6E+6
F3	15 000 €	0 €	-3 812 €	0.746	1.341	2.23E-06	269.4E+6	68.5E+6
F4	10 000 €	0 €	-435 €	0.956	1.045	3.16E-06	126.4E+6	5.5E+6
F4R	283 916 €	0 €	-274 351 €	0.034	29.683	3.16E-06	3.6E+9	3.5E+9
F5	525 000 €	22 500 €	-904 911 €	0.019	53.755	5.67E-06	6.5E+9	6.4E+9
C1	350 000 €	25 000 €	-759 453 €	0.040	24.935	3.72E-05	850.1E+6	816.0E+6
C2	184 150 €	0 €	-95 702 €	0.480	2.082	7.38E-05	99.8E+6	51.8E+6
C3	321 408 €	3 214 €	-355 644 €	0.059	16.819	5.74E-06	2.6E+9	2.5E+9

5.6 Sensitivity analysis and uncertainty

Tables 84, 85, and 86 display the impact of variating costs (Investment and Annual) on the BCR. The goal has been to modify these costs by +/-20% and then observe a potential change in the cost-effectiveness of each solution from an economic (and not loss of life) perspective.

20% has been set arbitrarily, because it was considered as a relatively strong variation, while not unrealistic.

This sensitivity analysis on costs includes, in a way, a sensitivity on the risk reduction level. Indeed, the BCR is the ratio between the value of benefits and costs. So:

$$BCR_{high} = \frac{Benefits}{Costs \times (1 - 20\%)} = \frac{Benefits \times (1 + 25\%)}{Costs}$$

And:

$$BCR_{low} = \frac{Benefits}{Costs \times (1 + 20\%)} = \frac{Benefits \times (1 - 18\%)}{Costs}$$

Hence, +25%/-18% was deemed satisfying enough as a range of variation for a sensitivity analysis on the benefits.

In the following tables, green cells indicate non-cost-effective RCOs that could possibly become cost-effective if some costs were reduced or benefits increased. Red cells indicate cost-effective RCOs that could become non-cost-effective in the case of a cost increase or a benefit decrease.

For the Twin Island ships, as it could be expected, the solution that can potentially become cost-effective after a cost reduction is **P1**, i.e., For this RCO the base BCR was calculated already close to 1. Similar, for the feeder, **F4** can potentially become cost-effective. For the Single Island ship none of the proposed RCO's can potentially become cost-effective.

As it can be noticed, none of the tables has any cells highlighted in red: this means that all of the RCOs considered cost-effective in CARGOSAFE would remain cost-effective, even after a 20% increase in their costs. This conclusion is reassuring for the next step, as it strengthens even more the cost-effectiveness of the selected solutions. Bold text highlights the proposed RCOs.

Table 84: Impact of cost variation on BCR and cost-effective solutions for the Twin Island (generic ship 1).

		Investment Cost								
		-20%			Base			+20%		
		Annual Cost			Annual Cost			Annual Cost		
RCO	ΔBenefits	-20%	Base	+20%	-20%	Base	+20%	-20%	Base	+20%
P1	1 079 186 €	1.14	1.08	1.03	0.95	0.91	0.87	0.81	0.78	0.76
P4	284 157 €	2.73	2.19	1.82	2.73	2.19	1.82	2.73	2.19	1.82
D1	404 247 €	0.94	0.94	0.94	0.75	0.75	0.75	0.62	0.62	0.62
D1R	404 247 €	0.12	0.12	0.12	0.09	0.09	0.09	0.08	0.08	0.08
D2	1 828 879 €	4.55	4.45	4.36	3.71	3.64	3.58	3.13	3.08	3.03
D3	253 592 €	0.07	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.05
D4	76 078 €	0.20	0.19	0.18	0.17	0.16	0.15	0.14	0.14	0.13
D5	357 782 €	77.00	65.00	56.24	72.27	61.60	53.67	68.09	58.53	51.33
F1	716 304 €	1.00	0.90	0.82	0.88	0.80	0.73	0.78	0.72	0.67
F2	91 060 €	7.59	7.59	7.59	6.07	6.07	6.07	5.06	5.06	5.06
F3	272 633 €	22.72	22.72	22.72	18.18	18.18	18.18	15.15	15.15	15.15
F4	116 278 €	14.53	14.53	14.53	11.63	11.63	11.63	9.69	9.69	9.69
F4R	116 278 €	0.14	0.14	0.14	0.11	0.11	0.11	0.09	0.09	0.09
F5	444 289 €	0.60	0.54	0.50	0.53	0.48	0.44	0.47	0.43	0.40
C1	5 843 641 €	4.01	3.52	3.14	3.61	3.21	2.89	3.29	2.95	2.68
C2	5 401 206 €	9.49	9.49	9.49	7.59	7.59	7.59	6.33	6.33	6.33
C3	419 882 €	0.40	0.39	0.37	0.33	0.32	0.31	0.28	0.27	0.27

Table 85: Impact of cost variation on BCR and cost-effective solutions for the Single Island (generic ship 2).

		Investment Cost								
		-20%			Base			+20%		
		Annual Cost			Annual Cost			Annual Cost		
RCO	**ΔBenefits**	-20%	Base	+20%	-20%	Base	+20%	-20%	Base	+20%
P1	172 467 €	0.435	0.414	0.394	0.364	0.348	0.334	0.312	0.301	0.290
P4	45 407 €	0.645	0.516	0.430	0.645	0.516	0.430	0.645	0.516	0.430
D1	56 542 €	0.314	0.314	0.314	0.251	0.251	0.251	0.209	0.209	0.209
D1R	56 542 €	0.039	0.039	0.039	0.031	0.031	0.031	0.026	0.026	0.026
D2	319 187 €	1.861	1.770	1.687	1.552	1.488	1.430	1.332	1.284	1.240
D3	62 542 €	0.020	0.019	0.019	0.017	0.016	0.016	0.014	0.014	0.013
D4	18 777 €	0.088	0.079	0.072	0.077	0.070	0.065	0.068	0.063	0.059
D5	39 371 €	8.473	7.153	6.189	7.953	6.778	5.906	7.493	6.441	5.649
F1	100 025 €	0.139	0.125	0.114	0.122	0.112	0.102	0.109	0.100	0.093
F2	27 265 €	2.272	2.272	2.272	1.818	1.818	1.818	1.515	1.515	1.515
F3	38 930 €	3.244	3.244	3.244	2.595	2.595	2.595	2.163	2.163	2.163
F4	34 430 €	4.304	4.304	4.304	3.443	3.443	3.443	2.869	2.869	2.869
F4R	34 430 €	0.088	0.088	0.088	0.070	0.070	0.070	0.058	0.058	0.058
F5	62 083 €	0.084	0.076	0.069	0.074	0.067	0.062	0.066	0.060	0.056
C1	449 389 €	0.338	0.297	0.264	0.304	0.270	0.243	0.277	0.248	0.225
C2	774 152 €	2.016	2.016	2.016	1.613	1.613	1.613	1.344	1.344	1.344
C3	112 943 €	0.175	0.168	0.162	0.144	0.140	0.136	0.122	0.119	0.116

Table 86: Impact of cost variation on BCR and cost-effective solutions for the Feeder (generic ship 3).

		Investment Cost								
		-20%			Base			+20%		
		Annual Cost			Annual Cost			Annual Cost		
RCO	**ΔBenefits**	-20%	Base	+20%	-20%	Base	+20%	-20%	Base	+20%
P1	30 989 €	0.166	0.158	0.150	0.139	0.133	0.127	0.119	0.115	0.111
P4	8 171 €	0.344	0.276	0.230	0.344	0.276	0.230	0.344	0.276	0.230
D1	8 188 €	0.097	0.097	0.097	0.077	0.077	0.077	0.064	0.064	0.064
D1R	8 188 €	0.012	0.012	0.012	0.010	0.010	0.010	0.008	0.008	0.008
D2	52 960 €	0.511	0.471	0.437	0.439	0.409	0.383	0.384	0.361	0.341
D3	13 059 €	0.008	0.007	0.007	0.006	0.006	0.006	0.005	0.005	0.005
D4	2 682 €	0.018	0.016	0.014	0.016	0.014	0.013	0.015	0.013	0.012
D5	2 029 €	0.437	0.369	0.319	0.410	0.349	0.304	0.386	0.332	0.291
F1	15 159 €	0.021	0.019	0.017	0.019	0.017	0.016	0.017	0.015	0.014
F2	7 800 €	0.650	0.650	0.650	0.520	0.520	0.520	0.433	0.433	0.433
F3	11 188 €	0.932	0.932	0.932	0.746	0.746	0.746	0.622	0.622	0.622
F4	9 565 €	1.196	1.196	1.196	0.956	0.956	0.956	0.797	0.797	0.797
F4R	9 565 €	0.042	0.042	0.042	0.034	0.034	0.034	0.028	0.028	0.028
F5	17 153 €	0.023	0.021	0.019	0.020	0.019	0.017	0.018	0.017	0.016
C1	31 730 €	0.050	0.044	0.039	0.045	0.040	0.036	0.041	0.037	0.033
C2	88 448 €	0.600	0.600	0.600	0.480	0.480	0.480	0.400	0.400	0.400
C3	22 483 €	0.074	0.072	0.069	0.061	0.059	0.058	0.052	0.051	0.050

6. RECOMMENDATIONS FOR DECISION-MAKING

Table 87 compiles the RCOs that were evaluated during the cost-effectiveness assessment.

Table 87: Compilation evaluated RCOs.

Layer of protection	RCO ID	Name	OD/BD
Prevention	P1	Container screening tool	OD/BD
	P4	Improved control of lashing	OD
Detection	D1	Optimizing current system	BD
	D2	Heat detection looking at individual container temperature rise	OD/DB
	D3	Fixed IR cameras. Coupled to a software solution to automate detection	OD
	D4	CCTV - AI - smoke detection	OD
	D5	Portable IR cameras for crew to enhance manual detection	OD/BD
Firefighting	F1	Increasing effectiveness of current CO_2 system	BD
	F2	Improved manual firefighting tools for individual container breaching and firefighting	OD
	F3	Manual firefighting tools that increase reach	OD
	F4	Methods for unmanned fire fighting	OD
	F5	Water mist turbine	OD
Containment	C1	Active protection underneath hatch covers to protect from fire spread towards the deck	BD
	C2	Passive protection to protect from fire spread towards the deck	BD
	C3	On-deck container stack cooling/ containment system	OD
	C4	Flooding cargo hold to limited degree	BD

Below are tables sorted in highest to lowest according to BCR. RCOs highlighted in green have a BCR exceeding 1. Indeed, strictly speaking, an RCO is cost-effective only if its BCR is above 1. Although, due to uncertainties in the values used in the costs (see sensitivity analysis above), it was decided to also keep RCOs which BCR was close to 1, to avoid disregarding potentially cost effective RCOs. These ones, spotted during the sensitivity analysis, are highlighted in yellow.

The sensitivity analysis showed that the RCOs identified as cost-effective remain cost effective even if their price will be significantly increased.

RCOs in bold are in the top two of their layers of protection. RCOs ending in an “R” are referring to the retrofitted version of the RCO with a different cost estimation.

6.1 Feeder (Generic ship 3)

Table 88 shows result for the Feeder. Bold text highlights the proposed RCOs.

Table 88: BCR-sorted RCOs for the Feeder (generic ship 3).

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
F4	10 000 €	0 €	-435 €	0.956	1.045	3.16E-06	126.4E+6	5.5E+6
F3	15 000 €	0 €	-3 812 €	0.746	1.341	2.23E-06	269.4E+6	68.5E+6
F2	15 000 €	0 €	-7 200 €	0.520	1.923	1.57E-06	382.5E+6	183.6E+6
C2	184 150 €	0 €	-95 702 €	0.480	2.082	7.38E-05	99.8E+6	51.8E+6
D2	85 440 €	2 500 €	-76 599 €	0.409	2.446	3.03E-05	170.8E+6	101.0E+6
D5	1 520 €	243 €	-3 779 €	0.349	2.862	9.96E-07	233.1E+6	151.7E+6
P4	0 €	1 680 €	-21 477 €	0.276	3.629	5.08E-06	233.5E+6	169.1E+6
P1	184 417 €	2 769 €	-202 294 €	0.133	7.528	1.93E-05	483.8E+6	419.5E+6
D1	106 038 €	0 €	-97 850 €	0.077	12.950	7.73E-06	548.5E+6	506.2E+6
C3	321 408 €	3 214 €	-355 644 €	0.059	16.819	5.74E-06	2.6E+9	2.5E+9
C1	350 000 €	25 000 €	-759 453 €	0.040	24.935	3.72E-05	850.1E+6	816.0E+6
F4R	283 916 €	0 €	-274 351 €	0.034	29.683	3.16E-06	3.6E+9	3.5E+9
F5	525 000 €	22 500 €	-904 911 €	0.019	53.755	5.67E-06	6.5E+9	6.4E+9
F1	500 000 €	22 500 €	-881 905 €	0.017	59.177	1.35E-05	2.7E+9	2.6E+9
D4	71 405 €	6 560 €	-184 489 €	0.014	69.778	5.77E-07	13.0E+9	12.8E+9
D1R	856 588 €	0 €	-848 400 €	0.010	104.611	7.73E-06	4.4E+9	4.4E+9
D3	1 800 000 €	18 000 €	-2 104 593 €	0.006	162.160	2.84E-06	29.9E+9	29.7E+9

Analysis of the results of Table 88 makes it possible to draw the following conclusions for the Feeder (generic ship 3) regarding cost-effectiveness of the RCOs:

- None of the RCOs is attractive from a GCAF perspective as they do not meet the CAF criterion of 8.7M €.
- From a NCAF perspective, F4 (5.5M €) is attractive as it meets the CAF criterion of 8.7M €.
- From an NPV and BCR perspective only F4 is close with an NPV of -435 € and BCR of 0.956. However, D5 is also near to be positive with an NPV of –3779 € and BCR of 0.349. Same as F3 with an NPV of -3812 € and BCR of 0.746.
- From Table 88 it should be observed that F4 becomes much less attractive for the retrofitting scenario where NPV and BCR falls to –274.352 € and the BCR to 0.034.

For the Feeder (generic ship 3) the cost effective RCO is **F4, for new build vessels** and optionally **D5** and **F3** can be recommended for further implementation taking both loss of life and economic aspects into consideration.

6.2 Single Island (Generic ship 2)

Table 89 shows result for the Single Island (generic ship 2). Bold text highlights the proposed RCOs.

Table 89: BCR-sorted RCOs for the Single Island (generic ship 2).

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
D5	1 520 €	243 €	33 563 €	6.778	0.148	1.81E-05	12.9E+6	-74.3E+6
F4	10 000 €	0 €	24 430 €	3.443	0.290	6.59E-06	60.7E+6	-148.3E+6
F3	15 000 €	0 €	23 930 €	2.595	0.385	4.99E-06	120.2E+6	-191.8E+6
F2	15 000 €	0 €	12 265 €	1.818	0.550	3.51E-06	170.9E+6	-139.8E+6
C2	480 000 €	0 €	294 152 €	1.613	0.620	3.28E-04	58.5E+6	-35.9E+6
D2	170 320 €	2 500 €	104 749 €	1.488	0.672	1.30E-04	65.9E+6	-32.2E+6
P4	0 €	4 987 €	-42 601 €	0.516	1.938	1.75E-05	200.7E+6	97.1E+6
P1	391 389 €	5 877 €	-322 635 €	0.348	2.871	6.66E-05	297.3E+6	193.7E+6
C1	735 000 €	52 500 €	-1 212 095 €	0.270	3.697	2.61E-04	254.7E+6	185.8E+6
D1	225 167 €	0 €	-168 625 €	0.251	3.982	3.30E-05	272.6E+6	204.2E+6
C3	687 456 €	6 875 €	-695 838 €	0.140	7.161	1.59E-05	2.0E+9	1.8E+9
F1	500 000 €	22 500 €	-797 039 €	0.112	8.968	6.22E-05	577.0E+6	512.7E+6
D4	151 624 €	6 560 €	-248 614 €	0.070	14.241	2.50E-06	4.3E+9	4.0E+9
F4R	490 535 €	0 €	-456 105 €	0.070	14.247	6.59E-06	3.0E+9	2.8E+9
F5	525 000 €	22 500 €	-859 981 €	0.067	14.852	1.19E-05	3.1E+9	2.9E+9
D1R	1 818 917 €	0 €	-1 762 375 €	0.031	32.169	3.30E-05	2.2E+9	2.1E+9
D3	3 300 000 €	33 000 €	-3 819 819 €	0.016	62.076	8.34E-06	18.6E+9	18.3E+9

Analysis of the results of Table 89 makes it possible to draw the following conclusions for the Single Island (generic ship 2) regarding cost-effectiveness of the RCOs:

- None of the RCOs are attractive from a GCAF perspective as they do not meet the CAF criterion of 8.7M € though D5 comes close with a GCAF value of 12.9M €.
- From a NCAF perspective F3, D5, F2, F4, C2, D2 are all very negative (between -32.2 M € and –148.3M €) indicating either a large economic benefit, or a small risk reduction.
- From an NPV and BCR perspective, D5, F4, F3, F2, D2, C2 (in ranked order) are positive with NPV results between 12,265 and 294,152 € and BCR values at between 1.49 and 6.78.
- From Table 89 it can be observed that F4 becomes less attractive for the retrofitting scenario where NPV and BCR reduce to –456.105 € and 0.

For the Single Island (generic ship 2), from an economic perspective, 6 RCOs being **D5, F4 (only new building), F3, F2, D2, C2** (in ranked order) are very attractive and should also be considered as recommendable for implementation.

6.3 Twin Island (Generic ship 1)

Table 90 shows result for the Twin Island (generic ship 1). Bold text highlights the proposed RCOs.

Table 90: BCR-sorted RCOs for the Twin Island (generic ship 1).

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
D5	1 520 €	243 €	351 973 €	61.598	0.016	7.93E-05	2.9E+6	-177.6E+6
F3	15 000 €	0 €	257 633 €	18.176	0.055	1.62E-05	37.1E+6	-637.4E+6
F4	10 000 €	0 €	106 278 €	11.628	0.086	1.01E-05	39.7E+6	-421.7E+6
C2	711 200 €	0 €	4 690 006 €	7.594	0.132	1.02E-03	27.8E+6	-183.4E+6
F2	15 000 €	0 €	76 060 €	6.071	0.165	5.43E-06	110.5E+6	-560.5E+6
D2	458 240 €	2 500 €	1 326 521 €	3.641	0.275	3.95E-04	50.8E+6	-134.2E+6
C1	805 000 €	57 500 €	4 023 921 €	3.211	0.311	1.34E-03	54.2E+6	-119.8E+6
P4	0 €	7 360 €	154 273 €	2.188	0.457	5.18E-05	100.3E+6	-119.2E+6
P1	938 967 €	14 099 €	-108 591 €	0.909	1.101	1.97E-04	241.6E+6	22.1E+6
F1	500 000 €	22 500 €	-180 760 €	0.798	1.252	2.20E-04	163.0E+6	32.8E+6
D1	540 400 €	0 €	-136 153 €	0.748	1.337	1.10E-04	196.6E+6	49.5E+6
F5	525 000 €	22 500 €	-477 776 €	0.482	2.075	3.82E-05	964.4E+6	499.7E+6
C3	1 116 000 €	11 160 €	-893 062 €	0.320	3.127	2.62E-05	2.0E+9	1.4E+9
D4	363 899 €	6 560 €	-403 588 €	0.159	6.305	4.68E-06	4.1E+9	3.4E+9
F4R	1 037 284 €	0 €	-921 006 €	0.112	8.921	1.01E-05	4.1E+9	3.7E+9
D1R	4 365 400 €	0 €	-3 961 153 €	0.093	10.799	1.10E-04	1.6E+9	1.4E+9
D3	3 600 000 €	36 000 €	-3 981 711 €	0.060	16.701	1.56E-05	10.9E+9	10.2E+9

Analysis of the results of Table 90 makes it possible to draw the following conclusions for the Twin Island (generic ship 1) regarding cost-effectiveness of the RCOs:

- Only one of the RCOs, D5 is attractive from a GCAF perspective as it within a value of 2.9M € meets the CAF criterion of 8.7M € and no others are in the proximity of the criterion.
- From a NCAF perspective, D5, F3, F4, C2, F2, D2, C1 and P4, are all negative (between –119.2M € and –637.4M €) indicating that either for those eight RCOs the economic benefits are likely higher than the required investment and running costs. , For eight RCO's, the high positive values could be explained as having limited impact on fatality and PLL.
- From an NPV and BCR perspective, D5, F3, F4, C2, F2, D2, C1 and P4 are positive with NPV between 76.060 and 4.690.006 € and BCR values between 2.19 and 61.6. The BCR is close to be positive for P1. However, the NPV value is still far from becoming positive.
- From Table 90 it can be observed that F4 becomes less attractive for the retrofitting scenario where NPV and BCR reduces to –921.006 € and 0.11 respectively.

For the Twin Island (generic ship 1), for a purely loss of life perspective only **D5** can be recommended for further implementation. However, from an economic perspective eight other RCOs being **D5, F4 (only new building), F3, C2, F2, D2, C1 and P4** (ranked order) are very attractive and should be considered as recommendable for implementation.

6.4 Final conclusions and summary

When reviewing the task 4 results for the three vessel types that were considered in this study, and taking into account the results of task 2 and 3 the following conclusions can be drawn:

The cost-effectiveness for the proposed RCOs increases with ship size.

Only one RCO (D5: Portable IR cameras for manual detection) can be recommended from a GCAF / Loss of life perspective. For the Twin Island, the CAF criterion is fulfilled since it is below 8.7M €m, and for the two other types of ships, it has if not the lowest a low GCAF compared with the other RCOs.

Multiple RCOs can be recommend from an economic perspective considering NCAF, NPV and BCR calculations. F4 (Methods for unmanned firefighting) is the only RCO which is cost effective across all 3 vessel types, but only for the new buildings. D5 (Portable IR cameras for manual detection) and F3 (Manual firefighting tools that increase reach) is cost effective for all 3 vessel types, though less for Feeder compared to the other vessel types. D2 (Heat Detection), F2 (Improved manual firefighting tools for individual container breaching and firefighting) and C2 (Passive protection to prevent fire spread towards the deck) are cost effective for the Single and the Twin Island. Finally, P4 (Improved control of lashings) and C1 (Active protection underneath hatch covers to protect fire spread towards the deck) have some visible economic potential for particularly the Twin Island.

Table 91 summarizes these last points by displaying the cost-effectiveness of all assessed solutions for the three generic ships, once again based on BCR.

Table 91: Summary of cost-effectiveness of all RCOs for the 3 generic ships

RCO ID	Description	Twin Island	Single Island	Feeder
P1	Container screening tool	Maybe	No	No
P4	Improved control of lashing	Yes	No	No
D1	Optimizing current smoke detection system	No	No	No
D1R	Optimizing current smoke detection system (retrofitting)	No	No	No
D2	Heat detection looking at individual container temperature rise	Yes	Yes	No
D3	Fixed IR cameras. Coupled to a software solution to automate detection	No	No	No
D4	CCTV - AI - smoke detection	No	No	No
D5	Portable IR cameras for crew to enhance manual detection	Yes	Yes	No
F1	Increasing effectiveness of current CO2 system	No	No	No
F2	Improved manual firefighting tools for individual container breaching and firefighting	Yes	Yes	No
F3	Manual firefighting tools that increase reach	Yes	Yes	No
F4	Methods for unmanned fire fighting	Yes	Yes	Maybe
F4R	Methods for unmanned firefighting (retrofitting)	No	No	No
F5	Watermist canon	No	No	No

C1	Active protection underneath hatch covers to protect from fire spread towards the deck	Yes	No	No
C2	Passive protection to protect from fire spread towards the deck	Yes	Yes	No
C3	Fixed external container stack cooling system to stop spread between stacks	No	No	No

Benefits from reduction of cargo loss and ship loss account for the biggest part in the global benefits used in the computations (NCAF, NPV, BCR). However, salvage and environmental costs also have a significant impact on the results, albeit it does not change substantially the ranking. The results of the CEA without salvage and environmental costs can be found in Annex Q.

All the above mentioned RCOs consist of technologies that are at TRL 6 to 9. Therefore, at least pilot solutions had been demonstrated on relevant operational environments. There is therefore little risk with respect to the technological robustness of the proposed RCOs.
The CARGOSAFE study would recommend finishing a full CEA for the RCO combinations ranked with high interdependency as any of these combinations have a higher risk reduction than any single RCO by itself. The study supplies risk-reduction for all combinations, however the combined CEA is out of scope.
If recommendations should be provided across the three vessel types / sizes for two RCOs for each of the four fire protection layers, then Table 89 summarizes these. However, since there are major differences across the 3 ship sizes, CARGOSAFE recommends RCOs to be decided based on ship size criteria.

Table 92: RCO recommendations across all 3 ship sizes per layer of protection.

Fire Mitigation Phase	Prevention	Detection	Firefighting	Containment
1st RCO Priority	P4 (TRL7)	D5 (TRL9)	F4* (TRL8)	C2 (TRL8)
2nd RCO Priority	P1 (TRL6)	D2 (TRL9)	F3 (TRL9)	C1 (TRL9)

Appendix A List of Annexes

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Annex C	Terminology
Annex D	Prevention Fault Trees (FTs)
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Annex M	Risk Reduction Potential
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Annex P	Combined RCO's Risk Reduction
Annex Q	CEA Results without environment and salvage cost
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