European Maritime Safety Agency

CARGOSAFE EXECUTIVE SUMMARY

2021/EMSA/OP/17/2021

Date: 14 March 2023

EMSA

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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. TITLE

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

2. SUMMARY

2.1 Executive Summary

The CARGOSAFE study examines the risks associated with fires on container ships and evaluates measures to control these risks in terms of prevention, detection, firefighting, and containment. CARGOSAFE follows the Formal Safety Assessment (FSA) structure for use in IMO rule-making process. A dedicated risk model has been developed to assess the risks for the loss of life, cargo, ship, environment, and salvage. Finally, the study presents the results of a cost-effectiveness assessment (CEA) of the identified Risk Control Options (RCOs) for three generic ship types (feeder, twin island, single island) in both new building and retrofit scenarios.

2.2 Actions to be taken

The type of action requested is a review of the FSA, particularly the RCOs that were found to be cost- efficient and listed in section 7. The full CARGOSAFE report is linked below in section 2.3.

2.3 Related documents

The full report, including its annexes, can be downloaded from EMSA's website.

3. DEFINITION OF THE PROBLEM

3.1 Definition of the problem

The study aims at identifying cost-effective RCOs for cargo fires onboard containerships. Fires on containerships, in particular originating in containers, have gained increasing visibility in the last five years, even though cargo fires are already a known characteristic accident occurrence for such ship types. The increased attention to cargo fire accidents is 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 two years.

Previous fire accidents onboard can be attributed to the cargoes carried, their misdeclaration or non- declaration of dangerous goods, the technical design and specifications for containerships, the compact pattern of container stowage in containerships and the old and sometimes inadequate technical provisions for fire detection, fire location and firefighting on deck. This situation persists despite the amendments to SOLAS regulation II-2/10 in 2014 (resolution MSC.365(93)), where the additional equipment of containerships with mobile water monitors and at least one water mist lance was made mandatory for new buildings from 1 January 2016 onward.

3.2 Reference to the regulation(s) affected by the proposal to be reviewed or developed

The following regulations in SOLAS and associated codes would be affected by the proposals as attached in this submission:

- SOLAS Chapter II-2 Construction – Fire Protection, Fire Detection and Fire Extinguishing.
- SOLAS Chapter VI Carriage of Cargoes and Oil fuels.

3.3 Definition of the generic model

The study has encompassed both newbuilds and existing containerships. Moreover, it focuses on three generic vessel types: a 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 considered occurred between 1997 and 2021.

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

- Ships designated as "containerships". This includes the three following StatCodes from IHS StatcCode5: A33A2CC (Container Ship (Fully Cellular)); A33B2CP (Container Ship (Fully Cellular/Passenger ship) and A33A2CR (Container Ship (Fully Cellular/Ro-Ro Facility)).
- Gross Tonnage above 500GT.
- Built after 1980.
- No requirement on the classification by an IACS society.

Initially, the CARGOSAFE 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.

From the available databases analysed the sub-categories of containerships (i.e., "ULCS", "Post-Panamax") were not included. Thus, a polynomial relation between each containership's sub-category and the particulars (such as gross tonnage, length, and cargo capacity) was developed based on an IHS 2019 database, which included these sub-categories. This polynomial relation formula was then applied to ships in the CARGOSAFE fleet.

The three final categories and their respective representing generic ship are defined as follow:

1. Generic Ship 1, representing Twin Island ULCS/VLCS

   Thanks to the method described above, the ULCS/VLCS category were inferred in the CARGOSAFE database. To split the "Twin Island" from the "Single Island", a simple criterion based on the length was found by analysing pictures of ships. This analysis showed that ULCS with a length overall (LOA) between 334m and 364m are single island ships, while above 364m, they are twin island ships.

2. Generic Ship 2, representing 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 category's characteristics than if they had been studied amongst the smaller ships.

3. Generic Ship 3, representing Feeder with aft bay / 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, feeders with open cargo hold only accounted for less than 1% of the fleet. Thus, categories 3 and 4 (Feeder with aft bay and Feeder with no aft bay and open cargo hold) were included in the last category, which contains ships not belonging to categories 1 and 2.

4. BACKGROUND INFORMATION

4.1 Lessons learned from recently introduced measures to address similar problems

- FSA – Container fire on deck, Review of fire protection requirements for on-deck cargo areas, Details of the Formal Safety Assessment, Submitted by Germany, IMO FP54/INF.2, 2009
- FSA – Container vessels, Details of the Formal Safety Assessment, Submitted by Denmark, MSC 83/INF.8, 2007
- FSA – Container vessels, Details of the Formal Safety Assessment, IMO, MSC 83/INF.8, 2007
- Technical University of Denmark (DTU), Container ships: fire-related risks, Journal of Marine Engineering and Technology, 2021

4.2 Casualty statistics concerning the problem under consideration, including data analysis

The casualties considered in the CARGOSAFE study are cargo fires on containerships. Information sources used in this risk analysis were:

- data provided by EMSA:
- database from IHS MARINFO, describing casualties that happened on or after 2009 for containerships;
- database from LMIU ex-MARINFO, describing casualties that happened between 1997 and 2016 for containerships; and
- database from EMCIP, describing casualties that happened on or after 2011 for containerships.
- database owned by BV (IHS2019);
- accident reports; and
- websites.

Figure 1 displays the evolution of shipyears and fleet capacity amongst the CARGOSAFE fleet over the years, from 1997 to 2018. The most noticeable element is the stronger rate of increase for the capacity than for the number of ships. This is explained by the fact that bigger ships tend to join the fleet along the years. In total, since 1997, 124 accidents were deemed relevant for the CARGOSAFE study.

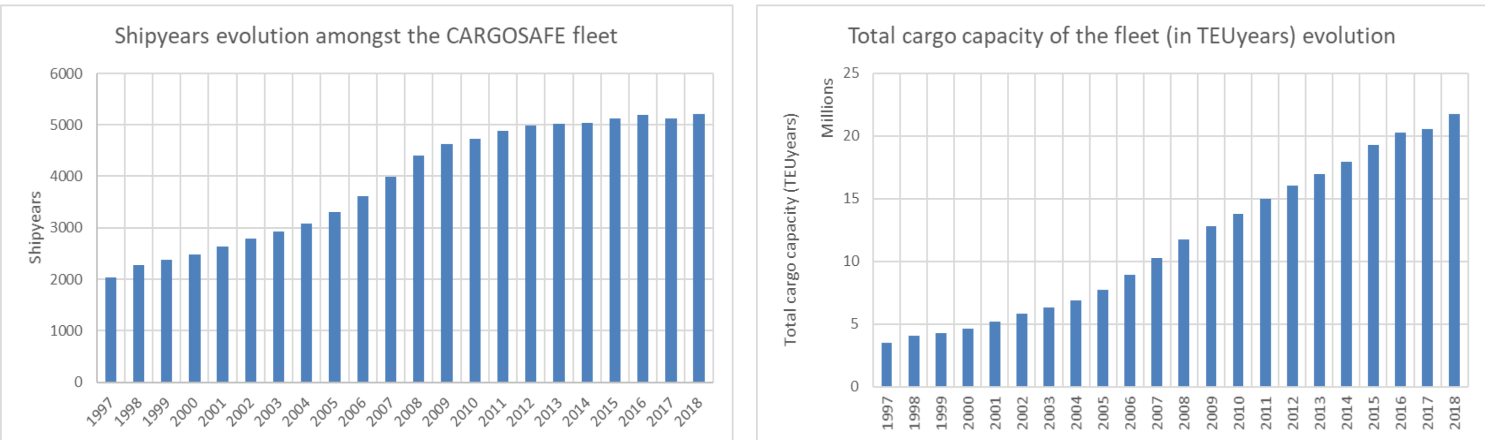


Figure 1:Evolution of shipyears and cargo capacity in (TEUyears) amongst the CARGOSAFE fleet along the years

Figure 2 displays the evolution of fire count, and Figure 3 displays the fire frequency, both per shipyear and TEUyear. 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. Further data are reported under section 6 at step 2 risk analysis.

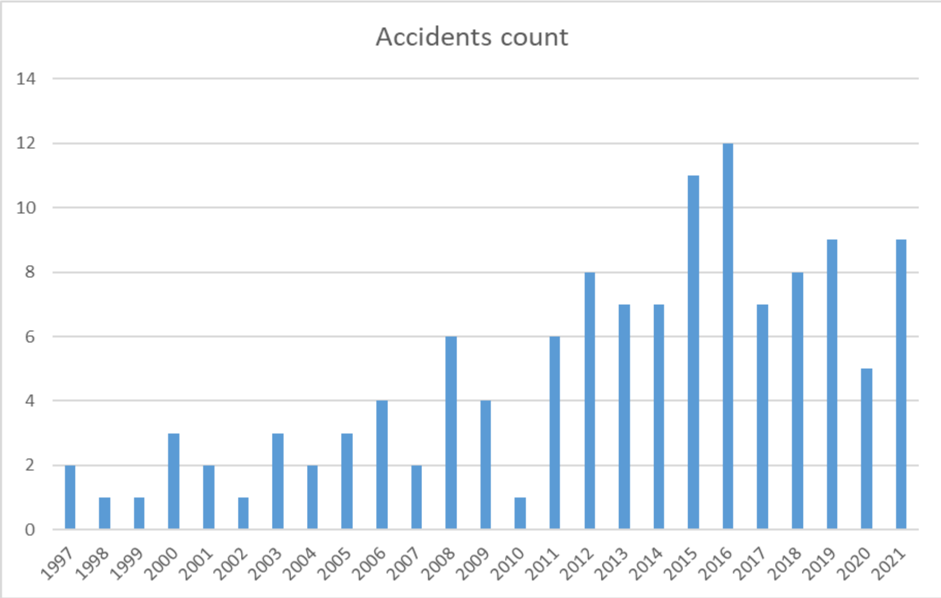
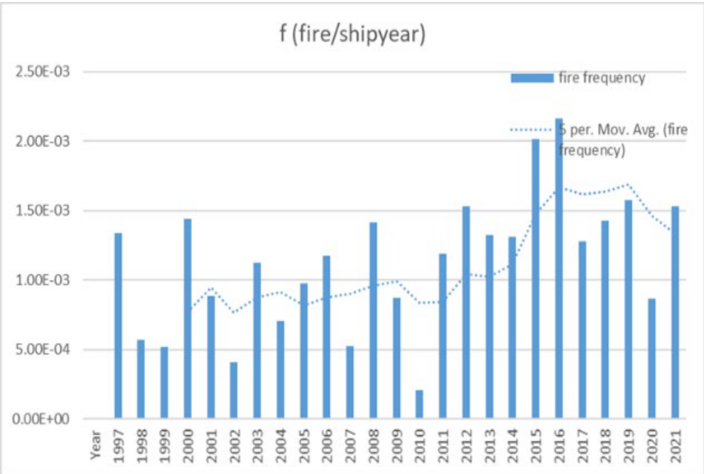


Figure 2:Fire (in cargo) count from 1997 to 2021.



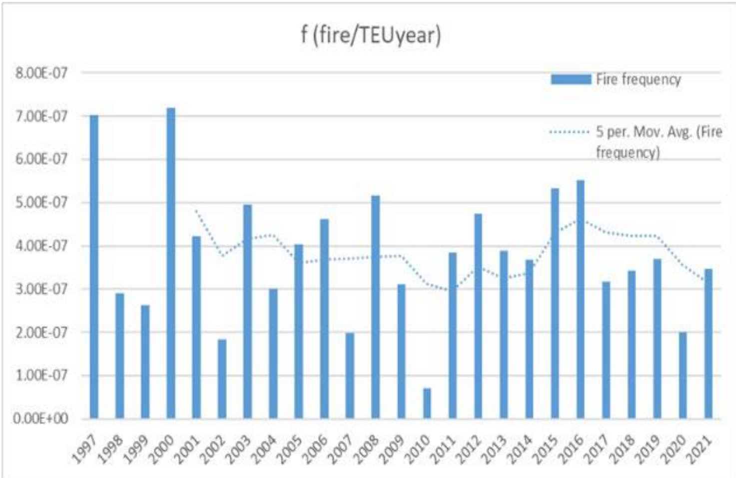


Figure 3:Fire (in cargo) frequency (in f/SY and f/TEUY) from 1997 to 2021

4.3 Any other sources of data and relevant limitations

Based on the IHS database provided by EMSA, 7677 ships were considered relevant for the study. IMO GISIS database has been used to double-check no relevant accident was left behind.

5. METHOD OF WORK

5.1 Composition and expertise of those having performed each step of the FSA process by providing and contact point of the coordinator of the FSA

The CARGOSAFE group consists of members from The Danish Institute of Fire and Security Technology – DBI (fire and security institute), Bureau Veritas Marine and Offshore – BV (class society), Research Institutes of Sweden – RISE (research institute with fire test laboratories), University of Southern Denmark – SDU (university), and Odense Maritime Technology – OMT (maritime consulting firm). Following is presented the core team involved in the FSA process. Several other individuals have partaken in and supported various steps during the study.

Table 1:CARGOSAFE group

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

For a more detailed description of the FSA team's backgrounds- and experience cf. Annex 4

5.2 Description of how the assessment has been conducted in terms of organization of working groups and, method of decision-making in the group(s) that performed each step of the FSA process

For the first step, the CARGOSAFE consortium conducted four Hazard Identification (HAZID) workshops to identify fire scenarios within the detection, containment, firefighting, and prevention layers. The four workshops were held online. Before the workshops, guide-work with a preliminary list of general assumptions was developed, and relevant background information (relevant ships, technological systems, statistical data, accident categories, dangerous goods classes, safety considerations, type of fires, as well as applicable regulations and codes) was provided to ensure alignment of knowledge among the participants. The workshops were developed and executed according to the Failure Mode and Effects Analysis (FMEA) procedure, which analyses the functions of hardware or humans and identifies failure modes and their effects. Pre-identified functional methods were selected for each fire protection layer, and a list of desired functions, affecting conditions, and failure modes and effects were identified collectively by the participants.

The online tool MIRO was used as an online whiteboard to facilitate the HAZID workshops. The whiteboards listed the pre-identified functional methods in question, and the participants were given time to reflect and respond to each theme on the whiteboard. The opinions and reflections were noted on a virtual sticky note and added to the board. In addition, at the end of each workshop participants discussed potential safety measures or RCMs. After each session, the sticky notes were reviewed by the moderators and DBI, and the data was imported into the premade FMEA spreadsheets. The responsible party for the workshop reviewed and supplemented the data with additional expertise, and the CARGOSAFE consortium reviewed all the sheets and information to ensure their correctness. Finally, the FMEA sheets were reviewed by the technical expert group (TEG)[1] and few amendments and additions were made. The final sheets can be found in cf. Annex 1.

The second step was the risk assessment. The FSA Guidelines 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). A fault tree is a logic diagram showing the causal relationship between events which individually or in combination occur to cause the occurrence of higher-level events. An ET is a logic diagram used to analyze the effects of an accident, a failure, or an unintended event. Thus, combining these results in the structure of the global risk model for CARGOSAFE, see Figure 4.

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. The prevention side of the risk model lies towards the left, which captures the causal relationships using the FTs. In the middle is the unwanted hazardous event (UHE), and towards the right is the onboard firefighting ETs (detection, containment, and firefighting) and the consequence model tree (assistance, damage, and evacuation).

The prevention FTs were developed based on the outcome of the hazard identification (HAZID) workshop dedicated

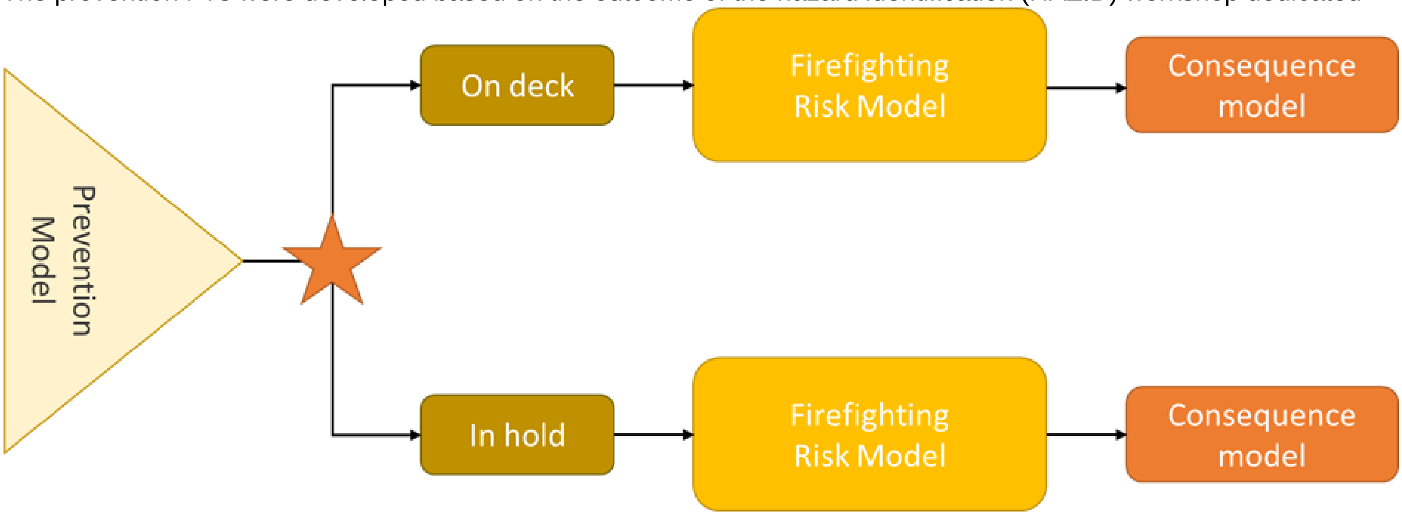


Figure 4:Basic structure of the global risk model in CARGOSAFE Step 2 Risk Analysis

to prevention. The fault trees are developed to capture the various failure pathways that can cause the UHE. Thus, the bottom nodes in FTs are used as tracing techniques to show how certain failures might occur leading to the top event.

The firefighting and consequence ET were quantified based on the CARGOSAFE database information. This information was also used to quantify the consequence of each of the scenarios. The severity of the losses was evaluated for potential loss of life, cargo, ship, environment, and salvage cost.

The third step was the proposal and evaluation of the RCOs. The process of selecting RCOs for analysis was achieved in several stages, as provided in the FSA methodology. In the first stage, the summary from the HAZID workshops was used. In the second stage, this summary was used to arrive at a list of potential Risk Control Measures combined into RCOs. 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 TEG, and the engineering and scientific judgement of the project team for each of the fire protection layers

[1] 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.

(Prevention, Detection, Firefighting, and Containment) – taking into consideration the analysis of the accidents and incidents carried out in this work.

Then, the effectiveness assessment of each RCO was derived by comparing two qualitative main parameters, namely, TRL (Technological Readiness Level), and its risk reduction potential. The first one was assessed based on the availability in the current market and its limitations. While the last one was quantified using fault trees (created from the database and the HAZID), by investigation of available failure data, using fire simulations, and expert judgement, in case none of the previous options were available. Finally, a simple analysis of the combined RCOs was carried out.

The fourth step was the cost-effectiveness assessment. First, the implementation cost of each of the RCOs was defined for both new and retrofitted vessels. Most of the RCOs proposed have a high TRL. Therefore, it was possible for most of them to have an estimation of the cost directly from suppliers. In some of the cases, it was required to add the installation, operation, maintenance, redundancy, and training cost. For some of the RCOs, only the main component systems of each RCO were identified, and the respective costs were estimated (installation, training, and maintenance). Essentially, the process involved calculating all the costs that could be reasonably associated with implementing the RCOs to provide a comprehensive estimate of the expenses involved.

Using the cost estimation and the risk reduction from the previous steps, the final cost-effectiveness of each RCO was calculated. It is expressed using indices like the Gross Cost of Averting a Fatality (GCAF), Net Cost of Averting a Fatality (NCAF), Net Present Value (NPV), and Benefit-Cost Ratio (BCR). In task 4, a study also carried out a sensitivity analysis of the cost-effectiveness results.

The fifth and final step was the assessment of the decision-making recommendations. The final recommendations are based solely on the cost-effectiveness assessment, since the proposed RCOs were those with a high TRL. The final recommendations are divided into those RCOs that could be implemented from the GCAF / Loss of life perspective, and those implemented from an economic perspective considering NCAF, NPV, and BCR calculation results. Finally, the recommendations were tailored for each of the generic ship types.

5.3 Start and finish date of the assessment

In December 2021, EMSA started the CARGOSAFE safety study to investigate the cost-efficient measures for reducing the risk from cargo fires in container vessels. Finish date: February 2023.

6. DESCRIPTION OF THE RESULTS ACHIEVED IN EACH STEP

- **STEP 1 – HAZARD IDENTIFICATION**

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 first HAZID was on detection, which pointed out detection in the cargo hold as fully reliant on the sample extraction smoke detection systems, since crew seldom go into the hold and fire patrols do not cover the holds. For on deck detection, it is reliant on visual identification by 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), and 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 explosions. All these loss of containment risks could be identified from the level of a single container up to the level of an entire hold or bay.

The third HAZID on firefighting looked at the use of CO_2 in the cargo holds and the limited amount carried onboard. In addition, the performance of the CO_2 system, also its extinguishment performance mainly depending on the cargo holds' air tightness and the CO_2's ability to penetrate the individual container units was highlighted. Furthermore, the maintenance of CO_2 system remains challenging, and crew the training is considered important for successfully extinguishing a fire inside a cargo hold. Local fire extinguishing in the container unit is limited and highly dependent on early detection, which is lacking when the current detection methods are used since they cannot support all possible scenarios. Location of the container is a critical parameter for local fire extinguishing, as access to the unit is critical. 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 a solution that was explored since this can theoretically applied in some cases; when the ship was designed to accommodate possible flooding scenarios, considering; water flow rates, adequate stability, and structural verification. However, flooding of a cargo hold may create mixing cargo that could result in additional hazards, and the methodology was considered not appropriate as a firefighting solution.

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 cargo declaration- or misdeclaration, were considered the main cause of the faults and errors occurring in cargo preparation. Issues related to differences in required frequency of shore-based cargo inspections were a concern, as well as lack of screening tools and information exchange between parties.

The prioritization by risk level was done quantitatively at the end of Step 2. It was plotted using the frequency of a fire per shipyear, obtained from the database. The consequence of the incidents is reported as Euro Loss.

- **STEP 2 – RISK ANALYSIS**

As discussed in HAZID workshops with the TEG, and in correspondence to the findings on the previous step, the high-risk areas which need to be addressed according with each protection layer are:

- Prevention: reduce the fire occurrence, particularly in relation to the misdeclaration/undeclaration or dangerous cargo.
- Detection: detected sufficiently early to try a local extinguishment by crew or release a first shot of extinguishing agent.
- Firefighting: extinguishing or at least control the fire in the hold of origin for a long period of time.
- Containment: control the fire at the bay of origin or the bay above the hold of origin.

The objective of the CARGOSAFE study is to reduce the risk of fire in containerships' cargo. This risk reduction shall be based on RCOs. An evaluation of each of these solutions will be performed in Step 4, to assess their possible cost-effectiveness. Hence, the goal of Step 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 adequate risk models and risk quantification, 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.

To address these challenges, the following actions were taken:

- Review of several previous studies available addressing containerships, of several types of risk models and selection of a relevant type of risk model.
- Development of the risk model structure and the selection of the most relevant tiers of a fire development.
- Collection of data from EMSA, gathering information about the fleet characteristics, evolution of accident frequencies, etc.
- Post-processing the collected data to develop an accurate risk model.
- Complement the risk model with risk quantification and consequence modelling.
- 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, the project SAFEDOR and a study proposed by DTU 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), due to its simplicity to be created and updated during the different steps of the study. The tiers of this risk model represent the different steps encountered when a fire occurs onboard. Starting from the ignition to the potential containment of the fire in the space of origin.

Based on the Prevention HAZID in Step 1, a risk model (fault trees) for prevention was developed in Step 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.

For each category of goods that ignite a fault tree was developed that shows the initiating events leading to ignition of the goods. The probabilities of ignition for the three types of goods were extracted from accident statistics. Each of the fault trees, one per good type, was quantified based on statistical analysis; if there was no information available, the quantification was obtained from an expert judgement workshop.

EMSA provided extensive data, including characteristics of the ships present in the fleet and information about the relevant accidents occurred onboard these ships during the period that was analysed, i.e., from 1997 to 2021. The data was used to characterize the fleet (i.e., number of shipyears (SY), evolution of cargo capacity, determination of a generic ship) and to collect information about accidents. 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 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.

- The data provided by EMSA were used to develop and quantify a new firefighting risk model. 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 CO2, if the crew had to evacuate).

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

PLLhist=1.45E-4 equivalent fatalities per shipyear

For the firefighting risk model two event trees (ETs) were developed: one for a cargo fire starting on deck, and one for a cargo fire starting in hold. The choice for these two ETs was guided by the differences regarding fire detection equipment, and firefighting systems and strategies between a fire starting either on deck or in hold. The tiers of the firefighting risk model represent the different steps encountered when a fire occurs onboard. From the ignition, including the potential containment of the fire in the space of origin, as well as firefighting operations such as manual firefighting or CO2 release in holds.

Finally, a consequence risk model was developed for each of the firefighting ETs. The model contains two main parts. First, it is the contribution consequence tree, where the tiers have been identified and accounted 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 was built for the consequence quantification. It accounts for the aftermath of a fire in terms of potential loss of life expressed as equivalent fatalities2; cargo loss as a percentage of the total TEU capacity; ship damage was considered qualitatively, and then assigned a percentage value for the new built ship; environmental loss assigned a values per TEU loss and ship damage; and the salvage cost was based on the ship damage.

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= 3.91E-4 equivalent fatalities per shipyear.
- PLCmedian= € 14,125 euro per shipyear.
- PLSmedian= € 3,712 euro per shipyear.
- EPLmedian= € 2,324 euro per shipyear.
- TPLmedian= € 22,762 euro per shipyear.

STEP 3 – RISK CONTROL OPTIONS

Gathering input from the HAZID workshops (Step 1), several risk control measures (RCMs) were explored for choosing the viable RCOs. The chosen RCOs were classified into ignition prevention, detection, firefighting, and 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 (Step 4).

Out of 18 RCMs, five RCOs were chosen for fire prevention, which included **container screening tools (P1),** maintaining a **database of rejected cargo (P2), planning stowage (P3**), **improvement of lashing on the deck (P4) and improvement of test methods on self-heating cargo (P5)**. The effective assessment for the majority of the RCOs aimed at fire prevention were assessed qualitative except for **P1** and **P4** that were quantitatively assessed. These two options were chosen as the most viable RCOs for prevention due to their higher TRL and the overall risk reduction potential.

Five RCOs for fire detection were further assessed in this study. They are **optimization of the current system in place (D1)**, **heat detection looking at individual container temperature rise (D2), fixed IR cameras for heat/ flame detection (D3)**, **CCTV-AI based smoke detection (D4)** and **portable IR cameras distributed among the crew (D5).**

- The performance of the current detection system was quantitively assessed using computational fluid dynamics (CFD). The long detection times calculated can be considered as an issue that needs to be further improved. 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 were considered. Implementing modifications in existing vessels was identified as a limitation.

- -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 cargo loading and unloading.

- Despite being proven to be effective in other industrial and commercial applications, using IR cameras and CCTV-AI based smoke detection were not applicable in the cargo holds due to weather effects, movement of the vessel and tight stacking of containers. 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.

Five RCOs were chosen for firefighting. They are optimization of the **CO2 extinguishing system (F1), introduction of novel firefighting tools (F2)**, **tools which increase the reach for the firefighters (F3), unmanned firefighting techniques (F4)** and **water mist turbines (F5).**

- 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.

- A handheld firefighting device which drills 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.

- 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.

- An unmanned 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 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.

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 (C1), passive fire protection on the cargo holds (C2), stack cooling techniques for firefighting on the deck (C3) and flooding the cargo hold (C4) 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. Water flow capacity, both for the spraying and the draining of the water must be consider. Moreover, the system only works for in-hold fires.

- 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.

- Water based containment solutions were investigated as on-deck cooling solutions. 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 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.

Table 2:Compilation evaluated RCOs.Table 2 compiles the RCOs that were evaluated during the cost-effectiveness assessment.

Table 2: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/BD
	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 CO2 system	BD
	F2	Improved manual firefighting tools for individual container breaching and firefighting	OD
	F3	Manual firefighting tools to 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

The risk reduction evaluation was performed using the event trees created on Step 2. A new failure probability was assumed depending on the RCO implemented. The values used are presented in cf. Annex 2. 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. This simulation allows 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 3 presents the mean results of the delta risk reduction in terms of Total Potential Loss (TPL) and Potential Loss of Life (PLL).

Table 3:Effectiveness in reducing risk for each of the RCOs.

RCO ID	Mean Δ TPL			Mean Δ PLL		
	Generic ship 1 Twin Island	Generic ship 2 Single Island	Generic ship 3 Feeder	Generic ship 1 Twin Island	Generic ship 2 Single Island	Generic ship 3 Feeder
P1	61 153 €	9 773 €	1 755 €	2.0E-04	6.7E-05	1.9E-05
P4	16 103 €	2 573 €	462 €	5.2E-05	1.8E-05	5.1E-06
D1	22 908 €	3 204 €	464 €	1.1E-04	3.3E-05	7.7E-06
D2	103 635 €	18 087 €	3 001 €	4.0E-04	1.3E-04	3.0E-05
D3	14 371 €	3 544 €	740 €	1.6E-05	8.3E-06	2.8E-06
D4	4 311 €	1 063 €	151 €	4.7E-06	2.5E-06	5.8E-07
D5	20 274 €	2 231 €	115 €	7.9E-05	1.8E-05	1.0E-06
F1	40 590 €	5 668 €	858 €	2.2E-04	6.2E-05	1.4E-05
F2	5 160 €	1 545 €	442 €	5.4E-06	3.5E-06	1.6E-06
F3	15 449 €	2 207 €	634 €	1.6E-05	5.0E-06	2.2E-06
F4	6 589 €	1 951 €	542 €	1.0E-05	6.6E-06	3.2E-06
F5	25 175 €	3 517 €	972 €	3.8E-05	1.2E-05	5.7E-06
C1	331 135 €	25 466 €	1 798 €	1.3E-03	2.6E-04	3.7E-05
C2	306 064 €	43 868 €	5 012 €	1.0E-03	3.3E-04	7.4E-05
C3	23 793 €	6 401 €	1 273 €	2.6E-05	1.6E-05	5.7E-06
C4	166 999 €	29 765 €	4 683 €	7.3E-04	2.7E-04	7.7E-05

Table 4 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 were ranked by using level 1 (no), 2 (weak) and 3 (high).

Table 4:RCO's interdependencies

	P1	P2	P3	P4	P5	D1	D2	D3	D4	D5	F1	F2	F3	F4	F5	C1	C2	C3	C4
P1																			
P2	1																		
P3	1	1																	
P4	1	1	2																
P5	1	1	3	1															
D1	1	1	1	1	1														
D2	1	1	2	1	1	1													
D3	1	1	2	1	1	1	1												
D4	1	1	2	1	1	1	1	1											
D5	1	1	1	1	1	2	2	2	3										
F1	1	1	1	1	1	3	3	1	1	2									
F2	1	1	1	1	1	2	3	3	2	3	1								
F3	1	1	2	1	1	1	3	3	2	3	1	3							
F4	1	1	3	1	1	1	3	3	2	3	1	1	2						
F5	1	1	3	1	1	1	3	3	2	3	1	1	1	2					
C1	1	1	1	1	1	3	3	1	1	2	3	1	1	2	2				
C2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	3			
C3	1	1	3	1	1	1	3	3	2	2	1	1	1	3	3	1	1		
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

P3 shows a clear interdependency with P4 and P5 within the prevention category. In isolation (stand- alone), P3 has limited or no effect on reducing the probability of ignition, however, it can work very well when implemented in combination with other fire tiers such as Detection (D2, D3, D4), Firefighting (F3, F4, F5) and Containment (C3). Detection RCOs show a clear interdependency with the firefighting RCOs. Earlier detection 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. Firefighting RCOs (F2, F3) show a strong interdependency due to their combination giving both increased efficiency in penetrating the container of origin (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 on deck fire scenarios, which will also affect the other firefighting RCOs to also be more effective due to higher loads of water. The containment RCOs (C1, C3) are also affected by the detection RCOs. They are active protection systems that relies on the fire being detected to be activated. Hence earlier detection will strongly influence the effectiveness. Finally, C1 and F1 are also interdependent because they both activate in case of a cargo hold fire. Together, they will have a greater suppression effect than separately.

- **STEP 4 – COST EFFECTIVENESS ASSESMENT**

The cost-effectiveness assessment was carried out for the three generic ship types for both a new building and retrofit solution scenario, in total 6 vessel categories. Four different indices 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 Benefit-Cost ratio is the difference between accumulated discounted benefits and the initial year zero investment, adding the accumulated discounted cost over the 25 years.

$$BCR = \frac{Sum\ of\ Benefit_{years}(25\ years)}{Initial\ RCO\ Investment\ + Sum\ of\ Discounted\ Annual\ Costs\ (25\ years)}$$

The benefit of the RCOs were obtained from Step 3. While the cost has been taken from various relevant vendors, and industry experts. The cost includes the initial investment, 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[2]. To judge if an RCO is cost-effective, a CAF assessment criterion of 8.7M € was estimated robustly based on the formula developed by Skjong and Ronold[3], which takes into account several indicators for OECD countries, at the considered year. Furthermore, other economic criteria such as NPV > 0 € and BCR >=1 were used as criteria to assess economically of the RCOs implementation for industry and society.

Table 5 presents the initial investment and the annual cost of the RCOs. There are no price differences between solutions for newbuilding vs vessels to be retrofitted. The only exception is D1 and F4. The retrofitted cost is represented with an R after the RCO identification number. It was not possible to make an accurate and appropriate cost assessment for C4.

[2] https://treasurydirect.gov/marketable-securities/treasury-bonds/
[3] Skjong & Ronold, *"So much for safety"*, Det Norske Veritas, 2002.

Table 5:RCOs cost estimates.

RCO	Generic ship 1 Twin Island		Generic ship 2 Single Island		Generic ship 3 Feeder	
	Investment	Annual	Investment	Annual	Investment	Annual
P1	938 967 €	14 099 €	391 389 €	5 877 €	184 417 €	2 769 €
P2	0 €	2 764 €	0 €	1 443 €	0 €	944 €
P3	1 000 €	1 000 €	1 000 €	1 000 €	1 000 €	1 000 €
P4	0 €	7 360 €	0 €	4 987 €	0 €	1 680 €
D1	540 400 €	0 €	225 167 €	0 €	106 038 €	0 €
D1R	4365 400 €	0 €	1818 917 €	0 €	856 588 €	0 €
D2	458 240 €	2 500 €	170 320 €	2 500 €	85 440 €	2 500 €
D3	3600 000 €	36 000 €	3300 000 €	33 000 €	1800 000 €	18 000 €
D4	363 899 €	6 560 €	151 624 €	6 560 €	71 405 €	6 560 €
D5	1 520 €	243 €	1 520 €	243 €	1 520 €	243 €
F1	500 000 €	22 500 €	500 000 €	22 500 €	500 000 €	22 500 €
F2	15 000 €	0 €	15 000 €	0 €	15 000 €	0 €
F3	15 000 €	0 €	15 000 €	0 €	15 000 €	0 €
F4	10 000 €	0 €	10 000 €	0 €	10 000 €	0 €
F4R	1037 284 €	0 €	490 535 €	0 €	283 916 €	0 €
F5	525 000 €	22 500 €	525 000 €	22 500 €	525 000 €	22 500 €
C1	805 000 €	57 500 €	735 000 €	52 500 €	350 000 €	25 000 €
C2[4]	711 200 €	0 €	480 000 €	0 €	184 150 €	0 €
C3	1116 000 €	11 160 €	687 456 €	6 875 €	321 408 €	3 214 €
C4	-	-	-	-	-	-

The cost-effectiveness assessment (CEA) of the RCOs is displayed in Table 6, Table 7, and Table 8.
For the Twin Island (generic ship 1), only D5 can be recommended from a purely loss of life perspective for further implementation. However, from an economic perspective 8 other RCOs being D5, F3, F4 (only new building), C2, F2, D2, C1, and P4 (in ranked order) are very attractive and should also be considered as recommendable for implementation.

[4] The price estimation was done for mineral wool covered by a steel plate. It is assumed that the steel plate will protect the wool from physical damage, and the mineral qualities are naturally resistant to deterioration. Other alternatives may result in a higher maintenance cost.

Table 6:CEA of the Generic Ship 1 (Twin Island).

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

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 7:CEA of the Generic Ship 2 (Single Island).

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

Continue table 7

RCO	Initial Investment	Annual Cost	NPV	BCR	CBR	ΔPLL	GCAF	NCAF
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 Feeder vessel (generic ship 3), F4 can be recommended for implementation in new build vessels taking both loss of life and economic aspects into consideration.

Table 8:CEA of the Generic Ship 3 (Feeder).

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

A sensitivity analysis was made to validate the robustness of the results. It was evaluated how RCO cost effectiveness results would change if implementation (investment and discounted annual) costs were increased or reduced by 20%. The sensitivity analysis revealed that all the RCOs considered cost effective in CARGOSAFE remain cost-effective, 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), the solution that can potentially become cost-effective after a cost reduction 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 can potentially become cost-effective.

– STEP 5 – RECOMMENDATIONS FOR DECISION MAKING

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. 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 BCR was close to 1 to avoid disregarding potentially relevant RCOs. As conclusion, several RCOs have been demonstrated to be potentially cost-effective, based on Cost-Benefit Ratio.

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.

Table 9 summarizes these last points by displaying the cost-effectiveness of all assessed solutions for the three generic ships, once again based on BCR.

Table 9: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	Improving current smoke detection system	No	No	No
D1R	Improving current smoke detection system (retrofitting)	No	No	No
D2	Heat detection	Yes	Yes	No
D3	Fixed IR cameras	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 CO_2 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 firefighting	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

7. FINAL RECOMMENDATIONS FOR DECISION-MAKING

Cost-effectiveness for RCOs generally improves as vessels grow in size.

Only one RCO (D5: Portable IR cameras for manual detection) can be recommended from a GCAF / Loss of life perspective, as it for the Twin Island (generic ship 1) is within the CAF criterion of 8.7M € and for the two other types within the uncertainty.

Multiple RCOs can be recommended from an economic perspective considering NCAF, NPV and BCR calculation results. F4 (Methods for unmanned firefighting) is the only RCO with visible economic potential across all 3 vessel types/sizes but only for the new building scenario. D5 (Portable IR cameras for manual detection) and F3 (Manual firefighting tools that increase reach) have visible economic potential for all 3 vessel types/sizes, 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) also carry a significant economic potential for particularly the Single and the Twin Island (generic ships 2 and 1, respectively). Finally, P4 (Improved control of lashings) and C1 (Active protection underneath hatch covers to protect against fire spread towards the deck) have some visible economic potential, particularly the Twin Island (generic ship 1).

Benefits from reducing cargo loss and ship loss account for the biggest part of the global benefits used in the computations (NCAF, NPV, BCR). However, salvage and environmental costs also significantly impact the result, albeit it does not change the ranking substantially. The results of the CEA without salvage and environmental costs can be found in cf. Annex 3.

All the above-mentioned RCOs consist of technologies that are at TRL 6 to 9. Therefore, at least pilot solutions had been demonstrated in relevant operational environments. Therefore, there is sufficient technological robustness in 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.

If recommendations should be provided across the three vessel types/sizes for two RCOs for each of the four fire protection layers, then Table 10 summarizes these. However, since major differences exist across the three ship sizes, CARGOSAFE recommends that RCOs be decided based on ship size criteria.

Table 10: RCO recommendations for 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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