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Container ship cargo fires, classification, analysis, and mitigation process using human factor analysis and classification system (HFACS-CSCF)

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CONTAINER SHIP CARGO FIRES, CLASSIFICATION, ANALYSIS, AND MITIGATION PROCESS USING HUMAN FACTOR ANALYSIS AND CLASSIFICATION SYSTEM (HFACS-CSCF)

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EGYPT

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

(Signature): ....

(Date): 08 |September 2022.

Supervised by Assist. Prof. Dr. Anish Hebbar and Dr. Serdar Yildiz

Supervisor’s affiliation: World Maritime University (WMU).

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Abstract

Title of Dissertation: **Container ship cargo fires, classification, analysis, and mitigation process using Human Factor Analysis and Classification System (HFACS-CSCF)**

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Fire safety on container ships is undoubtedly an essential aspect of safe maritime transport, considering the increasing demand and high growth rate of the container shipping industry. Therefore, this study analyzed fire accidents that occurred in the cargo area on board container ships between 2010 and 2020 to identify the root causes of incidents and mishaps in the current fire safety systems and, if any, in the relevant legislation.

The accident investigation reports were obtained from the Global Integrated Shipping Information System (GISIS) database; in total, 19 container ships' cargo fire accidents were counted in this period with published investigation reports.
The fire accident investigation reports were analyzed by utilizing the Human Factors Analysis and Classification System (HFACS), which suits to the research subject; a new framework was created through the research process, labelled HFACS for Container Ship Cargo Fire (HFACS-CSCF), to systematically identify trends in fire accidents and develop a procedure to mitigate them through recommendations. The undeclaration of dangerous goods by shippers proved to be the most frequent unsafe act that contributed to the occurrence of fire accidents in the cargo area of container ships.

Additionally, the current fire safety measures were evaluated, and measures were suggested to mitigate the risk of "fire contain and extinguish failure" in the cargo area of container ships, focusing on the atmospheric monitoring concept inside the container to track any humidity or temperature changes. Finally, a connection was made between the current ISO standards concerning containers and the International Maritime Dangerous Goods (IMDG) Code to determine the types of containers that shall be used to carry any specific containerized cargo.

KEYWORDS: Container Ship, Cargo, Fire Safety, HFACS

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List of Abbreviations

Abbreviations	Definition
AGCS	Allianz Global Corporate and Specialty
BSU	The Federal Bureau of Maritime Casualty Investigation-Germany
CASMET	Casualty Analysis Methodology for Maritime Operation
CASR	Consolidated Audit Summary Reports
CEJ	Centre for Environmental Justice
CFD	Computational Fluid Dynamics
CINS	Cargo Incident Notification System
CISI	Container Inspection Safety Initiative
CSCF	Container Ship Cargo Fires
DaaS	Data as Service
DBI	The Danish Institute of Fire and Security Technology
DOD	Department of Defence-USA
EMCIP	European Maritime Casualty Investigation Platform
EMSA	European Maritime Safety Agency
ER	Engine Room
EU	European Union
FAHP	Fuzzy Analytical Hierarchy Process
FCM	Fuzzy Cognitive Mapping
FSA	Formal Safety Assessment
FSS	Fire Safety System
FTP	Fire Test Procedure
GBS	Goal Based Standard
GISIS	Global Integrated Shipping Information System
HAZID	Hazard Identification

HFACS	Human Factors Analysis and Classification System
HFACS CSCF	Human Factors Analysis and Classification System-Container Ship Cargo Fires
HNS	Hazardous and Noxious Substances
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organization
IMSAS	IMO Member State Audit Scheme
IOT	Internet of Things
IPEN	International Pollutants Elimination Network
ISO	International Organization for Standardization
IUMI	International Union of Maritime Insurers
LL	International Convention on Load Lines
LMIU	Lloyds Maritime Information Unit
MAIB	Marine Accident Investigation Branch /UK
MARPOL	International Convention for the Prevention of Pollution from Ships
MEKP	Methyl Ethyl Ketone Peroxide
MSC	Maritime Safety Committee
MSIU	Marine Safety Investigation Unit /Malta
MSS	Machinery Spaces of Ships
NCB	National Cargo Bureau
Nordic	Sovereign states Denmark, Finland, Iceland, Norway, and Sweden, as well as the Faroe Islands, Greenland, and Aland
NoMIS	Nordic Marine Insurance Statistics
OGI	Oil and Gas Industry
ORGAX	Organizational Accidents
PV	Passenger Vessels
RCO	Risk Control Options
RFID	Radio-Frequency Identification Device
SHEL	Software Hardware Environment Liveware

SIBCI	Ship Icebreaker Collision in Ice Covered Waters
SOLAS	International Convention for the Safety of Life at Sea
SCM	Swiss Cheese Model
TEU	Twenty-foot Equivalent Unit
TIC	Thermal Imaging Camera
TSB	Transportation Safety Board of Canada
UASC	United Arab Shipping Company
UK	United Kingdom
USCG	United States Coast Guard
UNCLOS	United Nations Convention on the Law of Sea
WSN	Wireless Sensor Network

Chapter 1

Introduction

1.1. General context

The global automated service that provides easily and cheap cargo transfer is mainly based on the container (Levinson, 2016) and the container ship, and such process is known as containerization (Olsen, 2022), which pushed the logistics industry to another era (Olsen, 2022). The size of container ships has witness significant increase in the last 50 years (AGCS, 2022), associated with interconnected risks and complication of such increased size, the old new undeclared dangerous goods issue increases the level of fire safety challenge.

1.2. Historical Background

In the last five years more than 70 fires have been reported on board container ships (AGCS, 2022) The container fire rate increased significantly in the first quarter of 2019. Although the rate decreased in the following year of 2020, it remains above the rates before 2019. It will rise again in 2021 (Cefor, 2021), heightening the doubt about the effectiveness of current safety measures in use, even though those statistics include all ships designed to carry containers, such as RORO-containers and fully cellular container ships This gives a clear idea of the casualty rate in container ships.
In 2021, fire and explosion casualties represented 7% of the total number of casualties in the European region, according to the European Maritime Safety Agency (EMSA), with four fatalities reported. A fire on a container ship, specifically in its cargo area, continues to pose the greatest risk (EMSA, 2021).

In accident investigation reports recorded and kept by the European Maritime Casualties Information Platform (EMCIP) and Global Integrated Shipping Information System (GISIS) created by the International Maritime Organization

(IMO), it was highlighted that events start to appear also from the review related to chartered vessels and the knowledge of cargo inside container safety information.

1.3. Research Contribution

The research effort will always have a contribution to enhancing maritime safety in merchant shipping; therefore, focus has been put on the accident root cause identification process (Celik & Cebi, 2009). New versions of Human Factor Analysis and Classification System have been created named as Human Factors and Classification System Container Ships Cargo Fires (HFACS- CSCF) to suit the subject of investigation and analysis. Then the results and statistics were used to identify the gaps in the legislation framework and associated equipment and systems. Finally, recommendation based on the analysis incorporating the current available innovative technology with some novel idea for atmospheric control inside the dangerous goods containers.

1.4. Global container fleet and casualty rate

Container commodities represent 16% of the 2021 global seaborne trade calculated in million tons (Clarksons, 2022), and the 5650 container ships around the world represent 18% of world fleet by vessel type calculated in gross tonnage (Clarksons, 2022). There is significant increase potential as the container ships represent 38% of the order book by vessel type (Clarksons, 2022), which means that the shipping industry weight is shifted towards container shipping, and indeed the industry is looking forward for safer container ships.

In a review of container vessel fire casualties over the last decade, using the Nordic Marine Insurance Statistics (NoMIS), alarming contradictions have emerged, even though these figures include both Ro-Ro and fully-cellular container ships. It is a clear indicator about the safety level in this sector.

The number of container fire casualties in 2019 was 31 fire accident, which dropped to 25 accidents in 2020 before rising again to 36 in 2021 (Cefor, 2021), revealing the importance of root causes identification behind those rates in general (Figure1).

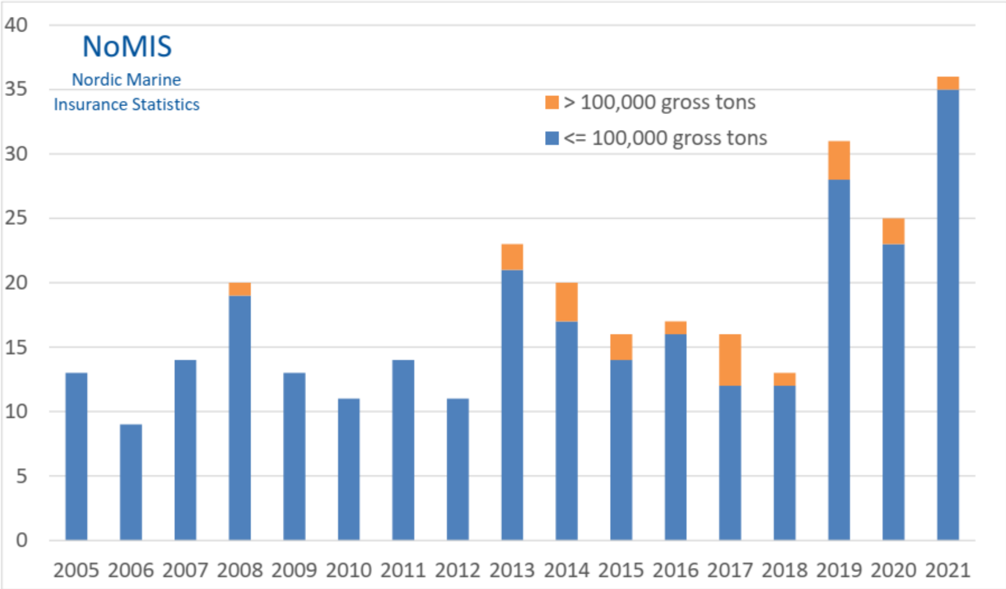


Figure 1 Container vessel fires- occurrence per year (Cefor, 2021)

1.5. Research Question

I. What are the trends in human factors that contribute to the fires on container ships and how to mitigate them?

II. To what extent do the current fire safety measures for the cargo area of container vessels address the safety goals stipulated in SOLAS?

1.6. Key assumptions and potential limitations

I. This dissertation focusses on fire accidents between 2010 and 2020 reported to Global Integrated Shipping Information System (GISIS) and the investigation was completed, documented, and published.

II. The dissertation analyses the fire onboard container ships in the cargo area only. Fires in other areas on board container ships and fire on board other ship types are excluded.

III. Time constraints and availability of all relevant data for the research study may limit the capacity to conduct a thorough investigation on the intended topic.

Chapter 2

Literature Review

2.1. Introduction

This chapter provides a critical review of the facts that can be found in the relevant literature pertaining to the subject of fires that occur aboard containerships in the cargo area. It is based on scientific literature, fire casualty reports, insurers perspective and current regulatory framework linked to container ship fire safety.

2.2. Negative impact on insurance industry

Fire casualties on container ships frequently impose a high cost on ship owners and associated insurers (Cefor, 2021). The fire claims have shown a trend in response to the 2019 high occurrence rate, in terms of claims above 500.000 USD (see Figure 2). All casualty claims have dropped since the 2007-2008 peak, except the fire and explosion claims, which have shown a more volatile frequency than other claims (Cefor, 2021), continuing to rise since 2018; however, the claims began to decrease from 2019 to 2020, then slowly decrease between 2020 and 2021 (Cefor, 2021)[1].

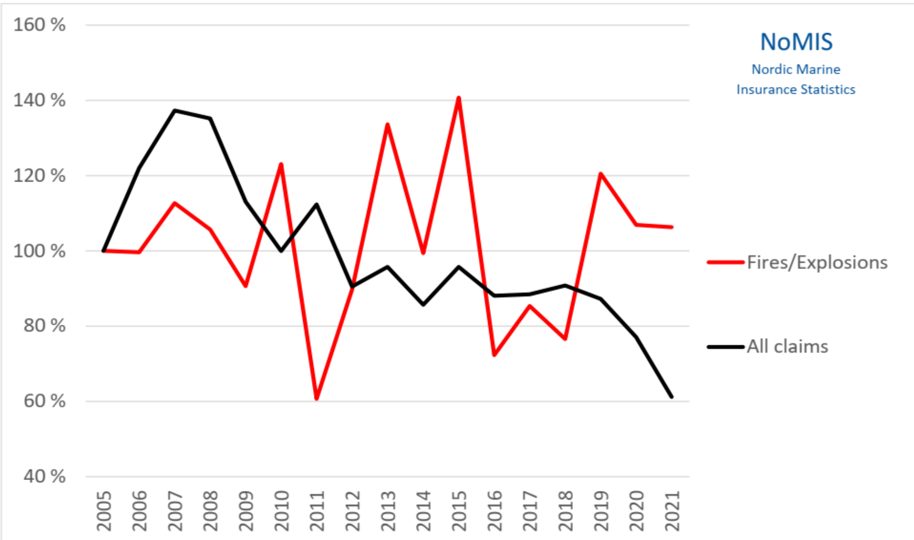


Figure 2 Container claims versus all other claims, claims above 500.000 USD (Cefor, 2021)

[1] Index 2005 = 100%

The rising trend in container fire claims specially in large container vessels is significant compared to any other ship type (see Figure 3) (Cefor, 2021).

The International Group of P&I Clubs indicate an increase of container ship claims, i.e., the average number from 1.4 in the period 2010-2015 to 5.2 in the period of 2016- 2021 (spglobal, 2021).

Container fires are a high priority item in the International Union of Marine Insurance (IUMI) with a view to amend the SOLAS Convention to reduce such casualty rates (spglobal, 2021).

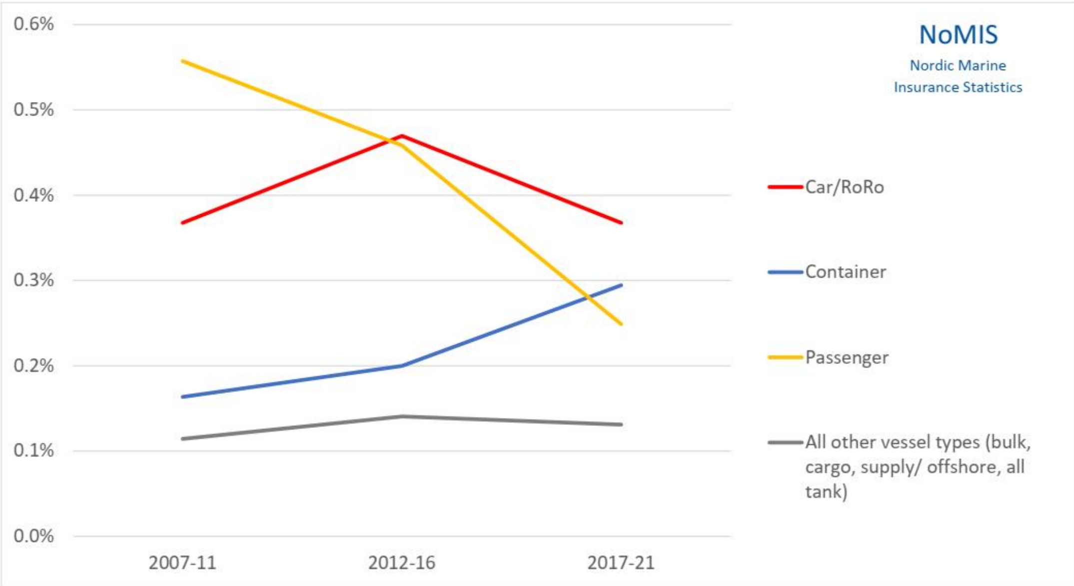


Figure 3 Fire and explosions frequency by ships type-claims >500.000 USD (Cefor, 2021)

2.3. Current regulatory framework covering fire safety on board container ships cargo area

2.3.1. IMO Instruments Related to Fire Safety

IMO's International Convention for the Safety of Life at Sea (SOLAS) is the main instrument for standardizing maritime shipping safety matters, and chapter II-2 addresses one of the main risks to ship safety, i.e., the fire risk (IMO, 2022d).

The International Code for Fire Safety Systems (FSS Code) include all technical specifications for firefighting equipment and systems on board the ship according to

SOLAS chapter II-2, while the International Code for Application of Fire Test Procedures (FTP Code) provides the approval criteria and tests for such equipment and systems (IMO, 2022a).

There are non-mandatory instruments that serve the scope of fire safety, such as the Code on Alerts and Indicators, and guidelines provided by the IMO for equipment and systems utilizations and tests (IMO, 2022a).

Chapter II-2 has been reviewed many times by the Maritime Safety Committee (MSC). There was a complete review in 1981, followed by 1990 review in response to the Scandinavian Star fire, then in 1996 the review and introduction of FTP, and the last major review was in 2000 with entry into force in 2002 (IMO, 2022b).

Knowing the evolution steps of chapter II-2 helps to know the status quo, and the development potentials in the future.

2.3.2. Review for chapter II-2 in 2000 and similarity with Goal-Based Standard (GBS)

The 2000 amendments were rational and structured (Huss, 2007) with the Goal Based Standard (GBS) similarity, as the chapter starts with objectives then functional requirements followed by rules and regulations to achieve such requirements. Every regulation has a purpose and functional requirements to assist implementation and open the way for novel designs or ideas (IMO, 2002).

The introduction of the International Code for Fire Safety System (FSS) through MSC.98(73) associated with the new chapter II-2 layout, with all technical details moved to the code instead of overcrowded old chapter II-2, the new chapter applied for vessels constructed on or after first of July 2002 (IMO, 2002), with some exceptions among its regulations (IMO, 2022b).

2.3.3. Review for chapter II-2 in 2014 and container safety measures

The amendments of 2014 by Resolution MSC.365(93) was created with the purpose to enhance the container ship fire safety, providing means for contain the fire and supress it (IMO, 2014c). The application for new ship build on or after first of January 2016 left all old ships, 5249 container vessels (Clarksons, 2016) without such enhancements, even though those are the minimum requirements.

The amendments include one water mist lance; in addition, the container vessel designed to carry five tiers or more on weather deck needs to carry two “mobile water monitors” if the ship breadth less than 30 meters and four “mobile water monitors” if the ship breadth is more than 30 meters (IMO, 2014c). The amendments include some technical specification for the “water mist lance” and “mobile water monitors”(IMO, 2014c).

Six years from mandating such requirements and in response to recent disastrous fires such as the Xpress Pearl, SOLAS provisions were deemed obsolete (Rubesinghe et al., 2022), with the urgent need to be amended coping with increased sizes of recent container ships. Fighting fires aboard container ships is a very risky crew task with the present equipment required by current SOLAS standards (AGCS, 2022).

The regulatory factors affecting the container ships fire safety are part of the Human Factors Analysis and Classification System (HFACS) framework used to analyse the 19 fire investigation reports of container ships cargo area.

The primary source of data used to build the HFACS framework are the casualty investigation reports, a critical review for the status of the casualty reporting and requirements will be supportive.

2.4. Fire Casualty investigation reporting and impact on the container ships safety

2.4.1. Current Regulatory framework for accident investigation and reporting.

The member states obligation to maritime casualties reporting was mandated through the SOLAS Convention regulation I/21 and XI-1/6, in addition to the MARPOL Convention article eight for harmful substances reporting and article twelve for casualties causing negative impact on the marine environment (International

Convention for the Prevention of Pollution from Ships, 1973). The International Load Line Convention covers such obligation in article 23 (*International Convention on Load Lines*, 1966) to create a robust framework to investigate and report casualties and duties of flag states fulfilling such obligations. All this IMO instruments can be seen as a derivative from the United Nations Convention on the Law Of The Sea (UNCLOS 82), article 94, which details the flag state duties and mandates the investigation and reporting responsibility through paragraph seven of the article (UNCLOS, 1982).

2.4.2. Development of IMO reporting system, Global Integrated Shipping Information System (GISIS) and positive impact on the safety of ships

When chapter XI-1 was amended in 2008 through MSC.257(28) and regulation six introduced under the name "additional requirements for the investigation of marine casualties and incidents"(IMO, 2008c), the scope was to assist the Member States to fulfil their casualty reporting and investigation responsibilities, taking into consideration national law applicability (IMO, 2014a), which will be vital to enhance and develop the safety on board ships globally through study and analysis lessons identified from such casualties (IMO, 2014a). The technical details for conducting effective investigation report mandated through MSC.255(84) were labelled Casualty Investigation Code (IMO, 2008b), with the pre-established Global Integrated Shipping Information System GISIS in 2005 (IMO, 2010a). As an international informative and reporting platform, the global reporting system elements seem to be available; however, the absent part was the commitment of the member states themselves to conduct such investigations and reporting. The IMO urges the member states through resolution A.1074(28) to utilize such system to fulfil its obligation (IMO, 2014b). The IMO also through resolution A.1075(28) provides guidelines to assist the causality investigation process and help the implementation of the Casualty Investigation Code (IMO, 2014a). (See Figure 4)

2.4.3. Missing fire casualty reports Summary with responsible flag state and negative impact on fire safety

Despite the IMO efforts to establish the GISIS as a direct reporting system (IMO, 2010a) and create a legal framework trough many instruments such as SOLAS 74, MARPOL 73/78, and Load Lines 66/88 in addition to the code and guidelines, many contracting governments did not fulfil their obligations. Casualty investigations, reporting to the IMO and circulating to other contracting governments were not done. Such findings were addressed in the "IMO Member State Audit Scheme (IMSAS) – Fifth Consolidated Audit Summary Report (CASR)" with the Root Causes and action to be taken to mitigate (IMO, 2021a).

The Casualty Investigation Code consists of three parts. Part one and two are mandatory requirements (IMO, 2008b), while part three is guidelines for the investigation process to be considered. Further, paragraph 14.4, part II mandates that the "marine safety investigation report" need to be released to "public and shipping industry" by the investigating authority (IMO, 2008b). The IMO Instruments Implementation (III) code, paragraph 40 and 41, detail part of flag state investigation requirements, which make the investigation report public and forwarded to the IMO. Reviewing the fifth IMSAS CASR revealed that the findings in paragraphs 108 and 120 are related to this matter, where member states failed to release the casualties reports to the public and failed to provide a mechanism for such release (IMO, 2021a). The deadline for corrective action set by the report was November 2022 for findings in paragraph 108 and December 2022 for findings in paragraph 120 (IMO, 2021a).

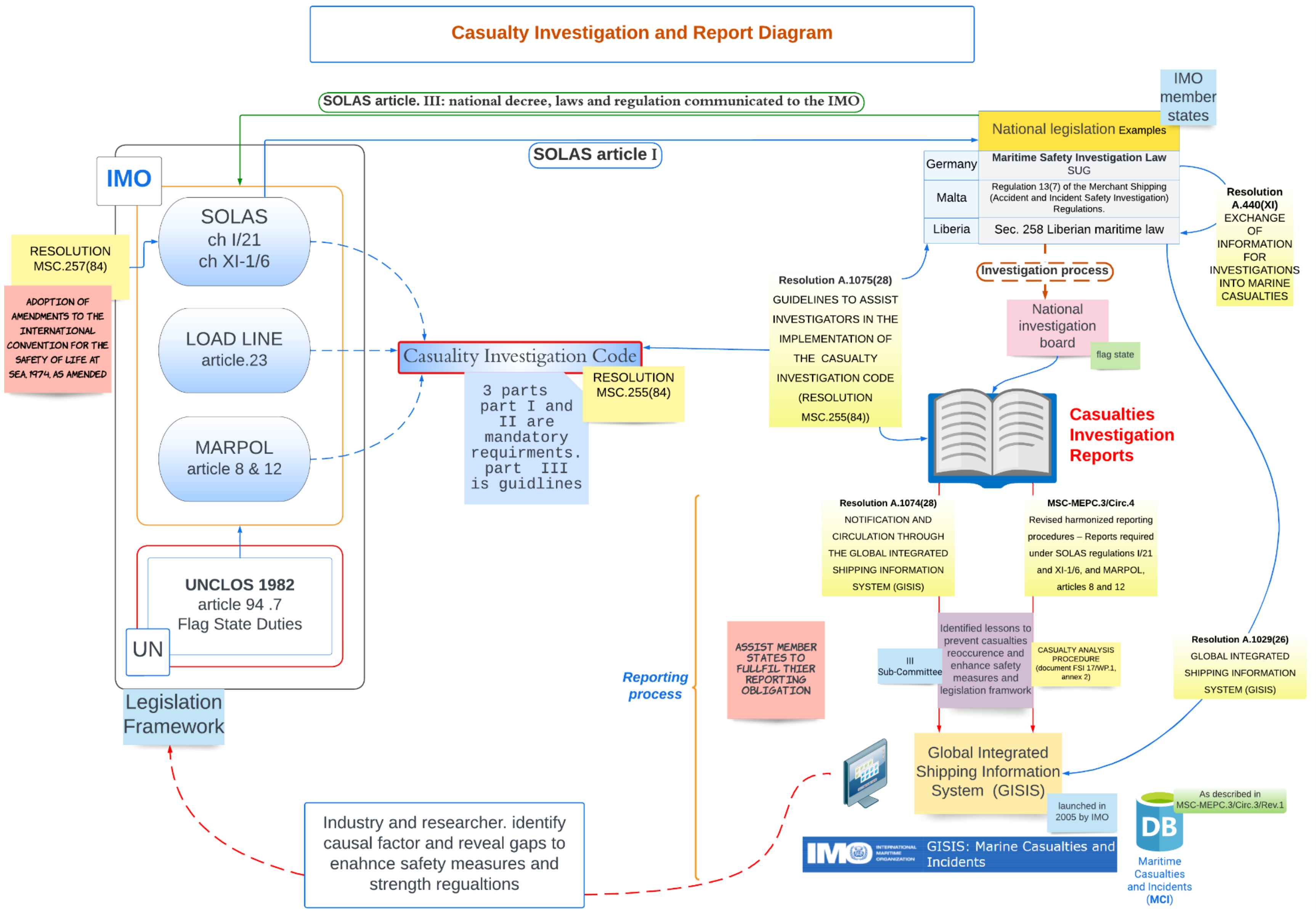


Figure 4 Casualty investigation and reporting diagram

In reviewing the fire casualty reports for container ships through the GISIS platform, many casualty reports were missing, while some were submitted to the platform but not available for public download (IMO, 2022e). The IMO cannot publish such reports if they have not been made public by the investigation authority itself. Such review with results reveals a gap in the research effort. Twenty-five missing fire casualty investigation reports in container ships' cargo area were counted, in the ten-year period from 2010 to 2020, eight casualties have an incident summary in GISIS without reports (IMO, 2022e), while seventeen container ship fire casualty reports were not published, neither on GISIS nor any national flag state or investigation board web site or source. (See Table 1, figure 5)

Table 1 Summary of missing container ships cargo fire casualty reports

S/N	Ships Name	Date Of Occurrence	Severity Of the Casualties (officially)	Responsible Flag State	Reports Forward to IMO	Reports available or not available for public and shipping industry download	Incident summary available at GISIS
1	APL LE HAVRE	09/08/2019	Not declared	Singapore	NO	NA	NO
2	KMTC HONG KONG	25/05/2019	Not declared	Korea	NO	NA	NO
3	ZIM QINGADO	21/03/2019	Serious	Israel	NO	NA	YES
4	ER KOBE	13/02/2019	Not declared	Liberia	NO	NA	NO
5	APL VANCOUVER	31/01/2019	Not declared	Singapore	NO	NA	NO
6	SSL KALKOTA	13/07/2018	Not declared	India	NO	NA	NO
7	MAERSK KENSINGTON	16/03/2018	Not declared	USA	NO	NA	NO
8	MAERSK KARACHI	22/05/2017	Not declared	Hong Kong	NO	NA	NO
9	MSC DANIELA	04/04/2017	Less serious	Panama	YES	NA	YES
10	WAN HAI 307	19/09/2016	Not declared	Singapore	NO	NA	NO
11	PHILIPA SHULTE	22/08/2016	Serious	Liberia	NO	NA	YES

12	NORTHERN VOLITION	24/11/2015	Not declared	Portugal	NO	NA	NO
13	CAP MORETON	12/09/2015	Not declared	Marshall Islands	NO	NA	NO
14	MARENO	30/08/2015	Not declared	Antigua and Barbuda	NO	NA	NO
15	UASC ALULA	28/08/2015	Not declared	Malta	NO	NA	NO
16	MAERSK SEOUL	19/07/2015	Serious	Liberia	NO	NA	YES
17	S KAMALA	10/07/2015	Less serious	Liberia	NO	NA	YES
18	MAERSK LONDRINA	25/04/2015	Not declared	Hong Kong	NO	NA	NO
19	COSCO PRIDE	13/07/2014	Not declared	Hong Kong SAR of China	NO	NA	NO
20	CMA CGM LILIAC	28/09/2013	Not declared	Hong Kong	NO	NA	NO
21	MAERSK KAMPALA	29/08/2013	Not declared	Marshall Islands	NO	NA	NO
22	AMSTERDAM BRIDGE	09/09/2012	Serious	Antigua and Barbuda	YES	NA	YES
23	MAERSK KINLOSS	17/07/2012	Not declared	UK	NO	NA	NO
24	CAP EGMONT	05/05/2012	Less serious	Liberia	NO	NA	YES
25	ALERT RICKMERS	04/04/2011	Less serious	Liberia	NO	NA	YES

- Fire on board MV Santa Rose in 2014 was not counted, no data found.

The missing container fire accident reports are creating an iceberg effect on the fire safety system of the container shipping industry, where a lot of data and root causes are buried with the accidents without any feedback to the industry to enhance the fire safety level; 57% of the container fire accidents are without published investigation reports. (See Figure 6)

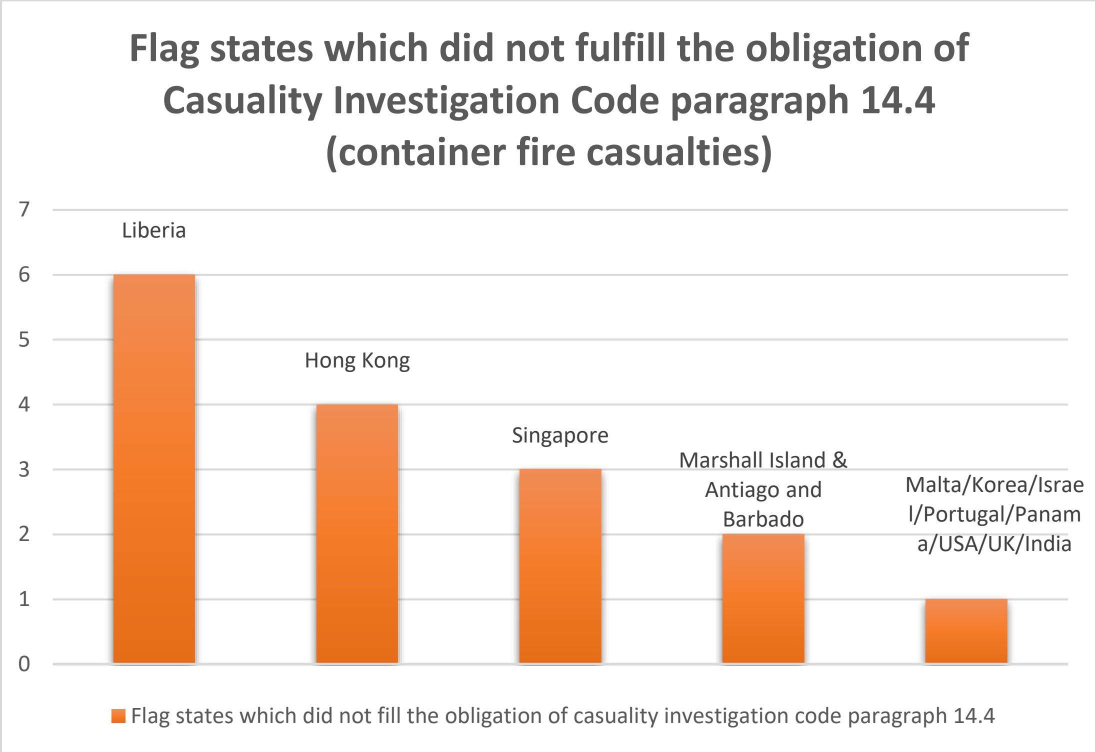


Figure 5 Flag states did not fulfill obligation of casualty investigation code paragraph 14.4

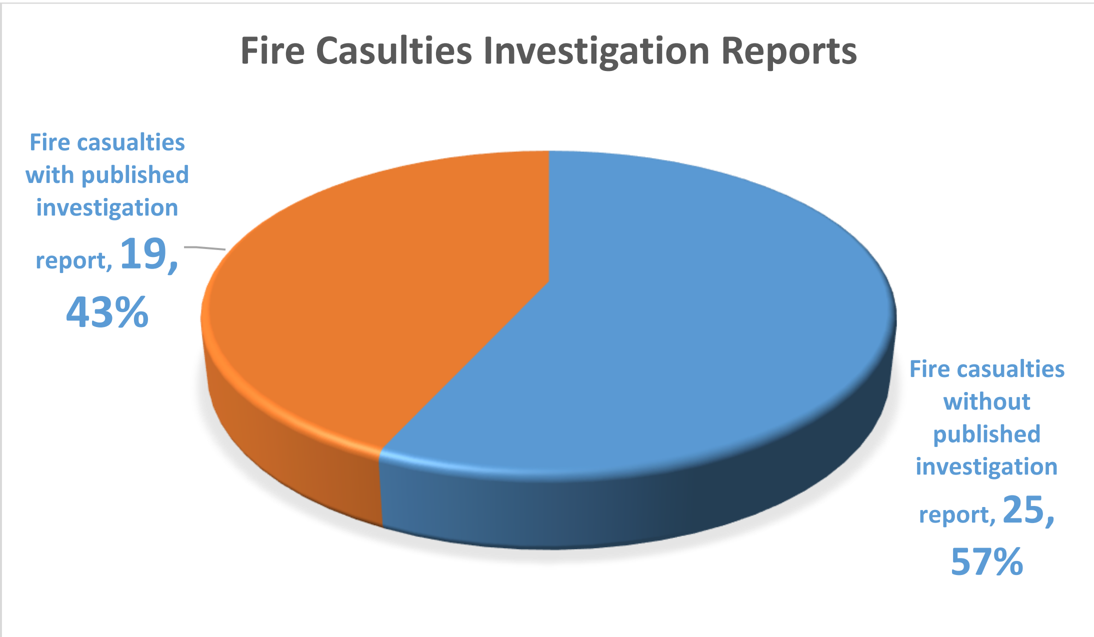
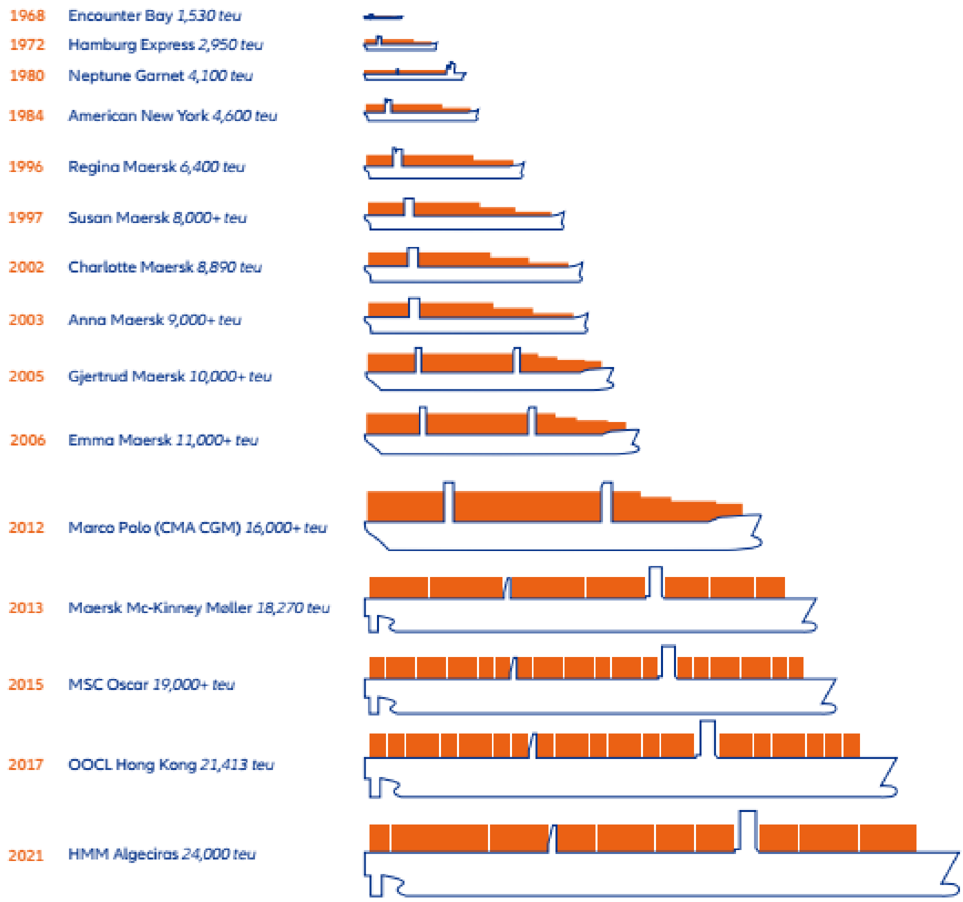


Figure 6 Fire casualties investigation reports

2.5. Dynamic container ships sizes and capacity with static fire safety regulation frame and requirements.

Twenty-foot Equivalent Unit (TEU) is used to measure the container ship capacity. Such capacity has been doubled in the last decade and witnessed a 1500 % increase rate compared with the 1968 figures (AGCS, 2022). While the fire safety provisions in SOLAS have seen a few changes that do not correspond to such an increase (Hulin et al., 2020), some insurers see that current SOLAS objectives cannot be achieved using current SOLAS provisions related to container ship safety (gard, 2020), many flag states have proposed papers to the IMO serving the scope of amending the current SOLAS,II-2 provisions to cope with the industry expansion (See Figure 7) (gard, 2020).



(AGCS, 2022)

Figure 7 Increased container TEU in last 54 years

2.6. Fire divisions in cargo hold area with the current SOLAS provisions

The purpose of regulation nine of SOLAS chapter II-2 is fire containment at origin space (IMO, 2022c). This purpose is derived from the "fire safety objectives" detailed in regulation two and following functional requirements in the same regulation, the use of fire divisions is provided to achieve the containment task. The criteria for fire divisions A, B and C detailed in regulation three are labelled as definitions (IMO, 2022c). The approval criteria are available in the FTP Code including testing of prototype by the flag state or Recognized Organization (RO) authorized by the flag state. Eight tables are provided in regulation nine to achieve such principle for different ship types; Table 9.1 to Table 9.4 are specified for passenger vessels, while Tables 9.5 and 9.6 for all cargo ships except tankers, which have two separated table s9.7 and 9.8 (IMO, 2022c).

Reviewing Table 9.5 for "Fire integrity of bulkheads separating adjacent spaces" reveals absence of any requirement regarding fire division between different cargo holds, except a note that such bulkhead needs to be "steel or any equivalent material" and it is not required to be "A" class standard (IMO, 2022c). This leads to an important question: What is the requirement set in SOLAS, chapter II-2 to provide the contain principle of the fire in container ship cargo hold if it is not achieved by fire divisions.

Considering Table 9.6 for "Fire integrity of decks separating adjacent spaces" of cargo ships, which is applied to container ships as a cargo ship, the separated deck between cargo holds and deck cargo does not have any fire division classification. The same note applied for the steel material; in other words, there is no division to help contain fire on deck and prevent spread to the cargo hold area or vice versa in vertical direction (IMO, 2022c).

Spaces	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Control stations (1)	A-0[e]	A-0	60	A-0	A-15	A-60	A-15	A-60	A-60	*	A-60
Corridors (2)		C	B-0	B-0 A-0[c]	B-0	A-60	A-0	A-0	A-0	*	A-30
Accommodation spaces (3)			C [a,b]	B-0 A-0[c]	B-0	A-60	A-0	A-0	A-0	*	A-30
Stairways (4)				B-0 A-0[c]	B-0 A-0[c]	A-60	A-0	A-0	A-0	*	A-30
Service spaces (low risk) (5)					C	A-60	A-0	A-0	A-0	*	A-0
Machinery spaces of category A (6)						*	A-0	A-0[g]	A-0	*	A-60[f]
Other machinery spaces (7)							A-0[d]	A-0	A-0	*	A-0
Cargo spaces (8)								*	A-0	*	A-0
Service spaces (high risk) (9)									A-0[d]	*	A-30
Open decks (10)											A-0
Ro-ro and vehicle spaces (11)											A-30 [j]

Figure 8 Fire integrity of bulkheads separated adjacent spaces in cargo ships SOLAS, II-2/9, table 9.5

Space below / **Space** above	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Control stations (1)	A-0	A-0	A-0	A-0	A-0	A-60	A-0	A-0	A-0	*	A-60
Corridor (2)	A-0	*	*	A-0	*	A-60	A-0	A-0	A-0	*	A-30
Accommodation spaces (3)	A-60	A-0	*	A-0	*	A-60	A-0	A-0	A-0	*	A-30
Stairways (4)	A-0	A-0	A-0	*	A-0	A-60	A-0	A-0	A-0	*	A-30
Service spaces (low risk) (5)	A-15	A-60	A-0	A-0	*	A-60	A-0	A-0	A-0	*	A-0
Machinery spaces of category A (6)	A-60	A-0	A-60	A-60	A-60	*	A-60[i]	A-30	A-60	*	A-60
Other machinery Spaces (7)	A-15	A-0	A-0	A-0	A-0	A-0	*	A-0	A-0	*	A-0
Cargo spaces (8)	A-60	A-0	A-0	A-0	A-0	A-0	A-0	*	A-0	*	A-0
Service spaces (high risk) (9)	A-60	A-0	A-02	A-0	A-0	A-60	A-0	A-0	A-0[d]	*	A-30
Open decks (10)	*	*	*	*	*	*	*	*	*	-	A-0 [j]
Ro-ro and vehicle spaces (11)	A-60	A-30	A-30	A-30	A-0	A-60	A-0	A-0	A-30	A-0 [j]	A-30 [j]

Figure 9 Fire integrity of decks separating adjacent spaces in cargo ships - SOLAS, II-2/9, Table 9.6

2.7. Review of research effort connected to fire and explosion in maritime shipping related to container fires

In 2007 and as part of IMO rule making process, a proposal paper submitted by the State of Denmark, representing the results of SAFEDOR project funded by the EU including container vessel Formal Safety Assessment (FSA) study (IMO, 2007), which demonstrated that the container ship operation Risk Profile sit within the ALARP[2] zone, and that fire risk represent 17% of the total risk onboard those ships. The aim of the FSA was to examine the risk level on board container ships for the sake of the whole industry, and the study identify early the undeclared dangerous goods as a root cause for many incident (IMO, 2007).

In addition, the study set the fire accident as the main contributor to the risk on human life according to Lloyds Maritime Information Unit (LMIU) data base statistics used in the assessment. The assessment methodology included a Hazard Identification (HAZID) step followed by risk analysis and then considering the available Risk Control Option RCO (IMO, 2018).

The Risk Control Option RCO identified for container ship fire risk provided by the study was "undeclared dangerous goods amount reduction" without providing any technical provisions or idea about how to start or achieve this (IMO, 2007).

The following step of the FSA was cost benefit assessment, which applied criteria for cost effectiveness and found that the proposed RCO for fire risk costly ineffective. Hence, no recommendation for mandatory requirements was adopted, and no mitigation procedure was considered (IMO, 2007).

The study was generic and focused more on the grounding and collision impact rather than the fire casualties (IMO, 2007).

The undeclared dangerous goods risk on container shipping was analyzed by Ellis (2011), with US[3] and UK extracted database records, for 1998-2008 period. The

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[2] ALARP: As Low As Reasonably Practical (acceptable risk level)

[3] Hazardous Materials Information Resource System (HMIRS) platform / USA

release of such material attributed to many factors in the preloading stage such as packing and stuffing (Ellis, 2011).

Globally 15% of fatalities identified in the same period were linked to release of containerized dangerous goods and self-ignition (Ellis, 2011).

Ship fires in general were the focus of many researchers in the past decade. Kwiecińska (2015) investigated ship fires using causes and effect analysis relations diagrams, and the scope was widened to include all ship types and fishing vessels (Kwiecińska, 2015). Fire or explosions represent 20% of casualties based on GISIS data between the 2009-2014 period. The fire accidents were distributed by ship type, and container ships represent 8% of all fire casualties, so the main outcome of the paper was fire interrelationship diagram, with cause-and-effect links contributing to fire occurrence (Kwiecińska, 2015).

Another analysis of causes of fire onboard ships was conducted by Raquel (2015). The scope of the analysis covered different types of vessels including only one container vessel among the 20 investigated fire and explosion accidents. The Casualty Analysis Methodology for Maritime Operation (CASMET) methodology was used to code the "accidental events" and 138 events was identified.

The analysis outcome revealed causal factors were related to lack of knowledge with 44%, inadequate operation 40% and firefighting factors with 30.7% (Raquel, 2015).

The results were crucial to identify Human Error as the leading cause of accidental events, with 57.2%, the equipment failure represents 32.6% of accidental events, including firefighting system as the most frequent one. Moreover, the inability to identify latent technical failure was presented as one of the main causes of such accidents (Raquel, 2015).

The study presented by Rath (2016) was dedicated to fires analysis on fully cellular container vessels; the analysis time frame covered the period of 2000-2015. Rath raised the debate about fire safety in relation to the increased size of container ships, utilizing the findings of German Council of Transport Authority 54th meeting held in January 2016 (Rath, 2016).

The council recommended a set of requirements as an emergency response provisions, related to equipment, training and external assistance as specialist fire fighters and port of refuge availability (Rath, 2016).

The study was set to be part of another FSA aim to enhance the fire safety measures regarding containing and supressing the container fires at IMO level. The fleet volume and development as well as legislation framework were illustrated, with focus on the equipment. Critical assessment was done, using a simulation process with specific criteria and fires in the timeframe of the research was analyzed and a set of charts represented the outcome data in various methods (Rath, 2016).

The study was utilized by International Union of Marine Insurance (IUMI) and presented as a position paper from insurers' perspective in 2017 (IUMI, 2019). The Union raised the fire safety of container ships again in Maritime Safety Committee (MSC) meeting 101, in 2019, with efforts to gain support from all stakeholders to amend the item in the IMO agenda for 2022 (IUMI, 2019).

Baalisampang et al. (2018) reviewed fire accidents in the maritime shipping domain between 1990 and 2015, categorizing the casualties into five main groups based on causation criteria, "human error, mechanical failure, reaction electrical fault and unknown", then, provided preventive and mitigation actions for each category (Baalisampang et al., 2018).

Human error caused 48% of claims, while mechanical failure came second with 22% and thermal reaction with 14% from fire and explosion causes. The study detailed human error as contributing factors (Baalisampang et al., 2018).

The safety engineering perspective in container fires causes and escalation was exhibited through Callesen et al. (2019), with a novel method to assess fire prevention and de-escalation alternatives (Callesen et al., 2019).

The timeframe of Callesen's work covers the period of 1996-2017, with 39 container ship fires recorded. The hazard analysis scope focused on dangerous cargo, specifically Calcium Hypochlorite, compressed charcoal briquette, rechargeable batteries and Divinylbenzene through the process. Causes and consequences for each material were examined; furthermore, the fire detection time reduction, using a simulation modelling with computational fluid dynamics (CFD) software was explained (Callesen et al., 2019).

In 2011 the initiative Cargo Incident Notification System (CINS) was launched by major container ships lines. The data base resulted from cargo incident information share used to examine specific cargo related risks with final objectives to enhance safety level on board container ships (CINS, 2022a). There have been many carriage guidelines issued through the platform, calcium hypochlorite and charcoal included (CINS, 2022b).

The Danish Maritime Institute funded project named CONTAIN, with the technical support of the Danish Institute of Fire and Security Technology (DBI), detailed all container ship fire casualties in the period 1996-2019 with fatalities statistics disclosing negative impacts in the insurance industry and gap in the regulatory framework of fire safety onboard container ships (Hulin et al., 2020). Many analyses of fire causes were included, and Raquel’s (2015) paper statistics and findings were enclosed (Hulin et al., 2020).

The project tried to answer questions about fire spread mechanisms among containers, and generally, the stakeholder perspective about container ship fires (Hulin et al., 2020). A critical review of the research shows success in this scope.

The potential of fire safety engineering was explored There was previous work of this by Callesen et al. (2019) and the project utilized Callesen’s work in causes of cargo fires and explosions in container ships (Hulin et al., 2020), helping to technically enrich the content of the research and as a part of technical review.

The objectives set for CONTAIN project was knowledge enhancement about container fires and bring stakeholders together in what can be described as workshop for container ship fires (Hulin et al., 2020).

However, the research did not clearly set a knowledge level and how can this be measured or effect positively in the risk mitigation of container fires.

Recent analytical research of container ships' cargo area fires was introduced by Krmek et al. (2022) covering the 2010-2020 period, stated that dangerous goods form 10-12% of globally transported containers. The paper analyzed 23 container fires in the cargo area, but using commercial web sites[4] and unacademic sources of information and data about fire causes and sources of ignition in the unpublished container fire casualties degrading the overall value of the paper (Krmek et al., 2022). The outcome of the paper focused on fire causes and ensured the in-effectiveness of current fire safety measures on container ships with ta negative impact to human lives.

Krmek et al. (2022) set their results with undeclared dangerous goods as main contributor elements, and specific dangerous goods as Calcium Hypochlorite and Charcoal as the most identified source of ignition connected to container ships' cargo area fires (Krmek et al., 2022).

Container ship accidents were also discussed by Rahim and Sunaryo (2019) in relation to stacked containers on deck only. The paper demonstrated some investigation board data and statistics on casualties onboard container ships, such as the Australian Transport Safety Bureau (ATSB), the Marine Accident Investigation Branch (MAIB) of the UK, the Federal Bureau of Maritime Casualty Investigation (BSU) of Germany and the Transportation Safety Board (TSB) of Canada (Rahim & Sunaryo, 2019). In addition, a novel Fish Bone diagram analysis of contributing factors in container ships accidents was presented due to stacked containers on deck, including ineffectiveness of ship firefighting systems, and undeclared dangerous goods as human error and as management deficiencies, with consequences such as incorrect stowage position and preloading problems like un-correct packing (Rahim & Sunaryo, 2019).

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[4] www.fleetmon.com
https://gcaptain.com/

The environmental impact resulting from large scale container fires was handled by Rubesinghe et al. (2022). The disastrous fire on board *MV Xpress Pearl* at the anchorage area in front of Colombo in Sri Lanka in 2021 has left devastating pollutants in the coastal waters and beaches of the area and nearby areas. The study was supported by the International Pollutant Elimination Study Network (IPEN) from the Swedish government and the Center of Environmental Justice (CEJ), a Sri Lankan public environment interested agency (Rubesinghe et al., 2022).

The air pollutant, toxic micro plastic and caustic soda were part of a killer pollutant mix released to the beaches of Columbo leaving a disastrous social and economic losses (Rubesinghe et al., 2022).

Again, Rubesinghe et al. (2022) doubted the effectiveness of current regulatory framework, including but not limited to SOLAS, Chapter II-2, and International Maritime Dangerous Goods (IMDG)Code. The research described that the contributing factors of the fire started with spill of Nitric Acid and sequences of events till the sinking and total loss of the vessel (Rubesinghe et al., 2022). The pollutant types and negative impact on the marine environment were analyzed, using a data collected by sampling the water in the accident and surrounding area. (Rubesinghe et al., 2022). The study ended with steps forward and recommendations including Hazardous Noxious Substances (HNS) Convention ratification and port of refuge availability for enhancing the future emergency response and the possibility of reoccurrence of such type of accident was also demonstrated (Rubesinghe et al., 2022).

Chapter 3

Research Methodology

3.1. Introduction

This chapter aims to introduce the methodology for the dissertation. There is no human performance without error (Shappell & Wiegmann, 1997); therefore, accidents involving human error will continue to occur. This chapter will create a framework for human error classification and analysis to suit container fires, to identify the human factor root causes contributing to fire accidents in the cargo area of container ships. Many accidents that were studied in the past have not disappeared, but new forms of accidents have emerged. In response to these advancements, the scientific community has created new investigation procedures and accident models (Lundberg et al., 2009).

3.2. Human error approach

Human error has two approaches, person approach and the system approach (Reason, 2000), where causation and management of error are different in each (Reason, 2000). The unsafe act is the main concept of the person approach, while the system approach focuses more on working conditions and the idea of defenses and barriers to prevent any adverse actions (Reason, 2000). The focus of the unsafe act within the person approach can isolate it from the ambient system, which is considered as one of the main defects in such an approach (Reason, 2000).

3.3. Organizational accidents and Swiss Cheese Model

When the accident causes are analyzed with system approach, the term organizational accident or what is known as ORGAX (Reason, 2016) can be understood. Despite the varieties between all organizational accidents, there are united characteristics for them such as hazards, failed barriers, and losses (Reason, 2016); in other words, unidentified hazards overcome the current safety barriers and cause losses to people, assets, and environment.

With the system approach focusing on the idea of safety barriers, such barriers may lose due to divergent objectives (Rasmussen, 1997). The effective risk management here will be how to enforce such barriers.

In a perfect world, the safety barriers or defenses of any organization will be intact (Reason, 2000), which is not the case as all barriers have spots of weakness or holes in the defenses (Reason, 2016). These holes or failures have two-component, active and latent failures (Reason, 1990).

Active failure is errors or violations that have a direct and immediate adverse effect (Reason, 1990), such activities conducted by frontlines operators. In the shipping industry context, these will be the ship's crew (Reason, 1990), while latent failure is unrevealed hazardous actions or designs or decisions (Reason, 1990) and will remain hidden until combined with active failure to result as an accident (Shappell & Wiegmann, 2003),. Such latent failures may be planted unintentionally by the designers or maintainers of the system and remain there dormant (Reason, 2016).

In 1990 James Reason defined his Swiss cheese model where he defined four levels of accident causation; one active failure and three latent failures within any system defenses, each consequent on the previous level, working backwards from the accident back to unsafe act to reach the organizational influences level (Shappell & Wiegmann, 2003).

3.4. Swiss Cheese Model SCM and Human Factor Analysis and Classification System HFACS

Due to the high rate of accidents in the United States Navy in the 90s, Dr. Douglas Wiegmann and Dr. Scott Shappell were assigned to reveal the causal factor behind such cases (Shappell & Wiegmann, 2000). Based on the Swiss Cheese Model of James Reason (1990), they developed their taxonomy for the failure modes defined as Human Factor Analysis and Classification System (HFACS)**.**

Their HFACS describes three levels of latent failures as Reasons include Precondition for Unsafe Act, Unsafe Supervision and Organizational Influences and Active Failure represented through the Unsafe Act level (Shappell & Wiegmann, 2003). Like the Reason Model, the HFACS follows the System Approach and covers the identification of organizational area contributing to the adverse action or accidents (Garrett & Jochen, 2009).

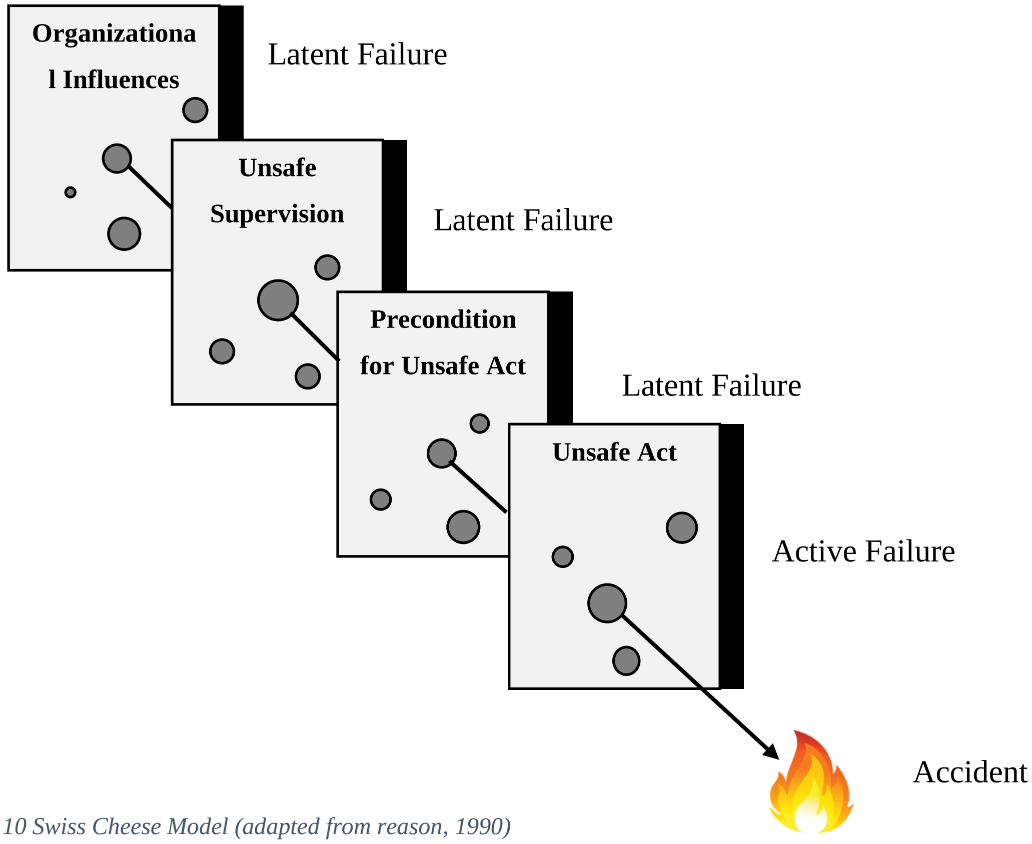

Figure 10 Swiss Cheese Model (adapted from reason, 1990)

3.5. Human factor analysis and classification system HFACS and adaptability

Since its creation in the 90s, the HFACS model has been modified to adapt to multiple usage (Theophilus et al., 2017), analysing human factors in a wide range of industries including aviation, maritime shipping, mining, construction, and health care. Modification includes adding a fifth level in some cases, such the HFACS-MSS for machinery space fires (Schröder-Hinrichs et al., 2011) and HFACS-MA for marine accidents (Chen et al., 2013) or increase the level of granularity as in Department of Defence DOD-HFACS (O'Connor, 2008).

Table 2 HFACS Versions

	Sector	Adapted HFACS	Main modifications	Author
1.	Maritime Shipping industry safety	HFACS- MA Maritime Accident	Modification of the precondition and add the fifth level, integrate the SHEL model into the framework as adopted tool by IMO (2000)	(Chen et al., 2013)
2.		HFACS- FAHB Fuzzy, Analytical Hierarchy Process	Integration with fuzzy algorithm	(Celik & Cebi, 2009)
3.		HFACS- MSS Machinery Space on Ships	adapted to machinery space features	(Schröder-Hinrichs et al., 2011)
4.		HFACS- PV Passenger vessels	Add operational condition level	(Yildiz et al., 2021)
5.		HFACS- FCM Fuzzy Cognitive Mapping	Integrate the HFACS with fuzzy theories to quantify the accidents analysis	(Soner et al., 2015)
6.		HFACS- Coll Collision	Based on the review of 27 collision accidents, adding fifth layer of outside factors and modified Precondition for Unsafe Act	(Chauvin et al., 2013)
7.		HFACS Ground Grounding	Based on HFACS Coll with modification to adapt to 115 reviewed grounding accidents	(Mazaheri et al., 2015)
8.		HFACS- SIBCI Ship Icebreaker Collision in Ice Covered Waters	Integrate the Fault Tree Model with the HFACS, using 17 collision accidents relevant to icebreakers operations to build the framework, external factors for HFACS MA were considered (Kaptan et al., 2021)	(Zhang et al., 2019)
9.	Offshore safety	HFACS- OGI Oil and Gas Industry	Modified level one to include Act of Sabotage as an Unsafe Act, modification in all levels accept unsafe supervision level three to adapt to offshore safety scope.	(Theophilus et al., 2017)
10.		HFACS ADF Australian Defence Force	Identical to extent to the original HFACS frame with numerous contextual and semantic differences.	(N. S. Olsen & Shorrock, 2010)
11.		HFACS ME	Framework change for adaptability	(Rashid et al., 2010)
12.	Aviation/ defence	DoD HFACS US Department of Defence	A fine-grain classification level was added (O'Connor, 2008).	US Department of Defence (DoD,2005)
13.	Mining	HFACS MI Mining	Based on 508 mining accidents, modification in precondition for unsafe act level.	(Patterson & Shappell, 2010)
14.	Railroad	HFACS RR Railroad	Classify the Unsafe Act to Errors and Contraventions and add the Act of Sabotage as a third tier under Contraventions beside Routine and Exceptional.	(Reinach & Viale, 2006)

In the maritime sector, eight versions of HFACS have been identified with minor changes for adaptability, i.e., the modification of the Precondition of Unsafe Act is presented in all maritime versions of HFACS (Kaptan et al., 2021). The addition of the fifth layer of factors is presented with different labels, named as outside factors in HFACS MSS, HFACS COLL and HFACS Ground (Kaptan et al., 2021) or external factors as HFACS MA (Chen et al., 2013).

The precondition level at HFACS MA include the SHEL model adopted by the IMO (2000). The software in that level includes organizational policies and procedures (IMO, 2000), which are covered in the organizational influence level, to avoid duplication or overlapping. This HFACS layout was not considered as a base to develop the Human Factor Analysis and Classification System for Container Ships Cargo Fires (HFACS CSCF).

The HFACS Coll framework referred to 27 collision accidents occurring between 1998 and 2012 (Chauvin et al., 2013). The HFACS Ground as a lightly modified the version of the HFACS COLL (Kaptan et al., 2021) was designed mainly for grounding accidents with 115 cases used to create such framework (Kaptan et al., 2021) Due to the specialty of the frame to the grounding accidents, it was not considered through the creation of HFACS Container Ships Cargo Fires (CSCF).

3.6. Introduction of Human Factor Analysis and Classification System-Container Ships Cargo Fire (HFACS-CSCF) as a new adapted version to suite the research subject

The granularity of HFACS was not designed to address container ship accidents; therefore, an adapted framework will be created to suit the research subject. The identification process for the high frequency of causal factors container ship cargo fires can be crucial to decrease such accidents. The Human Factor Analysis and Classification System for Container Ship Cargo Fire (HFACS CSCF) is based upon a modified version of HFACS MSS, with modification to the fourth tier of causal factors and redesignation the Outside factors of HFACS- MSS as Regulatory factors.

It is worthy to note that the international standards and flag state responsibilities and implementation are not outside factors, because in the maritime domain, nothing is outside factors. Therefore, the fifth layer was labelled with Regulatory Factors to ensure the system approach in dealing with the causal factors related to human performance affecting Container Ships Cargo Fires accidents.

The details of the third tier under the Regulatory Factors level include international standard and flag state implementation as HFACS MSS (Schröder-Hinrichs et al., 2011), in addition to port state implementation including the container control, inspection and content identification responsibilities.

The HFACS CSCF consists of five levels and 13 categories in the second tier corresponding to them, the Unsafe Act as the first level and only active failure, triggers the incident and reveal the remaining four latent failures in the system. (See Table 5)

Weather condition under ship operations is classified under precondition for unsafe act in the first tier and environmental factors in the second tier, with description of physical environment at the third tier of this category. Factors such air temperature either tropical or cold and sea state with associated winds are considered as contributing factors in many cases as noticed from the container fire reports, when weather conditions affect individuals and contribute to fire in containers (DoD, 2005). This is classified as physical environmental factors.

The design or operational failure in fixed firefighting system or critical firefighting equipment are classified under precondition for unsafe act as the first tier, environmental factors as second tier and technological factors as third tire. The criteria here is the equipment design that affects individuals and their actions in workplace and lead to “unsafe situation” (DoD, 2005).

Table 3 HFACS CSCF

	1ST TIER	2ND TIER	*3RD TIER*
Latent failure	**Regulatory Factors (Level 5)**	Statutory	*International standard*
			Port state implementation
			Ship Flag state implementation
	Organizational Influences (Level 4)	Resources	*Human resources*
			Technological resources
			Equipment/facilities resources
		Organizational climate	*Structure*
			policies
			cultures
		Organizational process	*Operation*
			procedure
			oversight
	Unsafe Supervision/ workplace factors (Level 3)	Inadequate supervision	*Shipborne and shore supervision*
		Planned inappropriate operations	*Shipborne operation*
		Failed to correct known problems	*Shipborne related short comings*
		Supervisory violation	*Shipborne violation*
	Precondition for Unsafe Acts (Level 2)	Environmental factors	*Physical environment*
			Technological environment
		Crew condition	*Cognitive factors*
			Physiological state
		Personal factors	*Crew interaction*
			Personal readiness
Active failure	**Unsafe Acts (Level 1)**	Errors	*Skill Based Error*
			Decision and judgment error
			Perceptual errors
			Operators' error
		Violations	*Ship's crew Routine violation*
			Ship's crew Exceptional violation
			Operator's violation

The human error research effort has focuse on the crew onboard the ship for decades as the only source of errors and violations (Sánchez-Beaskoetxea et al., 2021), while in the shipping industry system approach for human error, other individuals should not be excluded. The gantry crane operator, shipper or charterers and third-party maintenance or repair gang can perform unsafe acts triggering the sequence of events leading to misshapes or accidents. The tunnel vision of connecting human error accidents on board the ship only to the crew on board needs to be eliminated. The interface between the ship, port and other stake holders as charterers and shippers need to be considered.

Arguments here can arise if the shippers' or charterers' unsafe acts need to be classified as outside factors. In the system approach for the container shipping industry nothing is outside factors, so all the parts of the industry need to be examined as a whole system.

The unsafe act can be categorized as errors and violations (Kaptan et al., 2021). Errors are not exclusive to the ship's crew only; in other words, the unintentional acts that lead to triggering an accident can also be operator based. Conducting hot work near containers shows a lack of awareness from both the ship's crew and repair gang and can be classified as an error. Operator error causal categories are added to discriminate such type of errors.

Following such an approach, violations need to be classified as ship's crew violations and other operators' violations, which are included in the fourth tier. Related causal factors are shipping of undeclared dangerous goods by shippers or charters, the improper handling of a containers by crane operators or violations related to third party maintenance or repair gang.

HFACS violations represent the intentional bypass of regulations and rules governing the maritime shipping industry (Shappell & Wiegmann, 2003). The differentiation between routine and exceptional violations is often based on an organization's response to, and individual behaviour (Kaptan et al., 2021).

The Routine Violation as intended disregard to policies and regulations tolerated by the organization (Kaptan et al., 2021), described as habitual (Patterson & Shappell, 2010).

In analysing the unsafe act of mis declare or undeclare dangerous goods by shippers or charterers; its neither a habitual nor intentionally tolerated by the organization, it cannot be described as exceptional violation as its not "isolated departure from the authority", which doesn't reflect the individual behaviour nor organization tolerance (Patterson & Shappell, 2010). to enhance the granularity of the framework we create another causal factor in the third tier of violations named as Operator's Violations, defined as intended acts to disregard rules, policies, and regulations, tacitly encouraged by lack of organization technical ability to monitor all operations aspects, to prevent its occurrence.

Thus, the organizations' tolerance is neither a lack of awareness of the risks nor to enable flexing the rules, but rather a lack of technical capability and tools to monitor and identify the risks effectively.

3.7. The HFACS-CSCF coding process

Reviewing the Global Integrated Shipping Information System (GISIS), a total of 19 container ship cargo fire reports were analysed to create the HFACS CSCF codes revealed through each report. These were unified in tier four of causal factors in the five levels of HFACS CSCF and reviewed by two experts to agree on the coding process (See Figure 12). (See Appendix A)

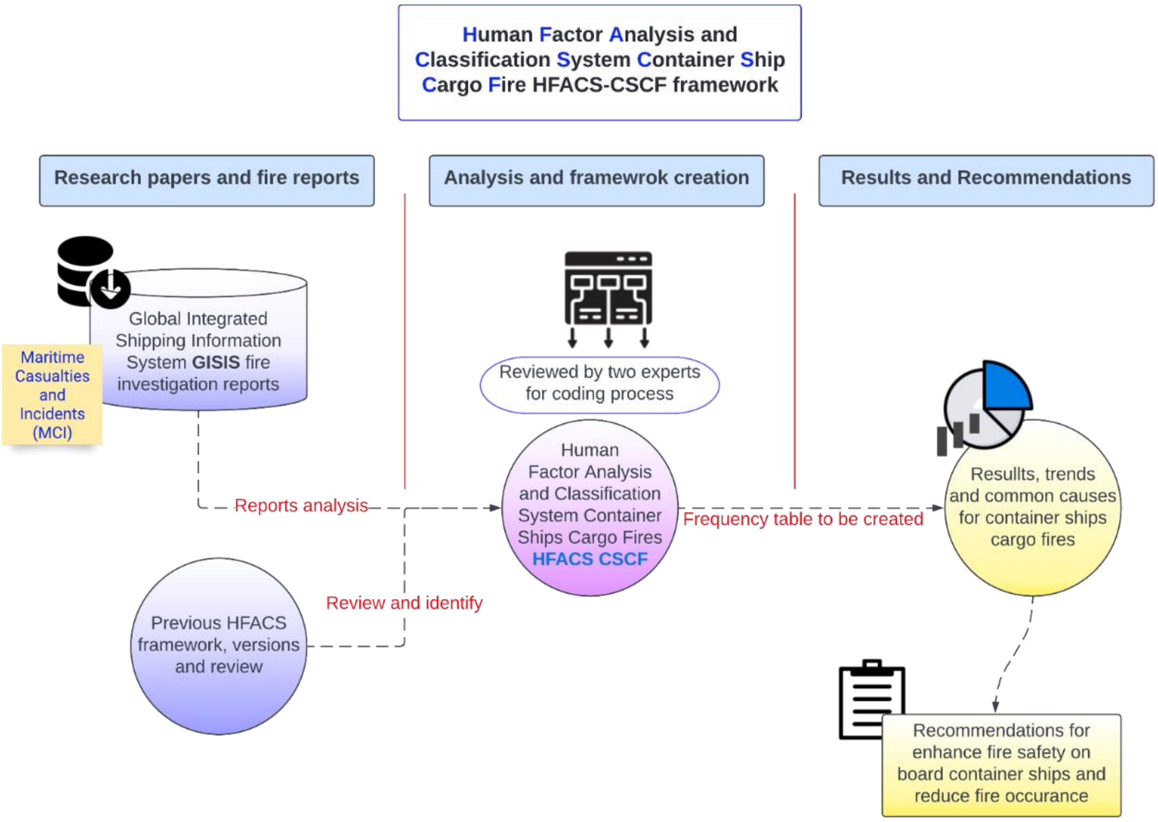

Figure 11 Human Factor Analysis and Classification System Container Ship Cargo Fires HFACS- CSCF framework

Chapter 4

Results and analysis

4.1. Introduction

Identifying the trends in container ship cargo fires using the Human Factor Analysis and Classification System for Container Ships Cargo Fires (HFACS CSCF) and create the causal factor data with classification, will contribute to increase the awareness for container ship cargo fires and help reveal the recommendations and mitigation process required.

4.2. Frequency and percentage of Causal Factor according to Human Factor Analysis and Classification System – Container Ship Cargo Fires (HFACS-CSCF)

Reviewing the 19 container ships fire accidents investigation reports in the period 2010-2020, obtained through GISIS platform using HFACS CSCF described in chapter three, 259-causal factors in the fourth tier were identified through the process and categorized under the five categories of HFACS CSCF with the corresponding second and third tier causal factors.

Table 4 Causal factor frequency and percentage using HFACS-CSCF

HFACS CSCF category	N	%
Regulatory Factors	**54**	**20.9%**
International standard	17	6.6%
Port state implementation	23	8.9%
Ship Flag state implementation	14	5.4%
Organizational Influences	**44**	**17.1%**
Human resources	1	0.4%
Technological resources	10	3.9%
Equipment/facilities / resources	23	8.9%
Procedure	6	2.3%
Oversight	4	1.5%
Unsafe Supervision/workplace factors	**27**	**10.5%**
Shipborne and shore supervision	20	7.7%
Shipborne operation	3	1.2%
Shipborne related short comings	4	1.6%
Shipborne violation	0	-
Precondition for Unsafe Acts	**84**	**32.6%**
Physical environment	59	22.9%
Technological environment	16	6.2%
Cognitive factors	5	1.9%
Physiological state	1	0.4%
Crew interaction	4	1.6%
Personal readiness		
Unsafe Acts	**49**	**19%**
Skill Based Error	9	3.5%
Decision and judgment error	11	4.3%
Perceptual errors	4	1.6%
operators' error	2	0.8%
Ship's crew Routine violation	2	0.8%
Ship's crew Exceptional violation	0	-
Operator's violation	21	8.1%
Total	**259**	**100%**

The less frequent set of causal factors contributed to container ship fire accidents are set in the Unsafe Supervision (US) category, while the high frequent contributed causal factors were set in the Precondition for Unsafe Act (PUA) category.

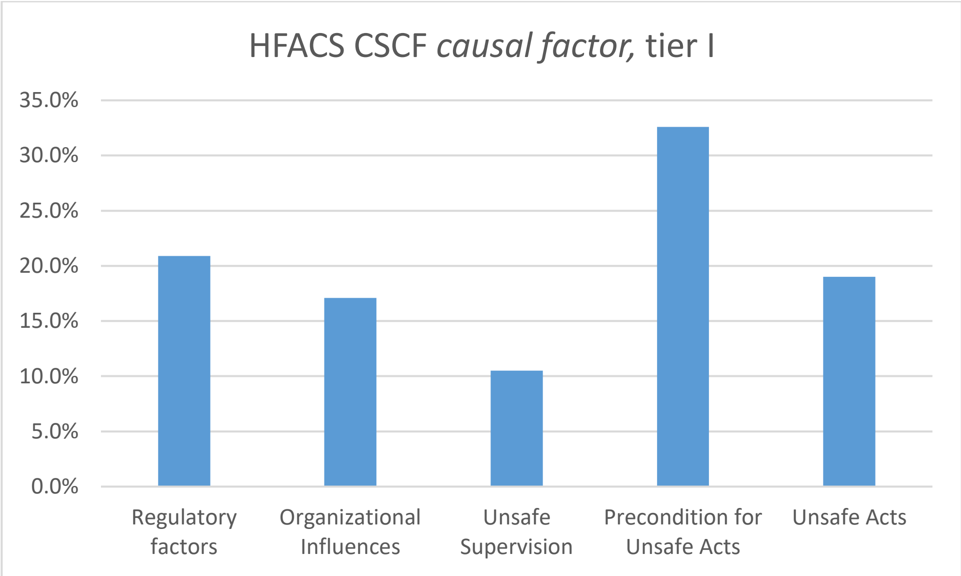

Figure 12 HFACS CSCF causal factors distribution

The Unsafe Act (US) causal factors represent 19% of total causal factors and together with the Precondition for Unsafe Act (PUA) represent 51.6% of total causal factors. The Operator Violation represent 42.9% of the unsafe acts, while representing 8.1% from total HFACS-CSCF causal factors, the operator violations corresponding granular factors in the 4^{th} tier show shippers' mis declared or undeclared dangerous goods, which through the analysis represent the most frequent Unsafe Act (US) unleashing the container ships fire accident sequence.

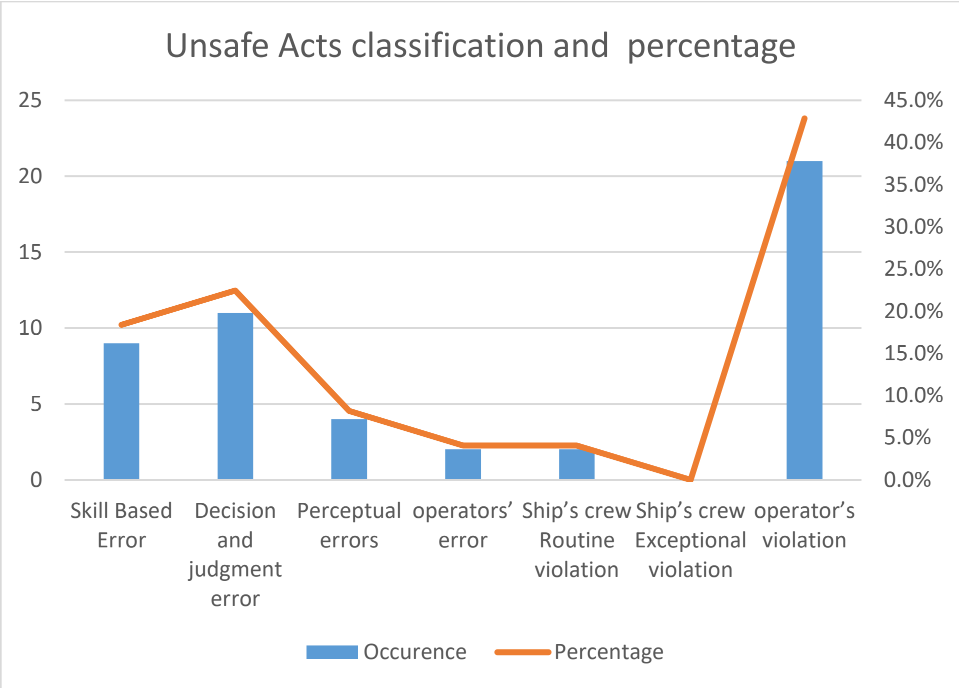

Figure 13 Unsafe Acts (US) 3rd tier distribution and percentage

The distribution of Errors to Violations in the Unsafe Acts (US) category trend to the Errors with 53%, while Violation represents 47% from all Unsafe Acts.

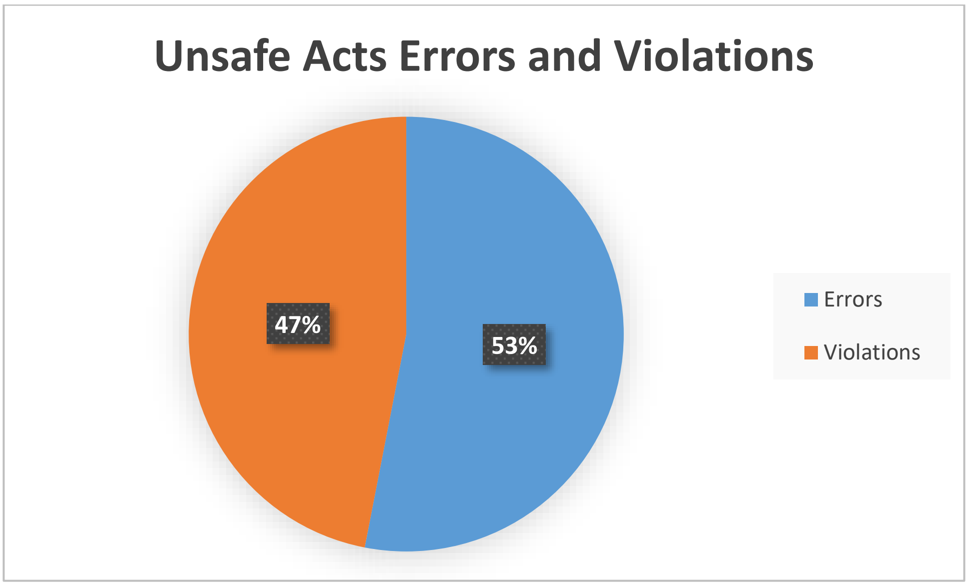

Figure 14 Unsafe Acts Errors and Violations

The precondition for unsafe act (PUA) with 84 causal factors represent 32.6% of all causal factors in container ships fire accident occurrence, with Physical Environment as the most frequent third tier causal factors forming 22.9% of all causal factors in the HFACS CSCF and 70% of the (PUA) factors set. Technological Environment come second with 18% from PUA factors set.

In the PUA tier three, physical environment, and corresponding tier four with detailed factors, the difficult of accessibility to the source of fires and absence of suitable ventilation inside the container, each form 4.7% of total HFACS CSCF causal factors. They represent combined 9.4% of the total causal factors.

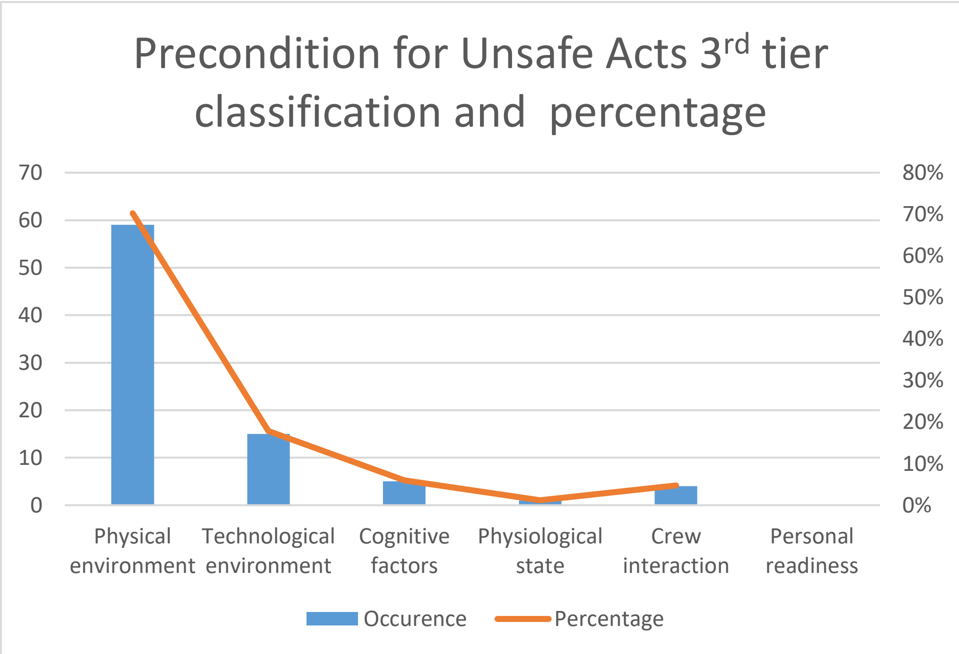

Figure 15 Precondition for Unsafe Acts (PUA) 3rd tier distribution and percentage

The unsafe supervision category contributes to 10.5% of total HFACS factors, with shipborne and shore supervision factors on top with 20 occurrences represent 7.8% of total HFACS CSCF causal factors.

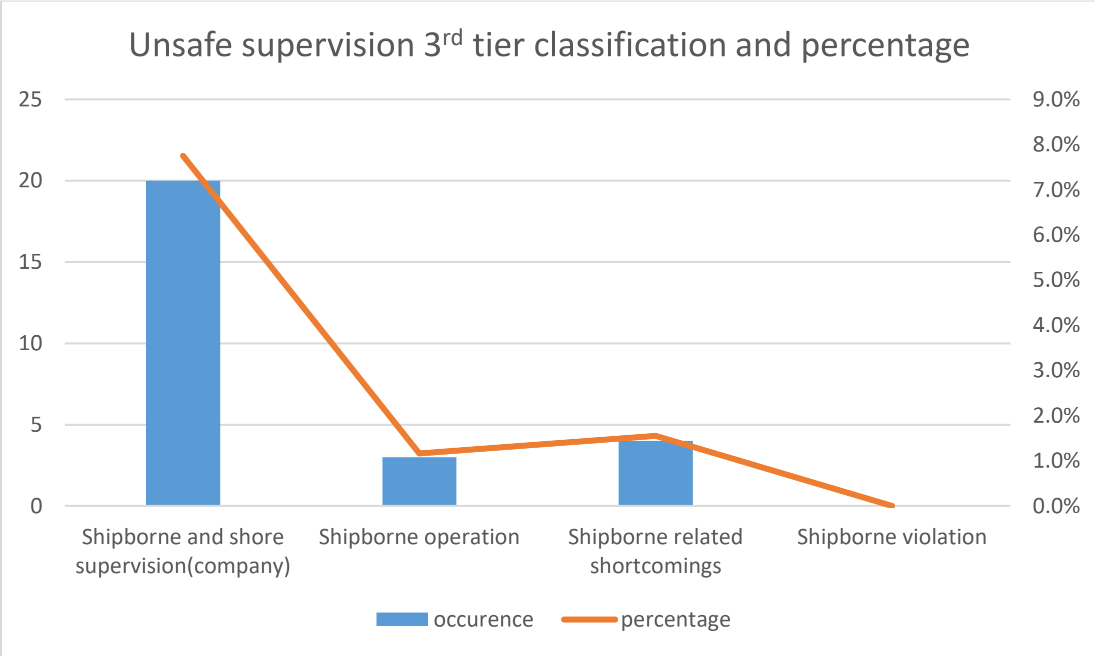

Figure 16 Unsafe Supervision (US) 3rd tier distribution and percentage.

The contributing factor related to Organization Influence (OI) category have 44 occurrences with 17.1% of total HFACS CSCF factors. Factors related to Equipment and Resources failure have majority percentage of this category, while representing 8.9% of total HFACS CSCF causal factors, the fourth-tier factors related to equipment and resources occurrence is absence of alternatives firefighting system to contain and supress the large-scale fires in cargo holds, which have seven occurrences with 2.7% of total HFACS CSCF. The second frequent set within the OI category is technological resources split between poor activation mechanism and poor design for fixed firefighting systems mainly the carbon dioxide, five of each has occurrence with 1.9% of total HFACS CSCF causal factors in the fourth tier.

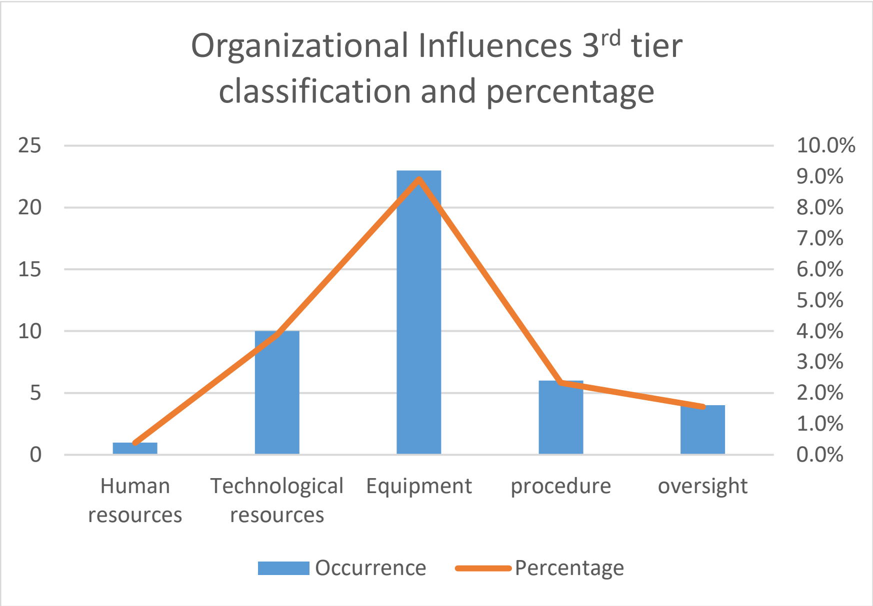

Figure 17 Organizational Influences 3rd tier distribution and percentage.

Regulator Factor (RF) as level one has 20.9% contribution to total causal factors, with failures related to port state implementation of international regulations regarding container inspection and content verification with focus on dangerous goods containers. These have 20 occurrences with 7.8%, in addition to the absence of legislation against false declaration of dangerous goods with three occurrences representing 1.2% of total causal factors.

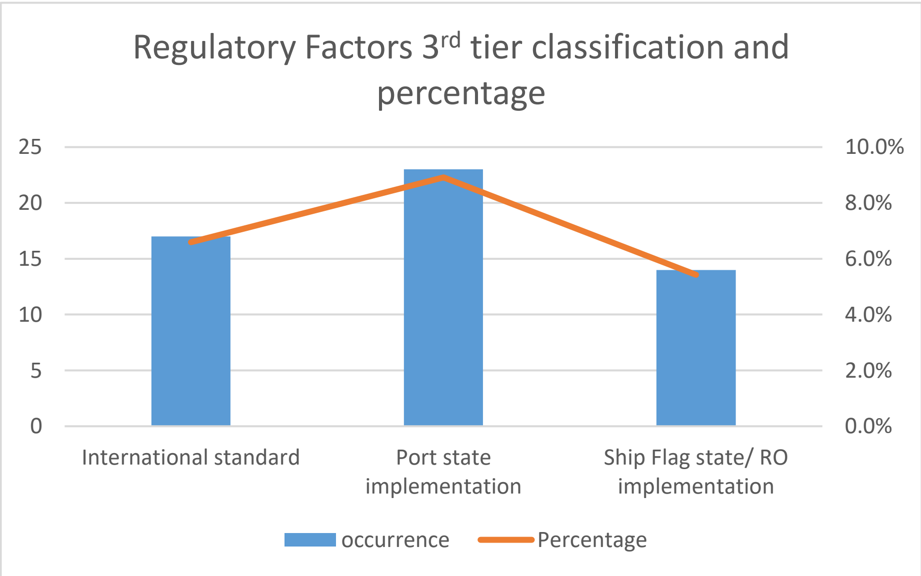

Figure 18 Regulatory Factors 3rd tier distribution and percentage.

4.3. Unpublished container fires investigation reports negative impact

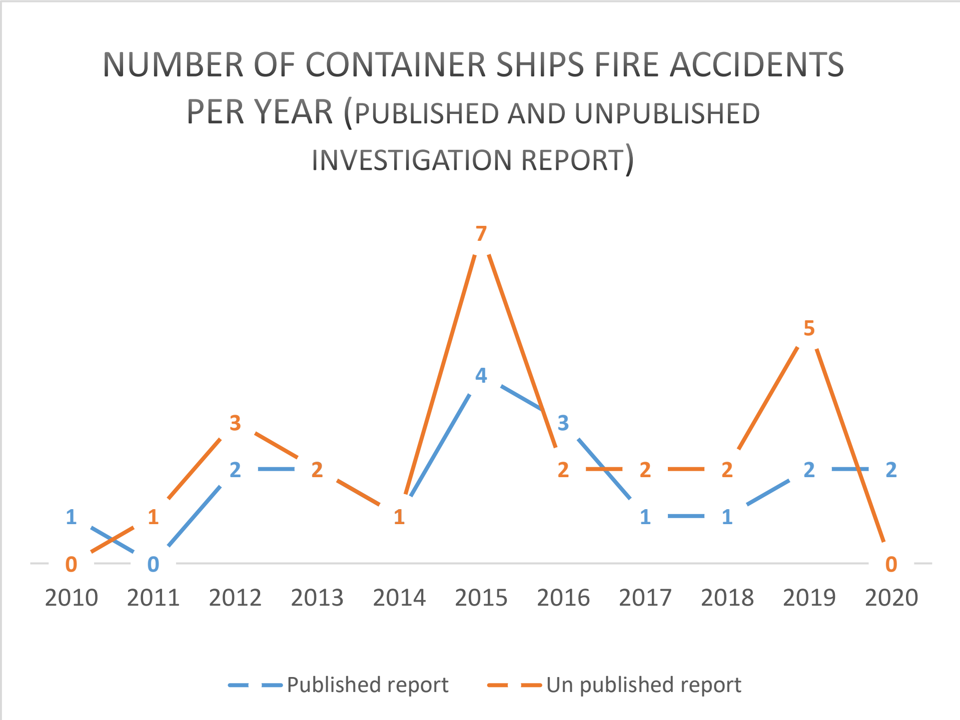

Figure 19 Container ships fire accidents per year- published and unpublished investigation reports

The feedback that the maritime industry and researchers get from casualties is the investigation reports, reviewing such reports and identifying lessons and creating mitigation measures to prevent reoccurrences. This is the only link to enhance the safety in general and the fire safety measure in the maritime domain. In absence of such link, reoccurrence of such disastrous fire accidents is probable. The number of fire accidents with published investigation reports are representing 43% of total container ship fire accidents, meaning that the causal factor revealed through HFACS CSCF is the tip of an iceberg with undetected latent causal factors represented in all these unpublished or unaccomplished investigations reports.

In the decade of 2010 -2020, the total container ship fire accidents peaked twice, once in 2015 with eleven occurrences, while others were in 2019 with seven occurrences.

4.4. Activation occurrence of Fixed Firefighting Systems – Carbon Dioxide and failure percentage

Among the 19 analyzed container ship cargo fires, the Carbon Dioxide as a Fixed Gas System for cargo hold protection has been used 11 times. The system was ineffective 10 times with failure percentage up to 91%. It is worth noting that in those 10 times, the system had technical failure on 4 occasions, while CO_2 was released on the remaining 6 occasions. Without efficiency in fire suppression, the failures were either due to human error or latent technical failure.

Fire in the container ship cargo area is deep seated fire, where solid material is involved and subject to smouldering (NFPA, 2022), accompanied with high temperature, dense smoke, and unexpected explosions.

The IMO mandate through SOLAS II-2/10.7.1.3 fixed a carbon dioxide gas system to protect cargo space for ships above 2000 gross tonnage. The same requirements apply through SOLAS II-2/10.7.2 for any cargo space authorized for dangerous goods carriage, and such requirements are applicable for all container and cargo ships (IMO, 2022c).

Carbon dioxide is used as a fixed gas system with smothering effect, which suffocates the fire by replacing the oxygen, preventing the fire from one necessary element to continue and escalate.

The Extinguishment Concentration for CO_2 is set through many standards including the NFPA-2001, measured by the cup burner method, and through such tests, the Minimum Extinguishment Concentration (MEC) and Associated Minimum Designed Concentration (MDC) are defined.

$$MDC = MEC \times safety\ factor$$

Where:

MDC: Minimum Design Concentration

MEC: Minimum Extinguishing Concentration

Safety factor: depend on type of protected item, material, or cargo

Equation 1 Minimum Design Concentration calculation

The carbon dioxide MDC depend on the type of cargo in the cargo space, as example for flammable gases and associated vapour the MDC vary and set in table 5.3.2.2 in NFPA 12 standard related to carbon dioxide extinguishing system, and in any case shall not be less than 34% from gross volume of protected space (NFPA, 2022).

Examining Resolution MSC.206(81), which entry into force at 2010 as fire safety system (FSS) code amendments, the required CO_2 gas concentration for cargo space protection equal to 30 % of protected space gross volume, knowing that carbon dioxide occupies 0.56 m^3 for one kilogram (IMO, 2010b), hence the discharge quantity of CO_2 depends on the available volume of the cargo hold.
The NFPA 12 standard set in paragraph 5.3.5.3 that for each 2.8°C above 93°C, one percent of gas concentration should be increased, such point needs to be considered, moreover, when two materials have different MDC will be available in the protected space, the higher MDC should be considered (NFPA, 2022), due to the nature of container shipping industry and the variety of cargo inside the hold, not mentioned the hazard of undeclared dangerous cargo inside the hold , the MDC for CO_2 fixed system need technical review in the awake of recent failure or un effectiveness of the system after release.

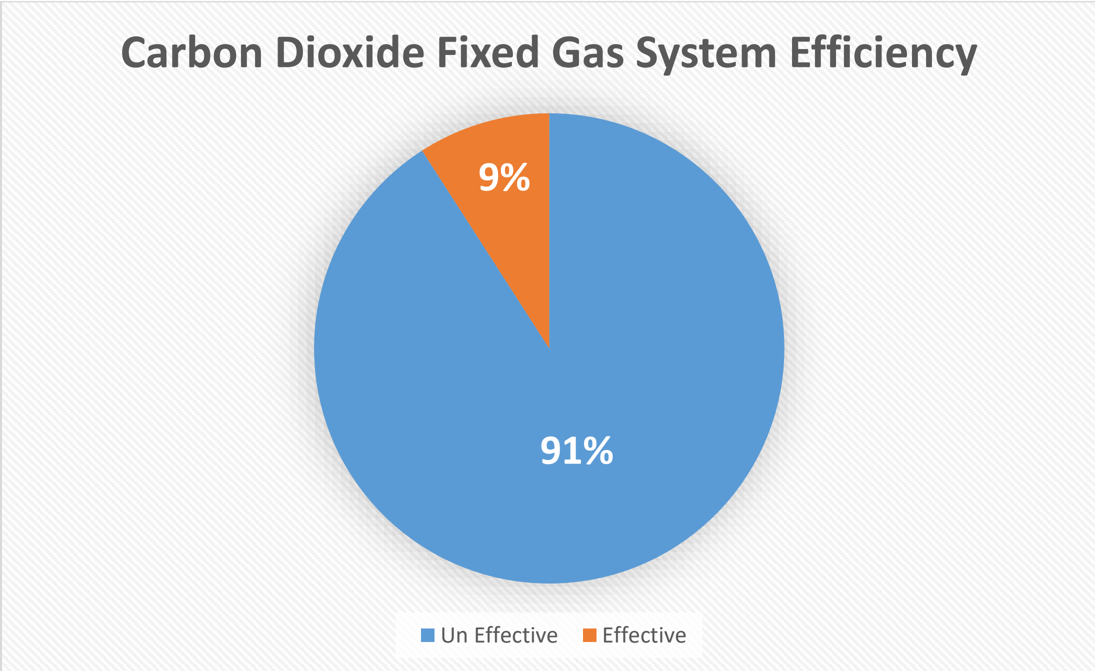

Figure 20 Carbon Dioxide Fixed Gas System Efficiency

The human error in starting procedure of fixed carbon dioxide system represented in Unsafe Act level (UA2) with two occurrence form 0.8% of total HFACS CSCF causal factors, the cases reveal such occurrence was Caroline Maersk in 2015 and MSC Flaminia in 2012 (BSU, 2014), in Carolina Maersk case, due to unfamiliarity with the system the control valve in the control station was not in fully opened position led to explosion in the CO_2 room itself (DMAIB, 2016).

Other failure occasions were due to latent technical failures which does not reveal through the last inspection or audit, the technical failure on one occasion caused by two leakage points at the system lines prevent the CO_2 to be delivered to the intended cargo space (MSIU, 2016), in the other occasion the time delay unit was not functional resulted the failure of gas release through the system pipelines (BSU, 2020) and last case of latent design failure was in MSC Flaminia with misconnected pipes and arrangement combined with the human error occur before the start of the system (BSU, 2014).

The CO_2 system discharge lines condition and time delay unit functionality are covered through IMO "Revised Guidelines for The Maintenance and Inspections of Fixed Carbon Dioxide Fire-Extinguishing Systems", "MSC.1/Circ.1318/Rev.1", in the "minimum required maintenance" at intermediate or renewal survey the system piping shall be blown with dry air or nitrogen after disconnected from the main system (IMO, 2021b), knowing that the intermediate survey can held within second or third anniversary with six months "time window" (IMO, 2012).

Furthermore, the detailed inspection and testing checklist attached to circular 1318 with discharging line integrity and time delay unit functionality included , the fact that vessels faced escalated fire situation due to such problems spot the light to the credibility of such service and maintenance schedule and quality, in addition, the integrity of carbon dioxide discharging lines under pressure can be checked by the crewmembers in annual base to maintain the readiness state of such critical firefighting system, with reported data back to the company and stakeholders.

4.5. Container fire casualties by flag state and severity for published fire investigation report in 2010-2020 period

The IMO Casualty Investigation Code has a definition for "very serious casualties" as "any marine casualty involving the total loss of the ship or life loss or severe environmental damage" (IMO, 2008b), But, neither "serious" nor "less serious" casualties have a standard definition in the code (IMO, 2008b).

The investigation authorities for member states have different criteria for severity classification (Wang et al., 2021), to facilitate the reporting procedure to IMO the casualties have been categorized into four categories, "very serious, serious, less serious and marine incident" (IMO, 2008a), where "serious casualty" can be defined as casualty not qualified as "very serious" accidents and involve fire, explosion or grounding lead to main engine disabled and extensive structural damage and required salvage or shore assistance (Wang et al., 2021), and accordingly the less serious casualties defined as accidents that does not qualified as “very serious” or “serious” casualties (Wang et al., 2021).

Retrieving data from the 19 identified container ship fire accidents in cargo area in 2010 – 2020 period through the provided investigation reports by GISIS reveal eleven serious, five less serious and three very serious container ship fire accidents, it’s clear that most of container fire accidents in cargo area have a serious severity (Figure 22), where external assistance were required, and ships suffer accommodation and structure damage, while three very serious casualties lead to total loss of the vessel or death cases or sever pollution , five less serious accident with light impact.

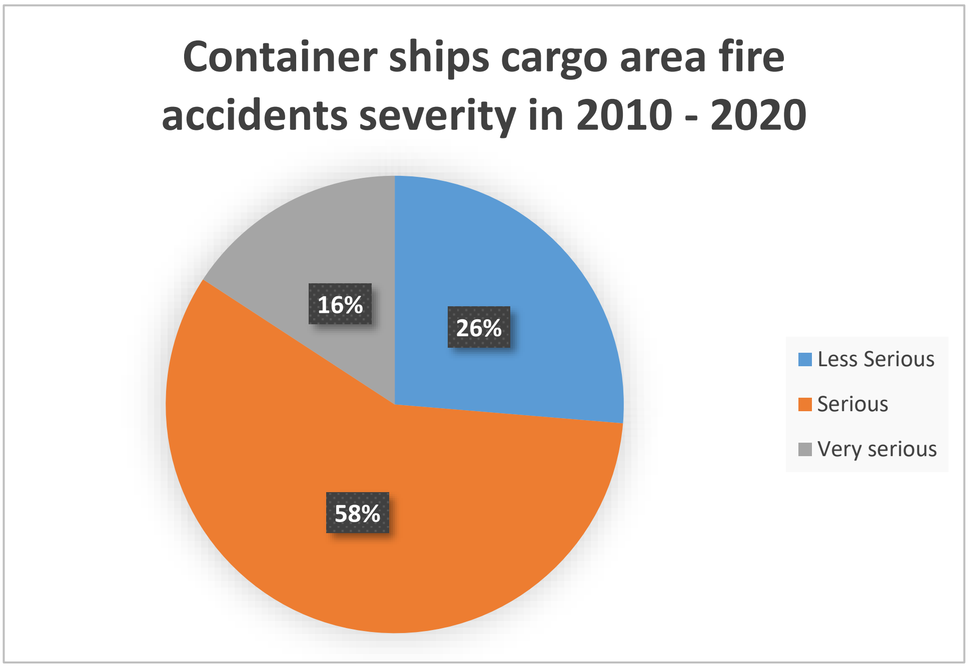

Figure 21 Container ship cargo area fire accident severity in the period 2010-2020

All casualties’ cases connected to the Denmark was serious, all was investigated in detail with excellent quality investigation report, while most of Maltese flag fire accidents was less serious, Liberian flag casualties either serious or very serious (Figure 23).

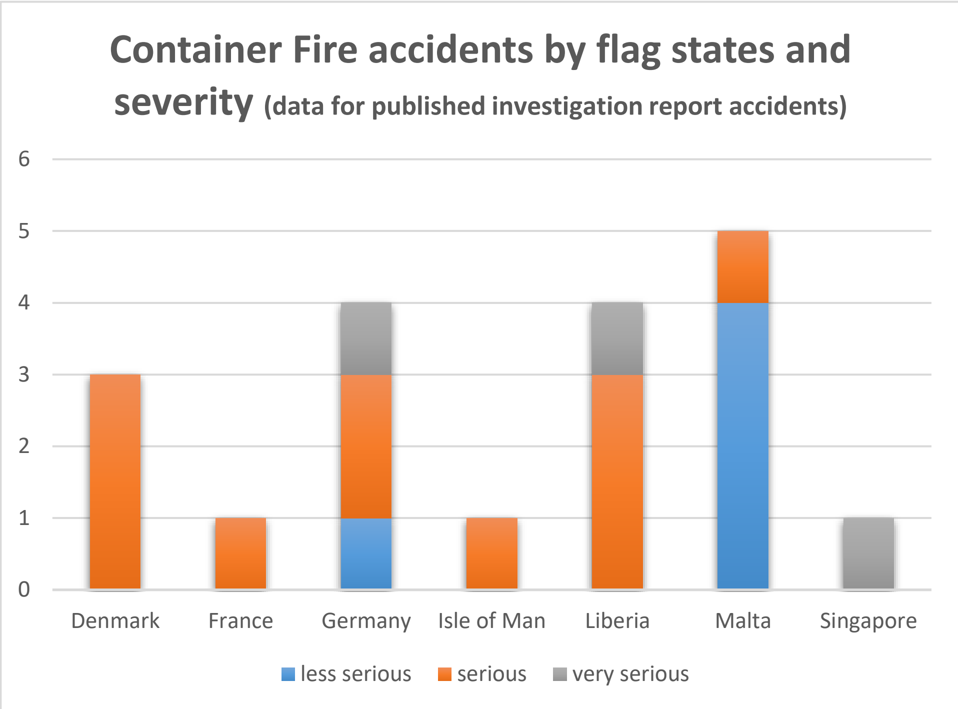

Figure 22 Container fire accidents by flag states and severity in 2010- 2020 period

4.6. Average duration of container ships fires in the period 2010-2020 and sustainability of Self-Contained Breathing Apparatus air supply

Part of increasing our awareness about container ships fires is knowing its characteristics, types, and behaviour in addition to spread mechanism.

The average duration for continuous fire on board container ships in the period 2010-2020 after reviewing the accidents narratives in the 19 published fire accident reports is seven days or 168 hrs, such prolonged duration reflect the challenges faced either by crew onboard (Table 7).

According to SOLAS II-2/10.10.1 all ships shall carry two firefighter outfit (IMO, 2022c), such outfit consist of personal set and self-contained breathing apparatus (SCBA) with Two spare cylinders for each set (IMO, 2019), which mean a total four spare cylinders to be available according to SOLAS, II-2/10.10.2.5 (IMO, 2022c).

In addition, cargo vessels authorized to carry dangerous goods as the container ships shall carry two SCBA with two spare cylinders for each set according to SOLAS, II-2/19.3.6.2 (IMO, 2022c).

Table 5 Container ships fires durations and average 2010-2020

Fire accident date	***Ships Name***	***Fire Duration in days***
28-09-20	X-PRESS GODAVARI	2
23-02-20	CROATIA	0
11-11-19	FILIA T	0.2
03-01-19	YANTIAN EXPRESS	18
06-03-18	MAERSK HONAM	6
12-02-17	APL AUSTRIA	3
01-09-16	CCNI ARAUCO	3
15-06-16	CMA CGM ROSSINI	5
21-02-16	LUDWIGSHAFEN EXPRESS	0.4
20-11-15	MSC KATRINA	0.8
07-09-15	BARZAN	7
26-08-15	CAROLINE MÆRSK	3.33
01-05-15	HANJIN GREEN EARTH	13
06-04-14	NOTHERN GUARD	1
15-07-13	HANSA BRANDENBERG	7
18-06-13	EUGEN MÆRSK	6
20-07-12	ZIM RIO GRANDE	0.1
14-07-12	MSC FLAMINIA	49
07-07-10	CHARLOTTE MAERSK	12
	Average	**7 days**

SOLAS convention considers the cylinders will be used during training and drills and mandate in Regulation 15.2.2.6 either that spare cylinders should be available to compensate the ones used in drills and training, taking into consideration the drills frequency, or means should be available for cylinders refilling (IMO, 2022c).

Summarizing SOLAS requirements for SCBA carriage and spare charges, the container vessels have to carry four sets of SCBA with two options regard the spare charges either eight spare cylinders and a number of additional spare cylinders to compensate drills activities related, or four spare cylinders if the vessel equipped with refilling means such Breathing Air Compressor (IMO, 2022c).

Considering that SCBA with air volume 1200L provide 30 minutes (IMO, 2019) and other types with air volume 1800L provide 40 minutes of air supply (ABS, 2022a), noting the aforementioned rules and first option ,which required 200% spare charges, 12 cylinders of air will be available in container ships in case of fire, knowing that any firefighting team consist of at least two crew members, which mean, every crew member of the team will have six cylinders, multiplying the cylinders number by 40 minutes per each, which is the maximum, leading to that time available with air supply for each crew member will be 240 minutes or four hours, in a ship type with average fire duration of a weak -seven days.

The sustainability of air supply to firefighting crew members onboard container ships as a regulation need to be revised, reviewing the causal factors in HFACS CSCF there have been four occurrence of air cylinder lack related to equipment and resources under Organizational Influence (OI) category represent 1.6% of all causal factors, with associated occurrence in regulatory factors (RF1) where current regulatory framework failed to sustain air supply for SCBA and firefighting effort accordingly.

Comparing with other ship type, in the scope of regulatory framework, the passenger vessels carrying more than 36 passengers are mandated according to SOLAS II-2/10.10.2.6 to carry either charging means for SCBA air cylinders or storage system with high pressure for air supply of the SCBA.

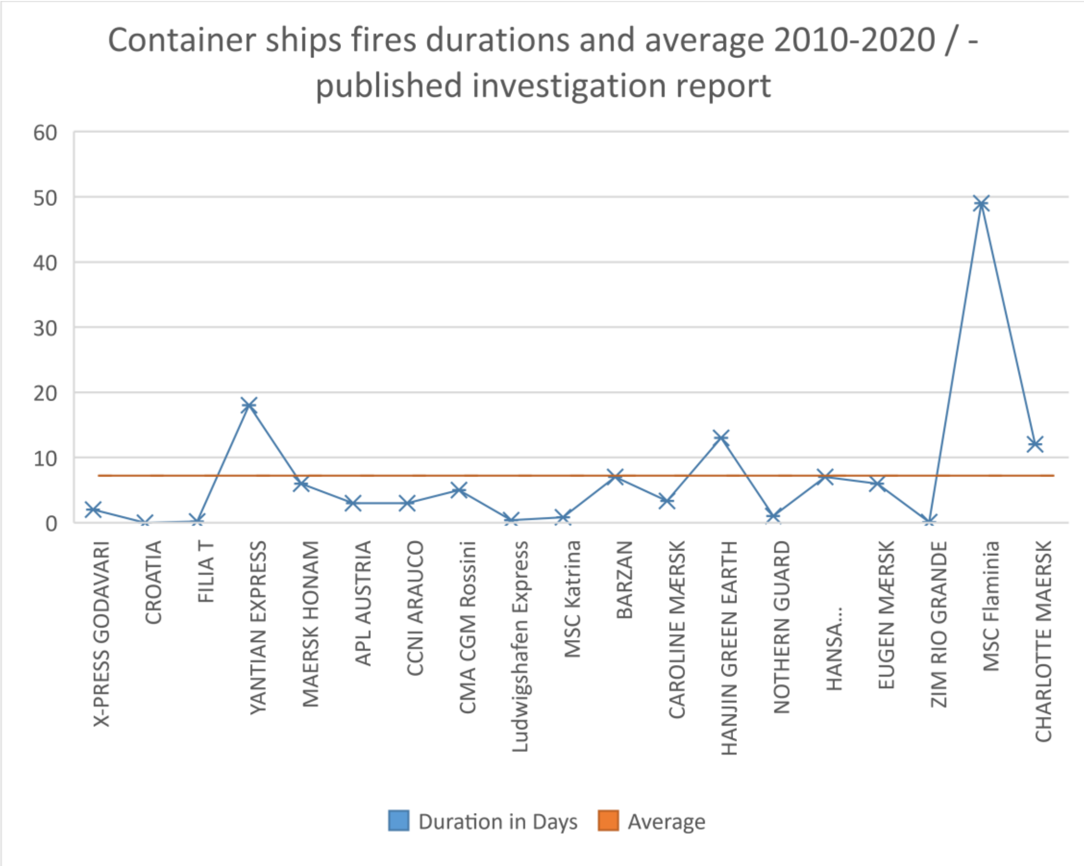

Figure 23 Container ships fires duration and average 2010-2020

Its worthy note that SOLAS give the maritime administration of any flag the right to increase the number of SCBA or spare charges (IMO, 2022c) in relation to type and size of the vessel according to SOLAS, II-2/10.10.2.4, furthermore, SOLAS convention as international standard known to set the minimum requirement also, meaning that flag state and RO can increase the numbers of SCBA, and spare charges based on HAZID.

According to American Bureau of Shipping (ABS) classification society, the rules for building and classing marine vessels, the same SOLAS optional requirements available regard to 200% spare charges for SCBA or 100 % spare charges if refilling means is available (ABS, 2022b), without mandating the breathing air compressor, meanwhile, the Enhanced Fire Protection notation for cargo area (EFP-C) issued by ABS as additional notation, eligible for container vessels, require breathing air compressor with independent power supply and 75 ltr/min charging capacity and for protection of open deck cargo area a total eight sets of SCBA to be available (ABS, 2022a).

In additional notations set by the DNV-GL classification society to enhance fire safety measures in the scope of equipment and design features, which is eligible for container carrier according to the notation, the breathing air compressor should be available, with the same requirement provided by ABS regard power supply and charging capacity (DNV GL, 2019).

Table 6 ABS and DNV-GL rules and notations related to Breathing Air compressor for SCBA refilling

CS	Rules/Notations	Part	Chapter	Section	Paragraph	Requirements
ABS	Marine Vessels **R**ules	4	7	3	15.5.1	Same SOLAS II-2/10.10 requirements for SCBA spare charges
ABS	Enhanced Fire Protection (EFP)	**g**uide	1	4	7.3	Breathing air compressor
ABS	Enhanced Fire Protection (EFP)	**g**uide	4	2	7.3	8 set of SCBA for open deck cargo area
DNV-GL	Additional class **n**otations , Equipment and design features	6	5	4	1.7.4	Breathing air compressor

These additional notations provided either by ABS or DNV-GL are not mandatory and act as additional requirements (DNV GL, 2019), exceeding the current standard set by classification society itself and applicable IMO instrument with SOLAS convention in the front.

Sustainability of air supply to refill SCBA cylinders mean sustainability in firefighting effort by crew members until they supported by external assistance or suppress the fire.

4.7. Fire space of origin either on deck or at cargo hold

Most of the container ships fires in 2010 – 2020 period with published investigation report originated in cargo hold, while 32% started on deck, the fire in cargo hold associated with many challenges such difficult accessibility to the seat of fire and impaired vision due to heavy smoke and unsuitability of fixed firefighting gas system to the type of cargo on fire (Figure 25).

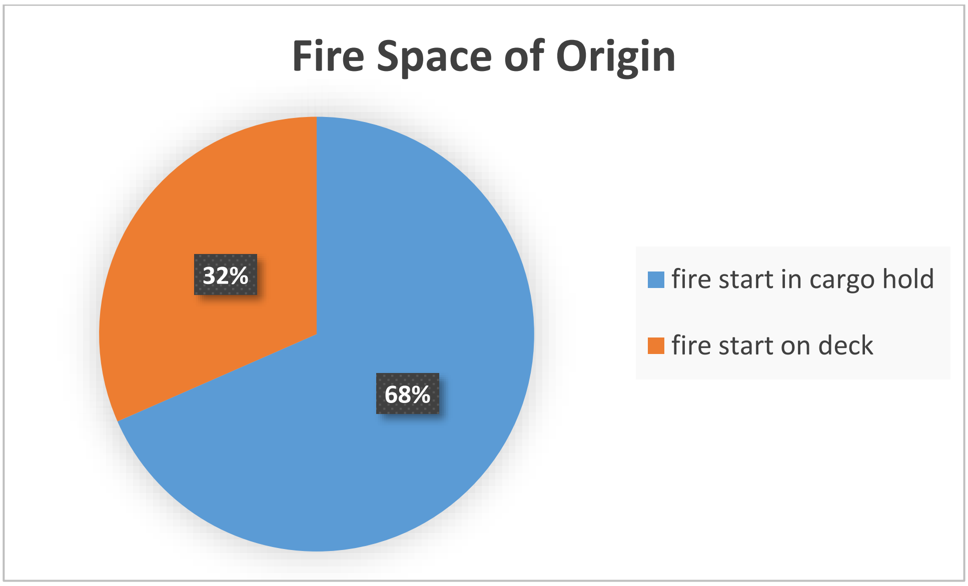

Figure 24 Container ships fires space of origin

Due to ineffective fire containment measures, and absence of fire divisions to help such principles, most of the cargo hold fires spread to the deck or vice versa, transverse bulkheads between the holds shall be covered with drenching system to help achieve such principle as a secondary option, with enhanced dewatering capabilities to avoid accumulation of water accompanying the container ships cargo hold fires.

4.8. Sources of ignition in the published fire accidents on container ships

Sources of ignition in container ships fires identified through the 19 investigation reports, the calcium hypochlorite and charcoal came on the top of the list with 16 % for each while lithium-ion batteries with undeclared unknown dangerous goods sources came second with 11% for each, most of other sources of ignition have one occurrence with 5 % from all sources (Table 9, Figure 26).

Table 7 Container ships fires sources of ignition

Sources of ignition	***IMDG Class***	***N***	***%***
Lithium-Ion Batteries	9	2	**11%**
Charcoal	4.2	3	**16%**
Calcium hypochlorite	5.1	3	**16%**
Calcium chlorite- calcium chlorate	5.1	1	5%
Thiourea Dioxide-Formamidine Sulfonic Acid	4.2	1	5%
Divinylbenzene-Diphenylamine	4.1	1	5%
Methyl Ethyl Ketone Peroxide (**MEKP)**	5.2	1	5%
Sodium Dichloroisocyanurate Dihydrate (**SDID)**	9	1	5%
Unknow-pyro char (coconut coal)	4.2	1	5%
Container collapse	n/a	1	5%
Cinnamon leaves	unclassified	1	5%
Cars spare parts/batteries/ flares /cigarette lighter/ fuel tank	unclassified	1	5%
Undeclared dangerous goods- unknown	n/a	2	**11%**
Total	**-**	**19**	

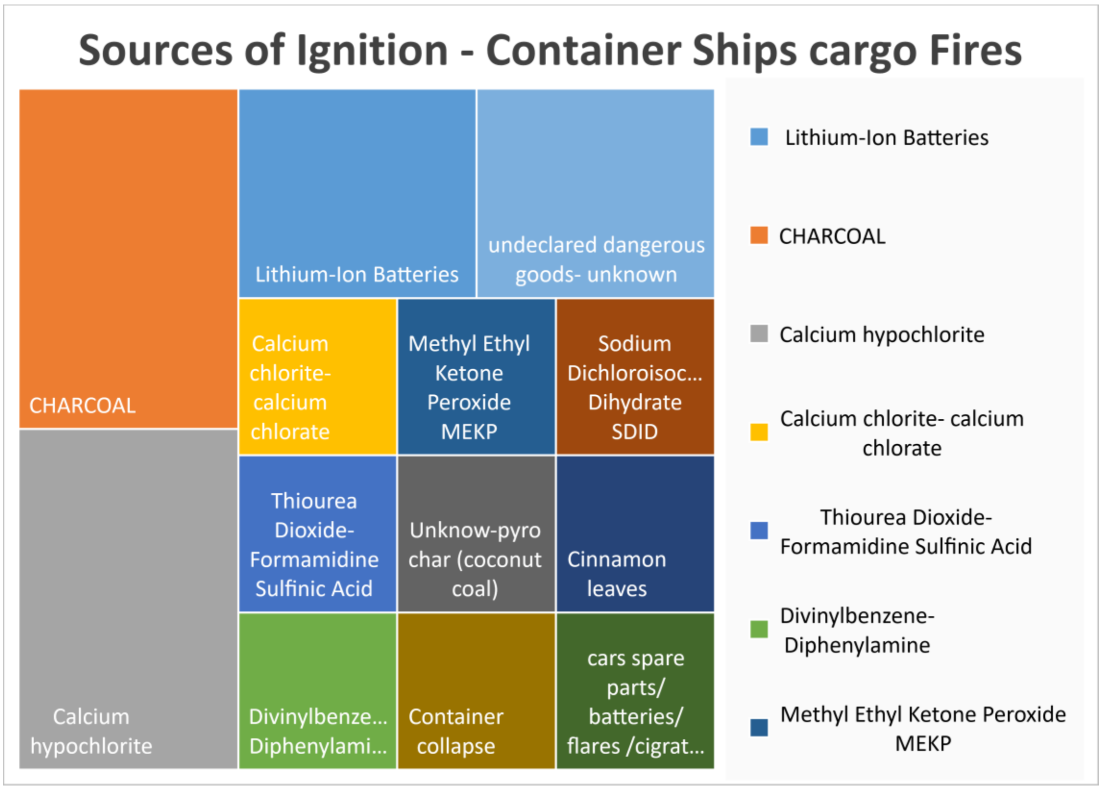

Figure 25 Container Ship Cargo Fires - Sources of Ignitions

4.8.1. Calcium Hypochlorite

The calcium hypochlorite has been identified as most frequent source of ignition in many studies and research (Callesen et al., 2019), the CINS platform has issued specific guidelines on the safe carriage of such material including limiting the weight inside the container to 14 tonnes and authorize the carriage either in dry or reefer container, the platform also specify that the control temperature for the reefer shall be 10°C, while the dry container carriage required risk assessment taking into account the temperature during the carriage (CINS, 2018), the CINS guidelines demonstrate the eight variants of the material and confirm the IMDG special provision no.314, which specify the hazard of thermal decomposition and carriage requirement as “stowage in shaded area away from direct sun light and heat source” (IMO, 2020a), but the undeclaration or misdeclaration of such hazardous material led to stowage in unappropriated location and unleash the sequence of fire accident.

The unsuitable stowage position for dangerous goods has been identified through HFACS CSCF in the Precondition for Unsafe Acts (PUA 9), with 13 occurrences represent 5% of all causal factors and most frequent factor in the PUA set, the elevated temperature associated with tropical weather identified in PUA 7 with 10 occurrences, furthermore, absence of ventilation or direct sun light in PUA 6 with 12 occurrence, all these factors contribute to the thermal decomposition of such materials and initiate fire or explosions accident, the CINS platform does not set a carriage temperature for calcium hypochlorite in dry container nor the International Maritime Dangerous Goods (IMDG) code, furthermore, there is no specific ventilation requirements (ex: passive, mechanical or nonmechanical[5]), nor temperature monitoring for the dry container carriage.

4.8.2. Charcoal

The charcoal has three occurrences for investigated container cargo fires with published investigation report in the 2010 – 2020 period, represent 11% of all sources of ignition in these casualties, in addition the pyro char, which is coconut coal used for shisha, has one occurrence on board MV Maersk Carolina (DMAIB, 2016).

Charcoal is identified as hazardous cargo due to self-igniting capabilities when stacked in bulk and with high ambient temperature (Wolters et al., 2003), the material classified as class 4.2 in the IMDG code with hazard identification as self-heated[6] material only when in large quantity and stored for prolonged period (IMO, 2020b), the charcoal classified within class 4.2 after verified by specific test set in the "Manual of Tests and Criteria, part III, 33.3.1.6" created by the UNECE[7] (IMO, 2020b), with two variants, activated and non-activated charcoal (IMO, 2020b), the

[5] ISO:6346

[6] "Self-heating is the process by which materials achieve temperatures higher than ambient because of internal exothermic reactions"(Wolters et al., 2003)

[7] UNECE: United Nations Economic Commission for Europe

IMO Dangerous Goods Committee (DSC) publish circular number four in 1997, included many dangerous goods accidents and among them the four fire accidents occur at 1996 in Rotterdam port with non-activated charcoal cargo -UN number 1361 class 4.2- named as the source of ignition with unapproved packing (IMO, 2020b), the DSC circular four was vital and attached to the IMDG code with other circulars in the following years related to the dangerous goods fires.

The IMDG special provision SP 925 has been used as a gap in the IMO instrument by shippers to avoid classifying the product as IMDG cargo with higher shipping freight, the criteria set in “Manual of Tests and Criteria, part III, 33.4.3.3” in the special provisions SP 925 cannot be checked or verified practically either in port or by charter during any container inspection, and the volume of coal in the criteria may vary from the real one shipped in the containers.

The recommendation provided by the BSU (2018) after the fire accident on board MV Ludwigshafen Express was to prohibit stowage under deck for any cargo has self-heating hazard even charcoal which is not declared as dangerous goods due to SP 925 (BSU, 2018), with all relevant information about such hazard provided for the crew and company.

4.8.3. Sodium Dichloroisocyanurate

Sodium Dichloroisocyanurate Dihydrate SDID is recognized as one of the ignition sources in container ships fires (TSIB, 2020), the material classified under IMDG class 9 but it had additional exothermic decomposition hazard revealed through the fire investigation report for container vessels Maersk Honam (TSIB, 2020), the IMDG code special provision SP135 exclude such material from class 5.1 for oxidizing materials (IMO, 2020a) which contribute to absence of standardized cargo risk factor information (RF4) about the material, such causal factor has been included in HFACS CSCF level one of regulatory factors and have four occurrence with 1.6% from all causal factors.

Subsidiary risk of SDID exothermic decomposition and classification as 5.1 class shall be considered in the next IMDG code amendments in the awake of the very serious casualty of Maersk Honam (TSIB, 2020), It was not permitted to store such material in the cargo hold if it was classified as 5.1 (TSIB, 2020), with absence of alternative firefighting system to deal with large scale fire in organizational influence OI6 factor, as carbon dioxide is un effective agent with oxidizing substances class 5.1 (IMO, 2020b), combined with Precondition for Unsafe Act PUA 6,7 for tropical weather and absence of ventilation inside the container, and PUA 9 with unsuitable stowage position for dangerous goods, leading to such severity.

4.8.4. Cinnamon leaves

Another source of ignition represents one occurrence but worth discussion as the absence of standardized cargo risk factor information (RF4) about the material is present, the Cinnamon leaves has been identified as a self-heating material through the fire investigation report of MV FILIA T (MSIU, 2020), which need to be considered through the IMDG code amendments, exploring the last version of the IMDG code showing that the material is not included at all in the Dangerous Goods List (DGL) of the code (IMO, 2020b).

Examining the risk factor from any recognized source led to the Transport Information System (TIS), from the German Insurance Association (GDV e.V.), the identified risk at TIS platform indicate that in absence of sufficient ventilation, a high level of humidity may form inside the container with chemical transformation of cinnamaldehyde, styrene may be formed when such humidity combined with temperature above 19°C (TIS, 2022), the TIS set the safe transport temperature within 15-19°C range, and the safe type of container as passive ventilated container in addition to prohibition use of standard container due to the absence of suitable ventilation (TIS, 2022).

The TIS set the storage condition onboard the ship as lowest temperature, away from direct sunlight, neither at high layer on deck nor in cargo hold (TIS, 2022).

The IMDG from other aspect has classified “Styrene” with all its synonymous such phenylethylene, cinnamene and Styrene Monomer as class 3, flammable liquid with united nation (UN) number 2055 (IMO, 2020b), neglecting the material that could produce Styrene under humidity and tropical weather due to exothermic decomposition (TIS, 2022) , which is cinnamon leaves, leaving such material without any transport requirements or carriage temperature control same as the TIS have set, leaving questions about the update and amendments mechanism for IMDG code technical information and provisions.

4.9. Dangerous goods as the main factor contribute to container ships cargo fires

95% from investigated container ships cargo fires caused by dangerous goods, with 11% from these dangerous goods are unclassified as dangerous goods, only 26% from these dangerous goods were probably declared, while 32% were mis declared and 37% undeclared at all, hazardous associated with undeclared dangerous goods and unsuitable stowage position, environment and ambient temperature are high and identified 15 years ago (IMO, 2007), the Risk Control Options RCO at that time was ineffective (IMO, 2007), and the Risk Control Options RCO today for sure will be more ineffective.

Table 8 Dangerous goods declaration status

	Ships Name	Dangerous goods		
		Declared	mis declared	undeclared
1	X-PRESS GODAVARI			x
2	CROATIA		x	
3	FILIA T	x		
4	YANTIAN EXPRESS		x	
5	MAERSK HONAM	x		
6	APL AUSTRIA			x
7	CCNI ARAUCO			x
8	CMA CGM Rossini		x	
9	Ludwigshafen Express		x	
10	MSC Katrina	x		
11	BARZAN			x

12	CAROLINE MÆRSK			x
13	HANJIN GREEN EARTH		x	
14	NOTHERN GUARD			x
15	HANSA BRANDENBERG			x
16	EUGEN MÆRSK	n/a	n/a	n/a
17	ZIM RIO GRANDE	x		
18	MSC Flaminia		x	
19	CHARLOTTE MAERSK	x		
	Total	**5**	**6**	**7**
		26%	**32%**	**37%**

Chapter 5

Recommendations

5.1. Introduction

It will be more logical to summarize the challenges identified through HFACS CSCF analysis, which the industry face before or during the container ships cargo fires, then try to mitigate such challenges with available innovative technology to minimize the cost and increase creditability, any recommendations will be based upon finding and statistics from chapter three of this dissertation.

The digitalization can introduce low cost and innovative technology helping overcome the challenges related to monitoring and control of temperature and humidity inside the dangerous goods container as a first stage, then the hole containerized cargo.

The same technology can be real time source of information for container content and best extinguishment agent in case of fire.

The Internet of Things (IoT) concepts and Radio Frequency Identification (RFID) applications and potentials will be explored as recommendations, considering the cost and availability of such technology

5.2. Summary of container ships cargo fires challenges and recommendations diagram

Through the 19 investigated container ships cargo fires many challenges have been identified, part of the challenges related to SOLAS convention were classified with the same sequence of chapter II-2 in SOLAS, prevention, detection, contain, supress the fire and operational requirements (IMO, 2022c), furthermore, other challenges related to other IMO instrument have been summarized (Table11), the recommendations will be arranged in the same way (Figure 27).

Table 9 Summarized challenges in container ship cargo fires

	Summarized Challenges	HFACS CSCF[8] reference	Classification according to SOLAS II-2
1.	Inability to fully detect undeclared or mis declared dangerous goods by shippers in the loading port.	Regulatory Factor and Unsafe Act trend UA12-UA13	Prevention
2.	Absence of some hazardous material classification and associated risk information and safe carriage requirements.	RF3- RF4	
3.	Delayed detection methods for fire or unsuitable detection methods or manual detection for cargo on deck.	RF1-UA1	Detection
4.	Absence of effective fire contain measures to achieve fire safety objective stated in SOLAS II-2/2.1.1.4 related to control and contain the fire in the space of origin, with associated functional requirements stated in SOLAS II-2/2.2.1.5.	RF1-PUA3	Contain
5.	Accumulation of seawater inside cargo holds due to high rate of extinguishment water than dewatering rate (bilge pump capacity).	PUA14	Suppression
6.	Ineffective or unsuitability of used fixed gas firefighting system.	Organizational Factors trend OI2-OI3-OI6	
7.	Sustainability of Breathing Air (BA) for firefighting operation with SOLAS non-mandatory requirement of BA compressor.	OI8-PUA15	
8.	Absence of means of accessibility to seat of fires and high tier container fires and non-coverage with foam applicator with fire hoses limited range.	Precondition for Unsafe Act trend	
9.	Lack of crew knowledge regard container ships cargo fires characteristics led to delayed or ineffective decisions or actions.	UA7-UA8-UA9	Operational Readiness
10.	Coastal state refusal for providing port of refuge for container vessels in fire, either due pollution impact fears and other responsibilities or lack of technical ability to provide assistance.		Other factors

[8] Refer to HFACS CSCF codes in Appendix A

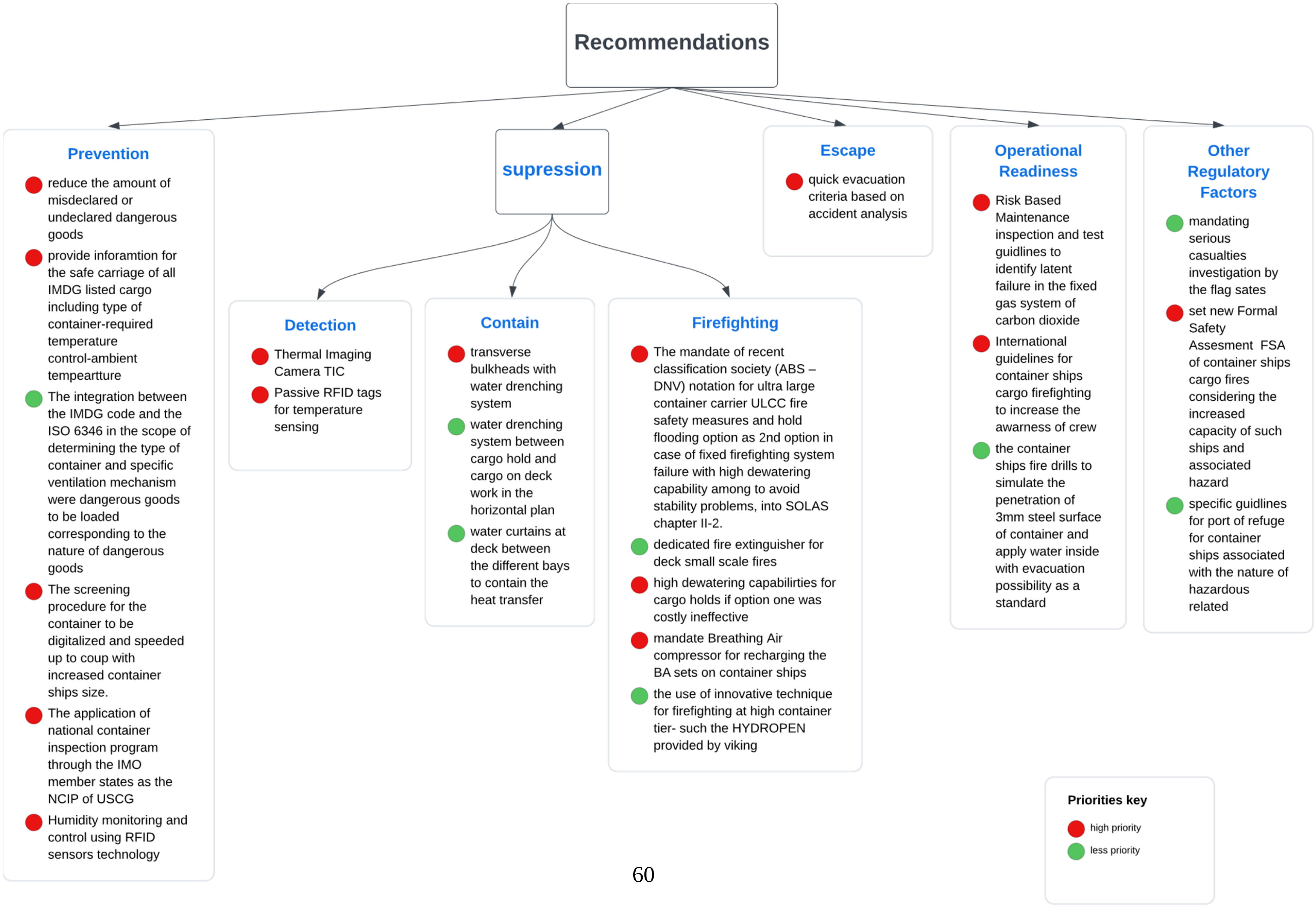

Figure 26 Recommendations for minimizing the container ships cargo fires

5.3. Prevention

5.3.1. Importance of humidity and temperature monitor and control and the cost challenge

Temperature and humidity are vital elements for fires starting in dangerous goods containers, the self-heating of charcoal induced by elevated ambient temperature (BSU, 2018), while the higher the water content in the charcoal the more heat absorption occur (BSU, 2018) leading to ignition.

Another hazardous material related is the Methyl Ethyl Ketone Peroxide (MEKP), which involved in other container fire later in 2007 (DMAIB, 2010), it was concluded that such material needs to be carried in reefer container, for controlled temperature and humidity carriage, but such proposal never sees the light (DMAIB, 2010).

Humidity and temperature in the storage area can determine the stability of some material such as Calcium Hypochlorite (DMAIB, 2010), setting on the top list of container fires sources of ignition, furthermore, the cargo moisture content is very important for its stability (DMAIB, 2010), calcium hypochlorite thermal decomposition can occur due to heat generated from small quantity of water ingress to the container (DMAIB, 2010).

Thiourea Dioxide[9] thermal decomposition was the root cause of MV Zim Rio Grande fire attributed to red sea high ambient temperature and humidity (MSIU, 2013).

Therefore, monitoring the humidity and temperature play vital role not only in fire detection, but in fire prevention also, as the most suitable technique to manage any fire, is to prevent its occurrence from the beginning as a proactive measure.

[9] IMDG class 4.2 Substances liable to spontaneous combustion

5.3.2. Temperature and humidity sensing as innovative packing and monitoring technology

Callesen et al. (2019) presented some technologies to enhance the fire detection principle in his paper for container ship fires risk, including temperature sensors and Thermal Imaging Camera (TIC) among other options, the Passive Radio Frequency Identification Device (RFID) tags commonly used for monitoring inventories and managing logistics (Pradhan & Qiu, 2020), can be used innovatively for temperature sensing (Pradhan & Qiu, 2020) inside the dangerous goods container as a first stage, the cost is effective (Callesen et al., 2019), the chips can be afforded for less than 10$ per piece (Callesen et al., 2019), the passive RFID tags technology is more than suitable for container atmospheric monitoring , the tags are easy to set and most important battery free (Pradhan & Qiu, 2020).

Many technological temperature traceability solution has been raised such the “Orbis traceability system”, using RFID subsystem combined with processing and information subsystem (Urbano et al., 2020) depending on the Internet of Things (IoT) principles and services, the common question about cost effectiveness or who will pay is answered through Data as Service (DaaS) principle to avoid the high cost of new implemented system, as the users will not pay for the installed apparatus but only for the consumed data (Urbano et al., 2020), despite the fact that Urbano et al. (2020) focus on the cold chain[10] monitoring for food transport as example, but the applications overseeds this scope.

The prevention principles start from the packing process till the final delivery of the container, along this supply chain the container yard at the port is important as the ship regard the stowage environment, the contradiction between dangerous goods regulations for different transportation means (Rail-Road-Sea) with associated manging risk (Gonzalez-Aregall et al., 2021), can be resit at this point.

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[10] “Low temperature control supply chain network”

The dangerous goods container normally stored at dedicated containers yard, Ding et al. (2016) set digitalized three layer system for container yard protection and monitoring with three functions including monitoring of environmental parameters in the yard or inside the containers, using the IoT as concept and RFID tags as information source and link, with extra function including firefighting related information as the most effective external agent to be used and the not preferred or less effective agent to be avoided (Ding et al., 2016).

Ding et al. (2016) focus his scope inside the container yard, which is important, but the applications can be widened to include the ship, neglecting the application cost as the DaaS principle could apply also (Urbano et al., 2020).

The passive RFID antenna-based temperature sensing proposed by Pradhan & Qiu (2020) can be utilized within ding scope, furthermore, the idea of using temperature sensor inside each container can be widened to include humidity and carbon dioxide monitoring inside the container (Ding et al., 2016).

Once a sensor applied in each container, a Wireless Sensor Network (WSN) will be formed, with monitoring centre unit (Ding et al., 2016), one of the feasible systems which apply such concepts is the “Senor monitoring node”, which collect real time data for temperature and humidity inside the container (Ding et al., 2016).

5.3.3. Dangerous goods containers and port held time risk

Entangled global supply chain result long held containerized dangerous cargo at the port, with lack of accurate information regard long standing consequences (Lloyd’s List, 2022), the total loss of MSC Flaminia attributed to dangerous goods container stowed for 10 days in hot climate, with unknown impact for such stowage (Lloyd’s List, 2022), another dangerous goods container held at the port for 60 days involved in the disastrous fire accident of Xpress Pearl (Lloyd’s List, 2022).

The industry considers the port held time for dangerous cargo as a risk (Lloyd’s List, 2022), ports mitigation process for such risk varies, at Auckland port of New Zealand the mitigation process for dangerous goods class 6 and 8 require limited storage time at ports for imports and exports (POAL, 2019), which does not exceed 72 hours (POAL, 2019), to minimize the risk of these hazardous substances.

A safer container before loading means less chance of a fire accident onboard a container ship.

5.3.4. The undeclared/mis declared dangerous goods containers mitigation process

Through the HFAS CSCF analysis process, the shipper Unsafe Act of undeclare or mis declare dangerous goods represent the most frequent factor in the unsafe act level initiate the sequence of events led to a fire accident.

The statistics indicate that shipper compliance with requirements directly proportional with the inspection chance for their container's (NCB, 2020), inspection authorities such United States Coast Guard (USCG) found it "unnecessary and impossible" to inspect 100% of containerized cargo either imports or exports (USCG, 2019), in lieu, the USCG set annual goal for numbers of containers to be inspected (USCG, 2019).

"Container Inspection Safety Initiatives (CISI)", launched by National Cargo Bureau (NCB) in the aftermath of Maersk Honam fire, revealed that 57% of the inspected dangerous goods container failed to comply with IMDG requirements, misdeclaration and failed documents represent 11% of the failure rate (NCB, 2022).

The dangerous goods transport cost reduction shall be considered as one of the solutions, combined with limited administrative burdens to assist such scope (Gonzalez-Aregall et al., 2021).

To summarize, the concentrated inspection program for either dangerous or non-dangerous containers elevate the shipper's compliance level with the regulations, and the reduction of port held time reduce the associated risk with dangerous goods containers.

5.3.5. The dangerous goods container digital screening process, development potentials and safety impact

A digital screening process can help mitigating the undeclared or mis declared dangerous goods risk, novel methods depend on screen booking details itself to detect “discrepancies” cargo documents (NCB, 2020) , new technology such “Hazcheck detect” presented by “Exis technology” providing real time information for non-compliant cargo using this concept (Existech, 2022).

The Exis can help detect the fraud by share detected cargo information to other companies without revealing any information related to business competition (Lloyd’s List, 2022), helping the marking of shipper’s unsafe act, the outcomes later can be translated to blacklist for shippers with “fraudulent” behaviour to help mitigating the undeclared or mis declared dangerous goods containers risk (Lloyd’s List, 2022).

5.4. Operational readiness

5.4.1. The change of CO_2 test procedure and mechanism to reveal or expose any latent failure, the Risk-Based Inspection, and guidelines.

The test procedure provided by MSC.1/Circ.1318/Rev.1 need to be amended, considering the failure risks of the carbon dioxide system, with instruction for blowing the system lines to the protected area with pressurized air every three months by ship’s crew to maintain the preparedness state of such critical system and detect any leakage, the current scheduled inspection and maintenance at “intermediate, periodical or renewal survey”(IMO, 2021c) showing ineffectiveness in revealing any latent failure, furthermore, means for checking the functionality of time delay unit to be included as self-test in monthly bases which shall be directed to the designers of the CO_2 systems, also guidelines for simple operating instruction to be followed by the designer and presented for the operators, to eliminate the feedback deficiencies revealed by the container ship fire investigation reports.

5.4.2. Crew awareness

Increasing crew awareness will help mitigate cargo fire risk and associated human loss. The recommendation related to this scope is providing International Guidelines for Container Ship Cargo Fires (See Appendix B); to enhance the awareness level by providing information about cargo fire Characteristics of container ships. In addition, the best-containing technique and good practices were identified through the HFACS CSCF analysis will be presented.

5.5. Other regulatory factors

5.5.1. The mandate of publishing the fire accident investigation reports as the only feedback from the industry to enhance the fire safety level of container ship

No doubt that the mandate of casualty investigation in serious accidents will increase the financial and administrative burdens on the casualty investigation boards, however, it will reveal more deficiencies and more root causes of fires, increasing our awareness and create more mitigation process or risk control options, assisting the researchers and industry to mitigate the container ships cargo fire risks, such scope need to be adopted for the sake of all stakeholders.

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Appendices

Appendix A

Coding Process for Fire Investigation Reports Of Container Ships

Name of the vessel:				IMO No:	Start at:	TEU:	n/a
	1ST TIER	2ND TIER	*3RD TIER*	CAUSAL FACTOR		CODE	Page
Latent failure	Regulatory Factors	Statutory	*International standard*	The regulatory framework failed to cover the fire safety system requirements of the ship-in relation to detection, containing, extinguishing or sustaining air supply for BA on board container ships.		RF1	
				The approved testing procedure by IMO for fixed firefighting systems failed to identify latent failure		RF2	
				Dangerous goods are not listed in the IMDG Code- IMDG code amendments required.		RF3	
				Absence of relevant standardized cargo risk factors information.		RF4	
			Port state implementation	Failure to identify the content of the container in the loading port.		RF5	
				Failure to detect undeclared dangerous goods in the loading port.		RF6	
				Absence of protecting legislation against the mis declared of IMDG containers in the loading port.		RF7	
			Ship Flag state/ RO implementation	Existing flag and recognized organization regulations failed to provide capability for crew detection, containing, extinguishing the fire		RF8	
				Failure to regulate the mandating of including all firefighting arrangements in the fire control plan		RF9	
				Latent risk design - co2 system components		RF10	

	Organizational Influences	Resources	*Human resources*	Failed to provide relevant training to mitigate the container fire risks by the company	OI1	
			Technological resources	Poor activation mechanism for critical fire safety systems	OI2	
				Poor fire safety systems design main fire line-co2 system	OI3	
			Equipment/facilities resources	Failed to present emergency firefighting tools alternatives.	OI4	
				Provide the ship with low-quality/unsuitable firefighting equipment and tools.	OI5	
				Absence of alternative firefighting systems to deal with large-scale fires.	OI6	
				Absence of dedicated firefighting equipment to deal with small-scale fire	OI7	
				Insufficient firefighting equipment – lack of air cylinders – water lances – fire suits	OI8	
		Organizational climate	*Structure*			
			Policies			
			Cultures			
		Organizational process	*Operation*			
			procedure	Conflicting SMS firefighting procedures	OI9	
				Failed to provide relevant fire emergency procedure in ship Safety Management System SMS to mitigate actual fire scenario	OI10	
				Failed to provide procedures for sustaining air supply for BA in case of emergency, 35 cylinders	OI11	
			Oversight	Failed to supervise the maintenance process and test on board the ship for fire safety-critical systems (fire pumps- fixed firefighting systems- emergency fire pumps-main fire line-drenching system).	OI12	
	Unsafe Supervision/workplace factors	Inadequate supervision	*Shipborne and shore supervision(company)*	Failed to probably test fire safety-critical systems (co_2-fire pumps-main fire line-hold sprinkler system).	US1	
				Failed to test the ship's firefighting tools and equipment and check durability.	US2	
				Failed to provide relevant training scenarios to mitigate the container fire risks.	US3	
				Failed to obtain correct data about container content in loading port or from shipper side.	US4	
				Failed to avoid known problem in sister vessel **high stack weight**	US5	
				Unproper maintenance by crew main fire line leak	US6	
		Planned inappropri	*Shipborne operation*	Ventilation flaps for the cargo hold left open without need for such action	US7	
				Block stowage for dangerous goods under deck near the accommodation	US8	

		ate operations		Planned unsafe repair/maintenance operation	US9	
		Failed to correct known problems	*Shipborne related shortcomings*	The ship fire control and safety plan did not show all firefighting arrangements (portable and fixed)	US10	
				Muster list did not detail designated crew duties clearly	US11	
				Ship emergency response plan did not cover all firefighting primary actions	US12	
		Supervisory violation	*Shipborne violation*			
	Precondition for Unsafe Acts	Environmental factors	*Physical environment*	Difficult accessibility/difficulty in reaching the seat of the fire or fixed extinguishing systems control	PUA1	
				Access to ventilation was blocked preventing the close operation and disrupting the gas integrity of the hold. By heavy dense white smoke	PUA2	
				The remoteness of the main fire line from containers in the holds.	PUA3	
				Visual obstruction from the bridge to the fire location due to high stacked containers	PUA4	
				Rough sea weather with associated winds- force 5 and up	PUA5	
				Absence of adequate/suitable/sufficient ventilation inside the container	PUA6	
				Elevated air temperature – tropical weather – with air temperature 18 c and above	PUA7	
				Low temperature considers as a challenge in fighting the fire.	PUA8	
				unsuitable DG Container Stowage position due to undeclared or mis declared DG by shipper/charter- exposed to direct sunlight – or under the deck (in hold)-knowledge defect	PUA9	
				Negative impact of the piracy countermeasures on the firefighting effort	PUA10	
				Accumulation of seawater inside the hold/s hinders or slows down the extinguishing process	PUA11	
			Technological environment	ineffective firefighting fixed systems or portable equipment used during critical firefighting	PUA 12	
				Fixed firefighting system technical failure at any component	PUA13	
				Hold bilge system failure bilge suction valve actuator failure	PUA 14	
				Breathing apparatus air compressor failure	PUA 15	
				Fire pump or emergency fire pump failure	PUA 16	
				Range limitation of seawater from nozzles	PUA17	
		Crew condition	*Cognitive factors*	Insufficient risk factors information	PUA18	
			Physiological state	Crew fatigue due to extended firefighting effort more than 6 hour –15 HR	PUA19	

		Personal factors	*Crew interaction*	Miss understands firefighting arrangement function or procedure	PUA20	
			Personal readiness			
Active failure	**Unsafe Act**	Errors	*Skill Based Error*	Failure to early detect the fire	UA1	
				Failure to probably use the firefighting equipment / activate fixed firefighting system	UA2	
				Failure to evaluate or estimate the casualty consequences	UA3	
				Misunderstand fire safety procedure	UA4	
				Unsuitable firefighting equipment use.	UA5	
				Leave critical firefighting equipment in hazardous areas with limited access.	UA6	
			Decision and judgment error	A wrong decision from leadership during firefighting procedure	UA7	
				Failure to take a critical decision in time –	UA8	
			Perceptual errors	Wrong assumption from the crew during situation assessment delayed reducing the ship speed /or/CO_2 RELEASE ASSUMPTION	UA9	
			Operators' error			
		Violations	Ship's crew Routine violation	Training drills on board the vessel did not simulate real emergency situations / no feed back to the company about such violation	UA11	
			Ship's crew Exceptional violation			
			Operator's violation	Shipping of Mis declared or undeclared dangerous goods -by shipper or charterer	UA12	
				Provide inconsistence cargo documents by shipper or charterer	UA13	

Appendix B
International Guidelines for Container Ship Cargo Fires

- **Characteristics of the container ship cargo fires**

- Rapidly developing fires- Charlotte Maersk.
- Unexpected explosion- MSC Flaminia/ Charlotte Maersk.
- Extended fire period, average time for the fires is seven days, led to resource limitations and exhausted crew.
- Deep seated fire with smouldering effect for solid materials.
- Unknown cargo properties or undeclared IMDG goods involved.
- Accessibility difficulties to the fire origin container or fire seat.
- Lack of crew knowledge about the type of fire they are facing.

- **Summarized Challenges during firefighting in container ships from 19 accidents fire reports in the period 2010 to 2020:**
- Accumulation of water in holds and bilge system failure with stability issues Yantin Express.
- Contain the fire is not effective due to lack of containment arrangement and systems or fire divisions in large scale fires.
- Absence of accurate information about containers content and undeclared or mis declared dangerous goods.
- Refusal from coastal state to provide port of refuges to the vessels in fire due to pollution fears and related responsibility or lack of technical ability to assist.
- Limited resources to fight extended fires, lack of air supply for Breathing Apparatus, absence of breathing air compressor to refill the BA cylinders.
- The detection of the fires at any deck cargo depending on the crew vigilance and alertness – all fires on deck cargo detected by crew from bridge.

- Failure of coastal state technique to assist, such using the Aeroplan to fight the containers fire by dropping waters - three attempts on charlotte Maersk led to no effect in firefighting,2010
- **Good practices identified through the 19 fire accidents reports**
- Turn the ship off the wind – to keep the smoke away from the bridge, accommodation ventilation and exposed muster station
- Approach the fire from windward side to minimize the exposure of the crew to the smoke / charlotte Maersk
- Reduce the speed of the ship
- Maintain good and effective shipboard organization to manage the firefighting efforts
- Adjust the watch keeping schedule and working hours to adapt with the emergency Eugen Maersk /charlotte Maersk
- The early activation of CO_2 system has pros and cons
  Pros is containing any fire will arise in the hold in early stage with benefits associated such saving resources and effort of crew to contain afire in cargo hold (Charlotte Maersk) and the cons that CO_2 system is one bullet gun, once you shoot it there is no alternative method to deal with large scale fire in cargo hold (Yantin Express/Barzan).
- Thermal Imaging Camera (TIC) and laser thermometer showing great benefit monitoring the flow path of the fire inside containers / MSC Katrina-
  CMA CGM Rossini p.20
- Drills on board container ship shall simulate the real emergency – and training include using drilling machine shall be part of it – also to test the driller durability among other equipment's.