Analysis of Maritime Fire and Explosion Accidents

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ABSTRACT: The aim of this work is the analysis of accidents involving fires and explosions in ships. To achieve this goal 20 accident investigation reports classified as fire and explosion are collected from which detailed information related to the accidental events is obtained. The accidental events are coded using the CASMET (Casualty Analysis Methodology for Maritime Operations) methodology and a detailed analysis of the results of the codification process is conducted. From the 20 accidents selected a total of 138 accidental events are identified and coded according to the CASMET taxonomy that addresses adequately the contribution of the human and organizational factors to the accidents. The results obtained show that the human error is the leading cause of the accidental events. As regards human factors, non-detection of technical failures is the main cause of accidents. In terms of causal mode, the operating procedures are the most common aspect in the accidents. Regarding daily operations, the supervision is the most common causal factor whereas issues related to emergency procedures, under the management and resources classification, occur frequently in the accidents analyzed. After grouping the 75 causal factors identified it is shown that lack of knowledge and operating and emergency procedures have the highest percentage of occurrence. Finally, a Bow-tie type diagram is developed to identify threats, barriers, escalation factors and consequences of a fire accident. The model is developed based on the results of the codification process taking into account the safety recommendations suggested by the investigation reports of the fire and explosion accidents.

Keywords: Analysis and codification of maritime accidents, fire and explosion, CASMET, human factors, risk management

1. Introduction

The analysis of fires and explosions accidents in the maritime context is the issue addressed in this dissertation. The aim is to outline and identify the main causes of typical accident scenarios involving fires and explosions.

There is a wide range of accident types. The types of accidents that may occur include collision, fire, explosion, capsizing, grounding, among others. Grounding and fire on board are the main types of maritime accidents.

In the maritime sector, fires are known by being a critical risk for the safety on board specially on passenger ships as the number of passengers on board is directly proportional to the potential life loss. A small fire in any location of the ship, when not proper solved, may result in disaster, as the case of the Princess 6 (in 2006), where the fire detection and combat systems were not used. This induces an increase of damage caused by the fire beside the life loss. Another case is the accident of the ferry Al-Salam Boccaccio (in 2005). A fire possibly originated in the machine room spread to the deck where the vehicles were stowage and the firefighting systems were not adequately used. At this point the excess of water on deck made the ship to roll and capsize resulting in the loss of more than one thousands of human lifes (Azzi et al., 2010).

Obstacles related to the change of technology, ship design, types of cargo should be identified and addressed with new regulations and operation procedures (Gentile & Dickenson, 1995).

When identifying the starting of a fire, if the containment of fire is not efficient there will be no time to make use of equipment on board to extinguish the fire This may lead to serious damage (Dutta & Kar, 2009). The available statistics indicate that more than 60% of the victims of fires occur in general cargo ships. The passenger ships (including ferries RO-RO) represent only 6% of all the incidents of fire (Vassalos, 2006).

According to EMSA’s (European Maritime Safety Agency) latest report from the years 2011 to 2014 the number of sea accidents have increased. In 2014 there were a total of 3025 accidents. The cargo ships are the ones with more accidents with a total of 44%, being followed by 23% of the passenger ships while the 15% are from service ships. The last with 9% corresponds to other ship types (EMSA, 2015).

The analysis of maritime accidents is crucial for evaluating the risk and to identify the main causes, contributions and organizational factors that will eventually result in the accidents (Guedes Soares et al., 2000).
A detailed analysis shows that 80% of the maritime accidents are caused by human factors, individual and organizational (Antão et al., 2013). The fishing industry is a clear example were accidents are mainly due to human factors (Antão et al., 2008).

2. Regulatory Framework

The overview of the regulatory framework for safety and fire prevention is portrayed. Fire and explosions are among the main risks of ship operations, despite the issues related to prevention and mitigation of these risks are widely covered by the current normative regulations.
IMO (International Maritime Organization) has an important role in maritime safety, more specifically the SOLAS Convention (International Convention for the Safety of Life at Sea). There are also flag and class societies regulations to control and implement maritime safety (Psaraftis et al., 1998).

2.1 Casualties

Under SOLAS I/ 21, articles 8 and 12 from MARPOL, every administration is responsible to report on each accident that may have happen with ships under their flag. These entities have to deliver detailed reports to the competent authorities in order collect the data for further studies.
The issue of human factors in accident analysis is a theme in the IMO. In order to standardize the information contained in the databases of maritime accidents, a marine casualty investigation code, Resolution A.849 (20) (IMO, 1997), was introduced. The code sets out a sequence of points to consider allowing official authority to detect and complete the factors involved, barriers to safety and preventive operation. Resolution A.884 (21) (IMO, 2000), after the previous one, aims to incorporate the investigation of human factors of IMO and ILO (International Labour Organization), and adopts various approaches to human factors such as the SHEL model (Hawkins, 1987), GEMS (Reason, 1990) and taxonomy error Rasmussen (1987).
Circular MSC-MEPC.3 / Circ.3 (IMO, 2008) is the update of the resolution referred to above, which explicitly defines the accident investigation procedures. They are encompassed all aspects of information for a given incident in a single form called "Reports on Marine Casualties and Incident". Corresponding information is collected to the accident, and this information is allocated in ten annexes; each directed to a particular subject. The accident classification is divided into four levels: "very serious casualties" are accidents involving the total loss of the vessel or life or severe pollution, "serious casualties" are accidents that are not qualified as "very serious casualties" but involving fire, explosion, collision, grounding, contact, damage due to bad weather, leak or suspected defect in the hull, structural damage that prevent the ship to navigate, pollution, (IMO, 1997). Additionally, accidents can be classified as “Less serious casualties" and "marine accidents", for which reporting is not mandatory.

2.2 Fire safety

The main objective of the SOLAS Convention is to specify the minimum requirements for the construction, equipment and operation of ships (SOLAS, 2014). In July 1, 2002, a new set of comprehensive measures dedicated to fire protection, detection and extinguishing fires on board ships entered into force as a new revised chapter II-2 of the 1974 SOLAS, as amended, incorporating advances aids in detection and extinction.
For the prevention of fires on board, there is the International Code for Fire Safety Systems, hereinafter FSS Code, that aims to provide international standards of intrinsic engineering specifications for fire safety systems required by chapter II-2 of SOLAS and became mandatory after 1 July 2002. Furthermore, the International Code for the Application of fire test procedures, called FTP Code provides international requirements of laboratory testing procedures, approval and fire test for products referenced under SOLAS, in force since July 1, 2012.

2.3 Alternative design

In the context of fire safety, the Rule 17 of Chapter II-2 of SOLAS guidelines introduces the concept of alternative design. This definition covers a wide range of measures, including alternative structures, systems with different configurations of the common and traditional structures and systems (IMO, 2001).
In this case engineering analysis is used to show that the alternative design provides a level of safety equivalent to the regulatory requirements of SOLAS Chapter II-2. This approach should be based on studies and practice of fire-related engineering, incorporating widely accepted methods, empirical data, calculations, correlations and computer models (IMO, 2001). All data and information generated during the preliminary analysis and fire project specification should serve as input to the evaluation process. The evaluation process may be different, depending on the required level (based on the target set during the preliminary analysis), but should generally follow the procedure in Figure 1.
For each assessment of selected alternative design must be analyzed in comparison to fire scenarios, to demonstrate compliance with the performance criteria with the agreed margin of safety, and must be selected from alternative evaluation models that meet the performance criteria and their safety margins.

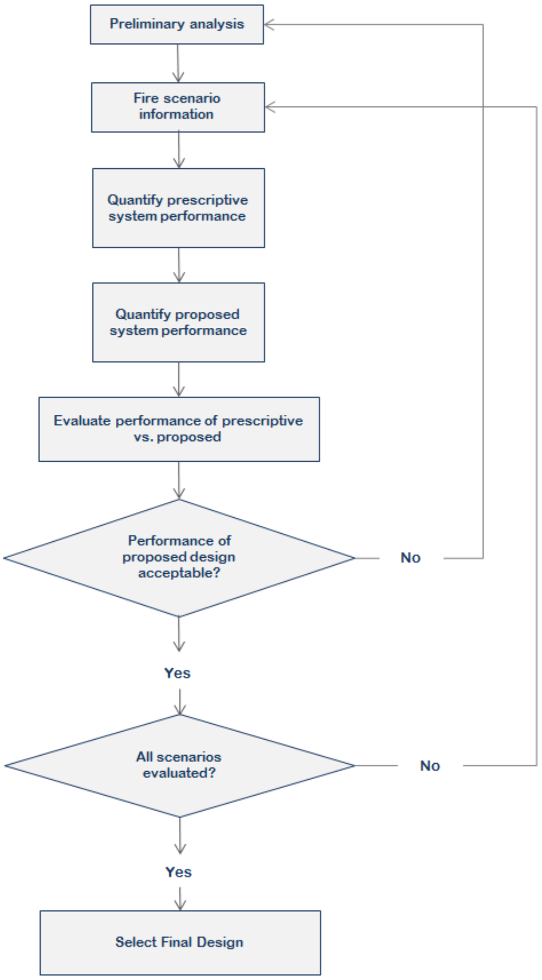

Figure 1 – Representative diagram of the alternative design, adapted from IMO (2001).

3. Accidents Coding with CASMET Methodology

3.1 CASMET Methodology

In the last decades several accident investigation methodologies together with appropriate taxonomies that provide the codification of the prevailing circumstances and contributing factors of accidents have been proposed. Among these methods is the CASMET (Casualty Analysis Methodology for Maritime Operations) methodology developed in a European research project (Caridis, 1999; Kristiansen et al. 1999). The approach consists of an analysis process that includes the initial data collection, identification and definition of the chain of events, the analysis of human and organizational factors (Caridis, 1999). In applying this methodology, data needed to explain a certain occurrence are collected and used to identified the sequence of accidental events, tasks, users and equipment involved, factors contributing to the occurrence and the root causes for each accidental event (Guedes Soares et al., 2000). The organization of information in a database requires a data coding structure directly related to the analysis process (Guedes Soares et al., 2000). The sequence of accidental events will be built for all events that are considered essential for the development of the accident. Thus, the events that are part of this sequence are essential, as if one had not occurred, the current would be interrupted and the accident would not occur. These events are classified according to Kristiansen et al. (1999) as hazardous material, environmental effects, equipment failure, human error and other agent or ship; each have parameters associated with it for its characterization. A number of factors related to people, equipment, working conditions and management are then identified to code the causes of the accidental events. According to Kristiansen et al. (1999), the basic causal groups of the CASMET methodology include daily operations and management resources. The first relates to operational decisions: is related decisions and conditions on board for the management, individual behaviour, equipment and working conditions; while management and resources is related to the organizational culture, management class, buying ships or equipment, hiring and training employees – facts pertaining to the top management of the organization (Caridis, 1999).

3.2 Accident Coding

In the maritime context, the fire and explosion accidents are typically analyzed and reported by various organizations. 20 reports are selected, provided by the MAIB (Marine Investigation Branch) and TSB (Transportation Safety Board of Canada), for coding with CASMET method. To illustrate the CASMET method, one of the twenty accidents report is now coded.

3.2.1 Identification of casualty

The case of a fire on the main deck of the ship RO-RO Corona Seaways is selected to exemplify the coding process with CASMET methodology, where all the steps of the method are presented.

Narrative

"At 0215 on 4 December 2013, a fire was discovered on the main deck of the ro-ro cargo ferry Corona Seaways while the vessel was on passage from Fredericia to Copenhagen, Denmark. The crew mustered, closed the ventilation louvres, established boundary cooling and operated the fixed CO_2 fire-extinguishing system. Although smoke continued to escape from the louvres, steady temperatures in the vicinity of the fire indicated that the CO_2 had been effective in controlling it. At 0640, the vessel entered the Swedish port of Helsingborg, where assistance was provided by the local Fire and Rescue Service. The vessel suffered light structural damage and the loss of some minor electrical supplies. Three vehicles and six trailers were severely fire-damaged and other vehicles suffered minor radiant heat damage. The fire was caused by an electrical defect on one of the vehicles' engine starting system. Recommendations to the management company include a review of its onboard instructions to take account of

the revised procedures since introduced by the operator for the carriage of used and unregistered vehicles.”

The first step is the identification of the casualty, type of casualty and attributes. Table 1 shows the data regarding the ship in question.

Table 1 – Casualty identification (Corona Seaways)

Fact group	Facts	
Identification	Case identification no.	1
	Vessel Name	Corona Seaways
	Terminal Casualty*	Fire
	Date of casualty	4.12.2013
	Geographical position	Helsinborg, Sweden
Vessel	Vessel Type	Ro-ro cargo ship
	Deadweight or GRT	25609 GT
	Service Speed	19 knots
	Main dimensions (L_{pp}, B, T)	187, 26.52, 6,80 [m]
	Cargo intake, draft (T)	11,235 metric tonnes
	Main engine type, propulsion system	MAN B&W
	Yard, country, year of built	Jinling Shipyard in Nanjing, China
	Owner, flag	Snowdon Leasing Company Limited, United Kingdom
	Classification society	American Bureau of Shipping
Operation *	Vessel operation phase	Sailing
	Operation onboard	Normal watch
Environmental conditions	Weather conditions, visibility	Cloudy, visibility good, wind south-westerly
	Beaufort no., current speed	force 4, wave height 0.5-1.0m, air temperature 7ºC
Manning	Number of officers and crew	19
	Nacionalities	
	Experience of key personnel	
Consequences	Damage to people, vessel and environment	Severe damage to 3 vehicles and 6 trailers.
	Economic consequences	Smoke damage to main deck, heat damage to 15m2 of steel deck and 8 longitudinals between frames 131 and 134. Fire damage to the forward mooring winch supply cables and to minor electrical circuits
Casualty	No.	1
	Casualty type and casualty subgroup	Fire
	Class	Extinguished
	State	Cargo space

Table 2 – Accidental events (Corona Seaways)

Event no.	Management	Officers	Crew	Vessel	Contributory factors
E1				170 units tightly stowed in hold	"*tighly stowed* "
E2	all cargo space fans stopped				In cargo ships, ventilation fans shall normally be run continuously whenever vehicles are on board
E3				Fire detection alarm system (..) fire in SB main deck	Fire in zone 12 starboard side in main deck / fire had started on the engine of a truck
E4				OOW viewed the main deck CCTV saw no evidence of fire	send the on-watch AB to check the status of the main deck
E5			AB opened the door but did not enter the space		because of the tightly packed vehicles
E6			teams started to close manually operated louvres of the 36 ventilation jalousies		
E7				Although the louvres were suported closed to the chief officer, a considerable amount of smoke continued to emit from them	there was a misunderstanding on board on how to lock the louvres in the ‘closed’ position
E8		decided to delay use of CO2			in case the fitter was mon the main deck - he was not equipped with a VHF radio
E9		Fitter arrived, the master approved CO2 main deck			Injection of CO2 into the main deck was delayed, allowing the fire to develop
E10				10 vehicle drivers started to become disruptive	had consumed alcohol and were now located at the muster station / started to affect the chief officer’s management of the incident
E11				Only 9t of the 213t of CO2 stored in the tank been released instead of the required 19.8t	there was no explanation for why the system apparently failed to discharge the allotted quantity of CO2 as designed
E12				10t of CO2 remaining in storage tank	

In the next step, individual events are selected with an appropriate context for them to be assigned a certain structure and order. Table 2 shows the relevant accidental events in rows in the chronological order of occurrence, and in the column the actor involved in that event. For this accident 12 accidental events are identified.

3.2.2 Accidental Events

Accidents are processes that involve a number of errors, failures and uncontrolled environmental impacts. This set of events is called accidental events, and each event is characterized by the following attributes: hazardous material, environmental effects, equipment failure, human error and other agent or ship. The coding of accidental events is shown in Table 4.

Table 3 – Coding of accidental events

No.	Accidental Event	Coded Parameters	
E1	FEQ: units tightly stowed	SYS: cargo TYPQ: inaccessible	LOCQ: vehicle deck PHY: overload
E2	HUM: all cargo space fans stopped	POS: Master PERF: decision making	TSK: cargo space maintenance ERR: ignored
E3	HAZ: fire in SB main deck	MAT: diesel oil HTYP: leak	LOCZ: vehicle deck TYPZ: toxic fumes
E4	FEQ: OOW viewed the main deck CCTV saw no evidence of fire	SYS: general safety TYPQ: out-of-range	LOCQ: vehicle deck PHY: material defect
E5	HUM: AB did not enter the space because of the tightly packed vehicles	POS: Bosun PERF: detection	TSK: deck maintenance ERR: not performed
E6	HUM: teams started to close manually operated louvres	POS: Deck crew PERF: manual control	TSK: cargo space maintenance ERR: inadequate
E7	HUM: a considerable amount of smoke continued to emit from the louvres	POS: deck crew PERF: perception	TSK: cargo space maintenance ERR: ineffective
E8	HUM: decided to delay use of CO_2	POS: master PERF: decision making	TSK: radio communication ERR: delayed
E9	HUM: Fitter arrived, the master approved CO_2 main deck	POS: Deck crew PERF: communication	TSK: cargo space maintenance ERR: inadequate
E10	HUM: 10 vehicle drivers started to become disruptive	POS: passengers PERF: perception	TSK: fire fighting operation ERR: improper
E11	FEQ: Only 9t of the 21.3t of CO_2 stored in the tank been released	SYS: fire fighting TYPQ: insufficient	LOCQ: vehicle deck PHY: not in operation
E12	FEQ: 10t of CO_2 remaining in storage tank	SYS: fire fighting TYPQ: insufficient	LOCQ: vehicle deck PHY: not in operation

3.2.3 Human Factor Analysis

The human factors (Table 3) are then coded in accordance with the evaluation of events compiled in Table 2. The Table 3 shows the identification and analysis of human factors for each accidental event. This procedure consists of, for each of the twelve events, identifying the external factors, which may affect the event and specify the relevant type of performance or behaviour pattern for detection, evaluation, decision or action, as observed in the External/ Performance column in Table 3. Then, for each Performance mode already identified, shortcomings in terms of personal factors, tools and tasks, and then the corresponding causal group are defined. Causal modes applied in this specific example are described in the last column of Table 3.

Table 4 – Analysis of interaction of human factors

Event	External / Performance	Personnel / Tool / Assignment
170 units tightly stowed in hold	E: P: Detection	P: T: A: operating procedures
all cargo space fans stopped	E: P: Action	P: T: A: operating procedures
Fire detection alarm system (…) fire in SB main deck	E: P: Detection	P: T: fire/ explosion A:
OOW viewed the main deck CCTV saw no evidence of fire	E: P: Detection	P: T: A: lack of info
AB opened the door but did not enter the space	E: P: Decision	P: T: A: operating procedures
teams started to close manually operated louvres of the 36 ventilation jalousies	E: P: action	P: T: A: emergency procedures
Although the louvres were suported closed to the chief officer, a considerable amount of smoke continued to emit from them	E: P: Action	P: inadequate training T: A: lack of info
decided to delay use of CO2	E: P: Decision	P: T: A: communication procedures
Fitter arrived, the master approved CO2 main deck	E: P: Action	P: T: A: communication procedures
10 vehicle drivers started to become disruptive	E: P: Action	P: T: A: distracters in task
Only 9t of the 21.3t of CO2 stored in the tank been released instead of the required 19.8t	E: P: Detection	P: T: unavailable equipment A:
10t of CO2 remaining in storage tank	E: P: Detection	P: T: unavailable equipment A:

3.2.4 Basic Causal Factors

The basic causal factors related daily operations (daily operation) and basic causal factors related to the management and allocation of resources (management & resources) are the two basic types of causal factors. The basis for the coding of these factors is primarily the analysis of human factors described above.

The factors have in common management, human resources, hardware and ergonomics in general. The reason for having two sets of factors is the need to distinguish between operational decisions and long-range strategic decisions. The two levels of decision should be interpreted:

- Daily Operations – decisions and conditions on board relating to manning, individual behaviour, equipment and the workplace;
- Management and Resources – decisions on the upper and intermediate level in the organization, related to the organizational culture, management style, the purchase of vessels and other equipment, hiring and training teams.

The coding approach is that for each causal factor, is first given a free-text description. The identification of the factors is largely triggered by an analysis of the identified accidental events. On Table 5 are identified and coded causal factors. Inadequate ventilation of the deck, the lack of inspections of vehicles and inefficiency of firefighting equipment are some of the causal factors highlighted in this study. In daily operation and management and resources column are assigned causal groups concerning each causal factor.

Similarly, the same study is carried out for 20 cases of fire and explosion, whose identified events are coded, resulting in frequency tables for each attribute.

Table 5 – Coding of causal factors

Causal Factors		Coding		Associated Event	
No.	Description	Daily	M & R	No.	Description
C1	inadequate control of stowage units in hold	SUPER	OPMAN	E1 E5	units tightly stowed AB did not enter the space
C2	inadequate ventilation in cargo deck	SUPER	SEMAN ORG&M	E2	all cargo space fans stopped
C3	no evidence of vehicle safety checks	SUPER MANN	ORG&M OPMAN SEMAN	E3 E4	Fire in SB main deck/ fire started in a engine truck OOW viewed the main deck CCTV saw no evidence of fire
C4	unefficient instruction of operating louvres	SUPER PERSON	OPMAN PEMAN	E6 E7	teams started to close manually operated louvres of the 36 ventilation jalousies a considerable amount of smoke continued to emit from the louvres
C5	delaying fire fighting because unknowing fitter whereabout / did not have VHF radio	SUPER MANN PERSON	OPMAN	E8 E9	decided to delay use of CO2 Fitter arrived, the master approved CO2 main deck
C6	affection the chief officer's management of the incident	SOCIAL PERSON	EPREP	E10	10 vehicle drivers started to become disruptive had consumed alcohol and were located at the muster station
C7	fire fighting equipment did not respond as it was expected	TOOLS MAINT	OPMAN SEMAN SYSAC EPREP	E11 E12	Only 9t of the 21.3t of CO2 stored in the tank been released 10t of CO2 remaining in storage tank

4. Statistical Analysis of Fires and Explosions in Ships

The sample of 20 accidents analysed contains 18 cases of fires and 2 cases of fires and explosions, in 6 fishing vessels, 1 container, 5 general cargo vessels, 2 passenger ships and 6 roll on roll of vessels.

4.1 Results of the codification process

An overview of the analysed data is presented in Tables 6 and 7. In Table 6 it can be seen that accidents related to fire in roll-on roll-off vessels are the most common in 138 events coded by the CASMET methodology.

Table 6 – Sample characteristics summary

Characteristics	
Sample	20
Casualty Type	Fire and Explosion
Vessel types	Ro-Ro
	Fishing Vessel
	Container Vessel
	General Cargo
	Passenger Vessel
no. accidental events	138

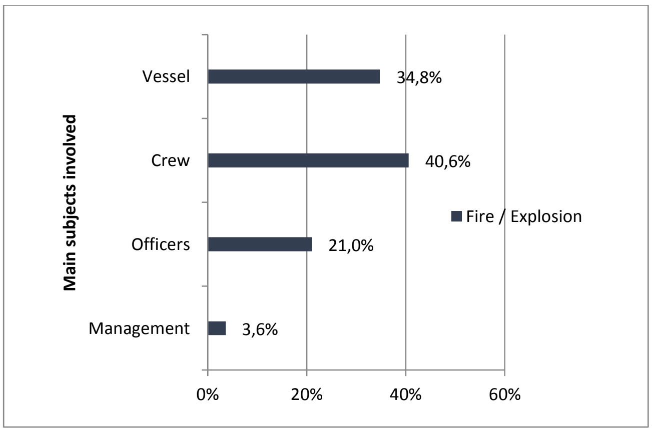

Figure 2 – Main subjects involved in accidents

The analysis of the accidental events related to the main subject involved shows that the crew is the entity involved in 40.6% of the 138 events and 34.8% are related to the vessel (Figure 2). According to the results, the selection of factors with the highest frequency of occurrence is presented.

4.1.1 Human Factor

Figure 3 shows that, with respect to performance, the detection of technical failure (56) and the lack of support (21) have highest frequencies. For actions, the following main factors are identified: personnel factor (17) and lack of support (16).

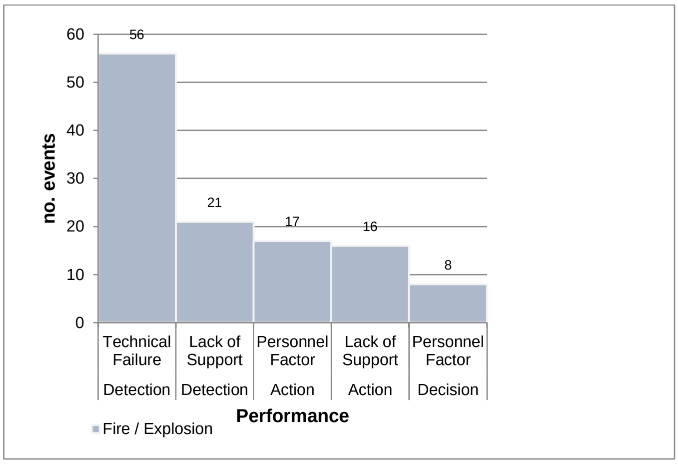

Figure 3 – Selection of 5 higher frequencies of Performance

With respect to causal modes, Figure 4 shows that the highest frequency is related to assignment in operating procedures (31), followed by unavailable equipment (25) and poor maintenance (24), and finally assignment of emergency procedures (22) and lack of experience (19) in personnel.

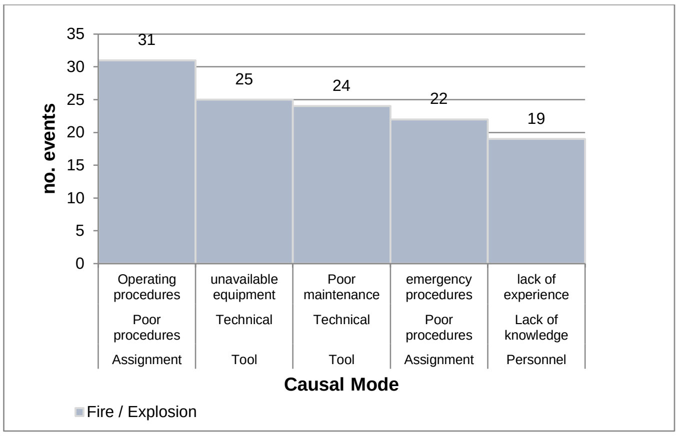

Figure 4 – Selection of 5 higher frequencies of Causal Modes

4.1.2 Accidental Events

With regard to accidental events, the 10 event types with higher incidence are shown in Figure 5. The highest value is performance in decision-making (39) related to human error. The equipment failure in the engine room is the second highest accidental event (24), followed by Mate in human error (22). The next relevant frequencies are also about human error, cargo space maintenance (19) and imprudent (18); following another human error type of accidental events, with respect to engineer position (17). The equipment failure type "not in operation" are the next (17), followed by human errors types: performance detection (17), engine maintenance (15) and Bosun position (15).

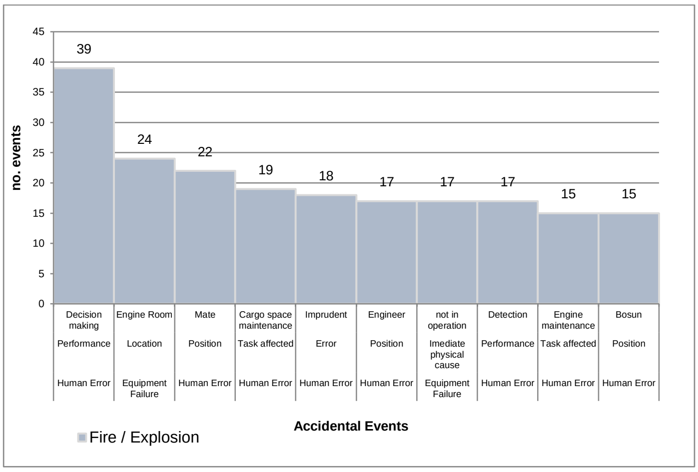

Figure 5 – 10 main Accidental Events

4.1.3 Basic Causal Factors

Figure 6 shows the 10 most relevant causal factors identified from the sample of coded accidents.

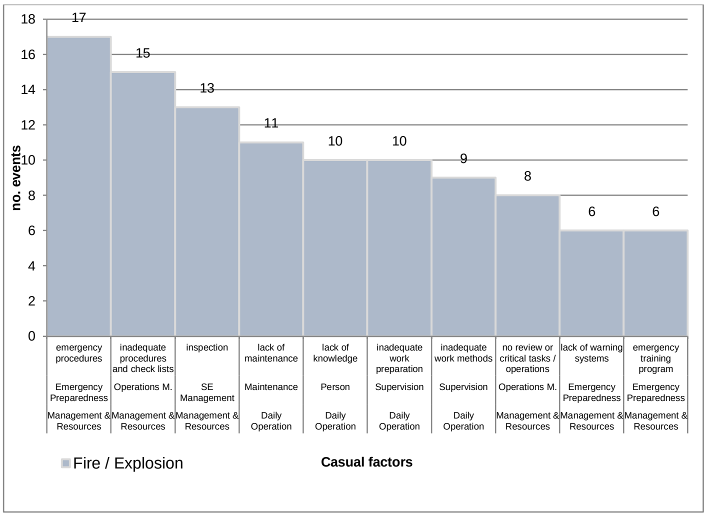

Figure 6 – Selection of 10 higher frequencies of Causal Factors

The three highest values are within the category management and resources, and accordingly, emergency procedures (17), inadequate procedures and checklists (15) and inspection (13). Next, is observed the lack of maintenance (11), lack of knowledge (10), inadequate work preparation (10) and inadequate work methods in daily operations. The last three values correspond to management and resources and are critical tasks or operations (8), lack of warning systems (6) and emergency training programs (6).

Table 7 shows the total values obtained most frequently for each stage of analysis. The highest frequency of events focuses on the crew, with regard to performance, detection of technical failures and operating procedures are the most common of poor procedures assignment. When the focus is on accidental events, the highest frequency of events lies in human error, with the most significant values involving the mate position, with corresponding task affected the maintenance of the cargo area, decision-making performance and error in the imprudent category. In terms of causal factors for the daily operation, maintenance, and more specifically, lack of maintenance is more concerning; while for management and resources, emergency preparedness, including emergency procedures has more impact.

Table 7 – Summary of the results more often in CASMET coding

Step Diagram				# events
Crew				56
Accidental Events				
Human Error	Position	Mate		22
	Task affected	cargo space maintenance		19
	Performance	decision making		39
	Error	imprudent		18
HF Analysis				
Performance	Detection	technical failure		56
Causal Mode	Assignment	poor procedures	operating procedures	31
Causal Factors				
Daily Operation	Maintenance	lack of maintenance		11
Management & Resources	Emergency Preparedness	emergency procedures		17

4.2. Causal Factors and Recommendations

75 different causal factors are identified in the accidental events coded. In order to allow a better interpretation of the results, these causal factors are divided into the following groups:

- Cargo control;
- Lack of training;
- Lack of communication;
- Lack of knowledge;
- Inadequate operating and emergency procedures;
- Firefighting equipment;
- Firefighting procedure;
- Equipment failure;
- Leakage;
- Security arrangements.

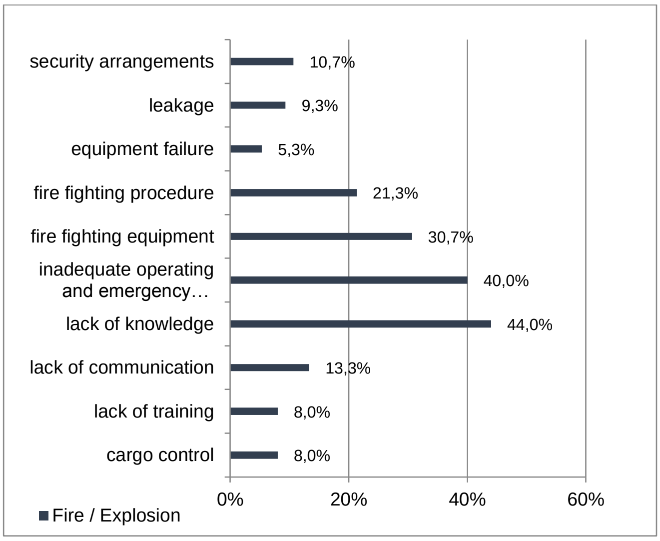

Figure 7 – Percentage values of causal factors group

Figure 7 shows the highest percentage values for lack of knowledge (44.0%), inadequate operation and emergency procedures (40.0%), followed by fire-fighting equipment (30.7%) and fire-fighting procedures (21.3%). Following the lack of communication (13.3%), leaks (9.3%), lack of training and insufficient cargo control (8.0%). The equipment failure is the last one (5.3%).

Once the causal factors of accidents are established, it is interesting to relate these factors with the recommendations of the organizations that have undertaken the accident investigation.

In the accident investigation reports safety recommendations are presented for all accidents. Table 8 shows several examples of safety recommendations collected from the accidents analyzed.

Table 8 – Example causes and their recommendations for various types of ships

Type of vessel	Causal Factors	Recommendations
Ro-Ro	Inadequate cargo control	Review onboard documentation and the "Unsafe Cargo" notice to take into account revised procedures for the carriage of used and unregistered vehicles
Ro-Ro	Inadequate ventilation on cargo deck	Ensure that cargo deck ventilation fans are run in accordance with current regulations
Ro-Ro	fire fighting equipment did not respond as it was expected	Investigate why the CO2 fire-extinguishing system apparently failed to discharge the allotted quantity of CO2 as designed
Container	Inadequate frefighting equipment and procedures	Review the functions and composition of emergency teams and define the roles of personnel in emergency teams by their post held onboard, to standardise procedures
Cruise	Crew's lack of knowledge and training	the required crew actions following the use of fixed instalation CO2 systems, aimed at improving the general knowledge of these systems, including inspections and checks os the system status after use
Fishing	No fire detection system	Fitting a smoke/ fire detection and alarm system in the engine room and accomodation areas to improve the chances of investigating and tackling a fire in the early stages of its development
Fishing	Crew with no technical competences in diesel engines	Engine manufacturer's maintenance instructions are understood and complied with/ attend 5 days diesel engine course

5. Bow-tie Analysis

A Bow-tie model is developed for the analysis and management of the risk of fire in vessels in order to identify threats, barriers and consequences of the accident. The method provides a clear view of the situation in which some risks develop in order to clarify the relationship between causes and consequences of the accident and their prevention and mitigation barriers.

The process starts with the identification of the critical event, followed by the identification of threats. For each threat proactive barriers are identified and included in the diagram. The diagram also lists possible consequences after the critical incident and the barriers that can reduce or mitigate these consequences. The model is developed through the causal factors obtained from the analysis of the accidents coded in the previous chapter. The hazard considered for this analysis is defined as “combustible materials and ignition sources in the engine room”, and the “fire” is the critical event. Figure 8 shows the Bow-tie simplified model, where threats correspond to:

- Leaks from pumps, pipes or tanks;
- Inadequate operating procedures;
- Crew’s lack of knowledge.

The consequences are:

- Impact on people;
- Environmental impact.

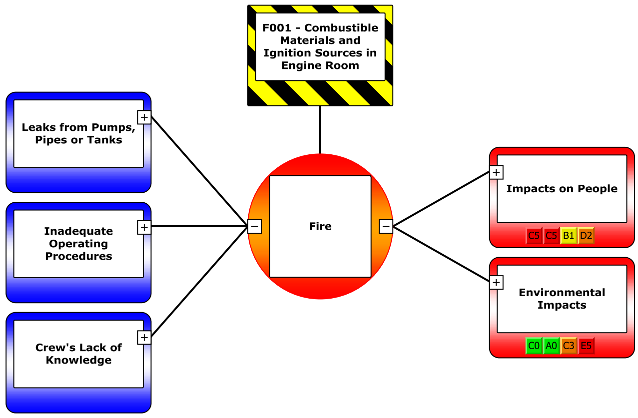

Figure 8 – Bow-tie model simplified

As mentioned previously, appropriate safety functions and barriers have been identified for each threat and therefore to avoid the critical event in question or mitigate its effects. As mention previously accident investigation reports include information on the safety recommendations that can be used in the definition of barriers. Taking the example of the threat " Leaks from pumps, pipes or tanks”, the barriers are as follows:

- Standardized connections;
- Periodic inspection and test equipment;
- Periodic certification of connections;
- Constant supervision by person in charge.

The last barrier has “fatigue” as escalation factor, wherein the actual work time is the corresponding secondary barrier. Another escalation factor for the barrier "constant supervision of the responsible person" is the communication with the bridge. For each barrier one or more factors increase.

Between the critical event and the possible consequences that may occur, there are also mitigation barriers, escalation factors and secondary barriers. Taking as example the consequence” impact on humans”, the mitigation barriers that have been identified are:

- Emergency procedures;
- Fire-fighting equipment;
- Evacuation plan.

The inadequate emergency procedures is an escalation factor for the first mitigation barrier above. Secondary barriers for this scenario are:

- Review of functions and composition of the emergency teams;
- Chapter II-1 of SOLAS: fire protection, fire safety and fire extinction;
- ISM Code Section 8 (Emergency Preparedness).

Considering the escalation factor “availability of fire-fighting equipment”, the secondary barriers are:

- Regular testing for the fire detection system;
- Clear indication spaces discharge protection mechanisms;
- Periodic certification of fire-fighting equipment.

6. Conclusions

This work has identified and analysed the main causes of accidents related to fire and explosion in the maritime context. To achieve this purpose, 20 reports on maritime accidents involving fires and explosions are selected. The reports are coded by the CASMET methodology. The sample of accidents under analysis consists of 18 cases of fires and 2 fires and explosions in 6 fishing vessels, 1 container, 5 general cargo vessels, 2 passenger ships and 6 roll on roll off vessels.
The analysis shows that the crew is the entity involved in majority (40.6%) of the accidental events. The most frequent accidental events are related to human error (57.2%). Within the human error, the Mate position is the one that is more involved in the accidents and the main affected task is the maintenance of the cargo area. Other accidental event, with lower incidence than human error, but still relevant, is the equipment failure (32.6%), being the fire-fighting system the most frequent one and the engine room the most likely location.
At the performance level, the detection of a technical failure is the most likely failure occurrence factor. The most important causal factor is related to poor operating procedures. Moreover, causal modes related to personnel and tool are also identified. In particular for personnel, the lack of knowledge, lack of experience is the most burdensome factor; and for tool, the most

frequent technical problem is the unavailability of equipment.

With regard to basic causal factors, it is concluded that between daily operations and management and resources, the second is more relevant. In management and resources, emergency procedures is the most frequent factor. For daily operations, lack of maintenance is the factor with the highest incidence in the accidental events.

The 75 causal factors coded are then gathered by causal groups. The types of causal factors with higher incidence in the coded accidents are lack of knowledge (44.0%), inadequate operation and emergency procedures (40.0%) and fire-fighting equipment (30.7%).

Finally, a Bow-tie diagram for fire risk assessment and management is developed. The fire is the critical event selected. Combustible materials and ignition sources in the engine room are the hazard in the model, which can lead to a fire. The model is developed based on the causal factors obtained from the analysis of the accidents and on the safety recommendations suggested in the accident investigation reports.

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