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Review

Review and analysis of fire and explosion accidents in maritime transportation

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ABSTRACT

The globally expanding shipping industry has several hazards such as collision, capsizing, foundering, grounding, stranding, fire, and explosion. Accidents are often caused by more than one contributing factor through complex interaction. It is crucial to identify root causes and their interactions to prevent and understand such accidents. This study presents a detailed review and analysis of fire and explosion accidents that occurred in the maritime transportation industry during 1990–2015. The underlying causes of fire and explosion accidents are identified and analysed. This study also reviewed potential preventative measures to prevent such accidents. Additionally, this study compares properties of alternative fuels and analyses their effectiveness in mitigating fire and explosion hazards. It is observed that Cryogenic Natural Gas (CrNG), Liquefied Natural Gas (LNG) and methanol have properties more suitable than traditional fuels in mitigating fire risk and appropriate management of their hazards could make them a safer option to traditional fuels. However, for commercial use at this stage, there exist several uncertainties due to inadequate studies, and technological immaturity. This study provides an insight into fire and explosion accident causation and prevention, including the prospect of using alternative fuels for mitigating fire and explosion risks in maritime transportation.

1. Introduction

The shipping industry is expanding globally, leading to an increase in worldwide shipping traffic (Hetherington et al., 2006; Tournadre, 2014; Yip). The growing number of marine vessels may lead to a rise in maritime hazards and accidents. Akten (2006) stated that shipping is, and always will be, full of risks despite increasing safety standards and improved technology. Celik et al. (2010) stated that the system complexity and automation, human error, human-centred system design, and potential design-based failures are different perspectives for ongoing shipping accidents. Due to this, international maritime authorities have made significant efforts to promote safety in the shipping industry (Hetherington et al., 2006; O'Neil, 2003) but despite this, there are still a high number of shipping accidents reported in recently published statistical reports (Baltic Sea Maritime Incidence Response Group (MIRG), 2017; Darbra and Casal, 2004; Eleftheria et al., 2016; Roberts et al., 2012). Shipping accidents by type are numerous, but common examples are collision or contact, capsize, foundering, breaking up, grounding, stranding, and fire or explosion (Abbassi et al., 2017; Akten, 2006). Broadly, human error, technical and mechanical failure, and environmental factors are common causes leading to shipping accidents but with different percentages (Karahalios, 2015; Uğurlu et al., 2015). The Major Hazard Incident Data Service (MHIDAS) (2002) database, considered eight types of possible causes of general accident, namely mechanical failure, impact failure, human error, instrumental failure, services failure, violent reaction, external events and upset process conditions. According to Allianz Global Corporate and Specialty (2017) foundering (sunk, submerged), wrecked/stranded (grounded), fire/explosion, collision (involving vessels), machinery damage/failure and hull damage have been the most frequent causes of losses at sea over the past decade (2007–2016).

Accidents are often assigned to a single category such as grounding,

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fire or explosion, human error, collision and foundering. This type of categorization ignores the fact that often accidents are caused by more than one contributing factor or sequence of undesirable events (Baksh et al., 2016; Papanikolaou et al., 2007; Wagenaar and Groeneweg, 1987). Most literature relating to shipping accidents (Butt et al., 2013; Bužančić Primorac and Parunov, 2016; Roberts et al., 2013) have highlighted the causal factors for general shipping accidents but root causes of a particular event are often ignored. For instance, human error can lead to collision which in turn may cause fire and explosion. In this case, if there are no causal factors for human error as the root cause, then human error, collision and its subsequent events would not have occurred. In order to prevent the consequences of all these events, causal factors for human error are required to be addressed. This indicates that the determination of root cause and potential safety barriers of any accident type are vital in order to prevent accidents.

In the past, a significant number of shipping accidents involved fire and explosions (Akten, 2004; Roberts and Marlow, 2002; Roberts et al., 2012). For instance, Darbra and Casal (2004) found that 29% and 17% of accidents in seaports are caused by fires and explosions respectively. Bulk carrier casualties world-wide, taken from Lloyd's records between 1980 and 2010, confirm that fires and explosions caused 19% of accidents (Roberts et al., 2013). Weng and Yang (2015) found that the contributing factors in shipping accident mortalities resulting from fire/explosion accidents are, on average, 132% higher than from accidents where no fire/explosions were involved. According to the report presented by Allianz Global Corporate and Specialty (2016), about 10% of total losses, between 2006 and 2015, were caused by fire and explosion. From 2007 to 2016, foundering accounts for the highest percentage of losses (50.42%), followed by wrecked/stranded with 20.57% with the third highest contributor fire/explosion (9.95%) (Allianz Global Corporate and Specialty, 2017). The MIRG project (2017) stated that from 2000 to 2015, among different types of marine vessels in European waters, the largest percentage of ship fires and explosions occurred on cargo ships.

The actual number of fire and explosion accidents could be much higher than the published statistics because of underreporting issues of maritime accidents (Hassel et al., 2011; Schröder-Hinrichs et al., 2011). It is often found that the number of fatalities from fire and explosion accidents in shipping is comparatively higher than that of other types of accidents. Fire and explosion usually occur unexpectedly which provides little evacuation time for passengers or crew members (National Research Council, 1991).

This shows that the risk of fire and explosion in shipping vessels is high. The consequence of ship fire and explosion depends on the presence and amount of hazardous materials and the employed preventive and control mechanisms. In the absence of appropriate protection and response, even a small error that leads to a fire and explosion event has potential to cause loss of vessels, environmental pollution, injuries, and deaths due to the instantaneous nature of ship fires (Shichuan et al., 2012).

Uğurlu (2016) investigated fire and explosion events that occurred between 1999 and 2013 in tankers transporting hazardous liquid cargoes and identified 13 root causes and five causal factors being violation of entry permit (VEP), violation of work permit (VWP), lack of risk analysis (LRA), deficiency in safety management system (DSMS), and deficiency in planned maintenance system (DPMS). This study was conducted in three stages. In the first stage, significance level of the root causes was determined using Fault Tree Analysis (FTA), in the second stage, the causative factors underlying the root causes were determined and in the final stage, the relationship between the causative factors and root causes was determined. The author argued that hot work, electric arcs, static electricity, and combustible gas accumulation are the most significant root causes of fire and explosion accidents in tankers transporting hazardous liquid cargoes and VWP and LRA are the main causative factors of fire and explosion accidents.

In this paper, the contributing factors for fire and explosion accidents in maritime transportation are reviewed based on published full investigation reports and literature. Accident investigation reports prepared by different agencies such as National Transport Safety Board (NTSB), Danish Maritime Accident Investigation Board (DMAIB), Australian Transport Safety Board (ATSB), Federal Bureau of Maritime Casualty Investigation (BSU), Transportation Safety Board of Canada (TSB), European Maritime Safety Agency (EMSA) and Marine Accident Investigation Branch (MAIB) are considered. Publicly available fire and explosion related accidents in maritime transportation between 1990 and 2015 are grouped into five categories according to their main causes, namely human error, mechanical failure, reaction, electrical fault and unknown. The percentage of fire and explosion accidents caused by each causal factor is given in Fig. 1.

These accidents are further divided into different categories in order to compare the number of fatalities and number of accidents in maritime transportation as shown in Fig. 2. This indicates that fire and explosion still pose a risk to maritime transportation despite technological progress. In order to avoid fire and explosion accidents, a comprehensive review of all contributing factors is essential.

Additionally, in this study, potential preventative or mitigation measures are discussed for each type of contributing factor. Identifying sources of flammable materials and replacing them with less hazardous materials may play a positive role in mitigating fire and explosion risks in ship. Marine fuels are highly flammable. In this study, it is found that 31% fire and explosion events are caused by accidental releases of fuel or lubricating oil in the engine room. Due to this, it is worthwhile to review from a safety perspective flammability properties of alternative fuels. The effectiveness of alternative fuels in mitigating fire and explosion hazards is reviewed based on the comparison of their flammability properties. Therefore, this study would help identify contributing factors for fire and explosion events in maritime transportation and would seek to highlight potential preventive measures.

2. Fire and explosion accidents causations

The causes of fire and explosion in marine operations identified by Kwiecińska (2015), provided characteristics of basic fire causes and the influencing factors in ships. These are namely damage to electrical equipment and cables, damage to mechanical equipment, damage to ship's hull or its equipment, damage caused by external factors, damage occurring during maintenance work/repairs, and spontaneous ignition of cargo. The author has shown the interrelationship of cause-and-effect links leading to fires on ships and argued that spontaneous ignition of cargo is the strongest interaction with other factors. This shows that identifying interrelationships among various causal factors of a broad accident category helps to explore the underlying causes. Thus, in order to identify causal and root causes, contributing factors that were responsible for past fire and explosion accidents in shipping are

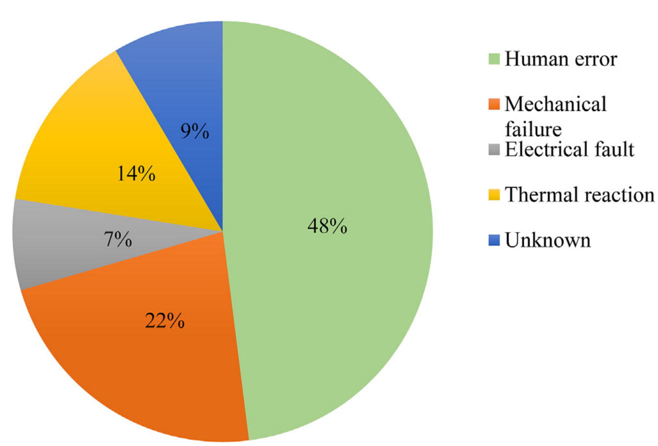

Fig. 1. Percentages of fire and explosion accidents.

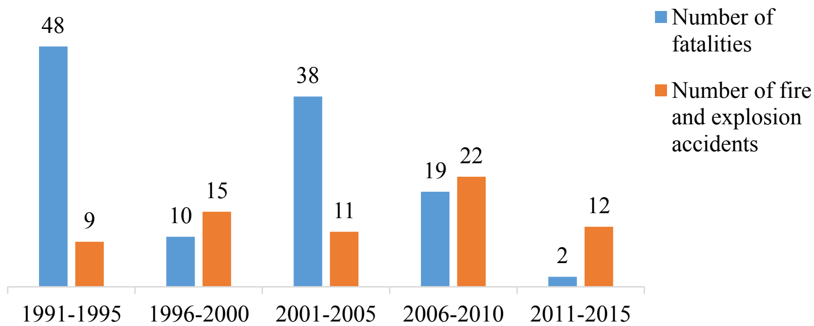

Fig. 2. Number of fatalities, and number of fire and explosion accidents during 1991–2015.

considered. This can provide different real scenarios of fire and explosion events and help identify real causes and their potential mitigation approaches. An overview of steps undertaken in this study is given in Fig. 3. This shows that the four causal factors and several underlying causes of fire and explosion accidents are identified using past accidents information and that general preventative measures are proposed qualitatively.

2.1. Human error as a cause of fire and explosion accidents

The American Bureau of Shipping (ABS) (2003) report stated that marine accidents directly associated with human errors in the MAIB, the ATSB, and the TSB reports total 82%, 85%, and 84%, respectively. This confirms that there is a consistency of causal factor findings among the data and reports in Australian, Canadian, and UK transport accident investigation authorities. This outcome has been supported by other studies (Baker and McCafferty, 2005; Rothblum, 2000; Wagenaar and Groeneweg, 1987). For instance, human error is involved in 75–96% of marine causalities (Rothblum, 2000). A study by Wagenaar and Groeneweg (1987) showed human error contributed to a total of 96 out of 100 marine accidents. Similar results were reported in Baker and McCafferty (2005) where within the period 1991–2001, 80–85% of the maritime accidents were due to human error, 50% were initiated by human error and 30% associated with human error.

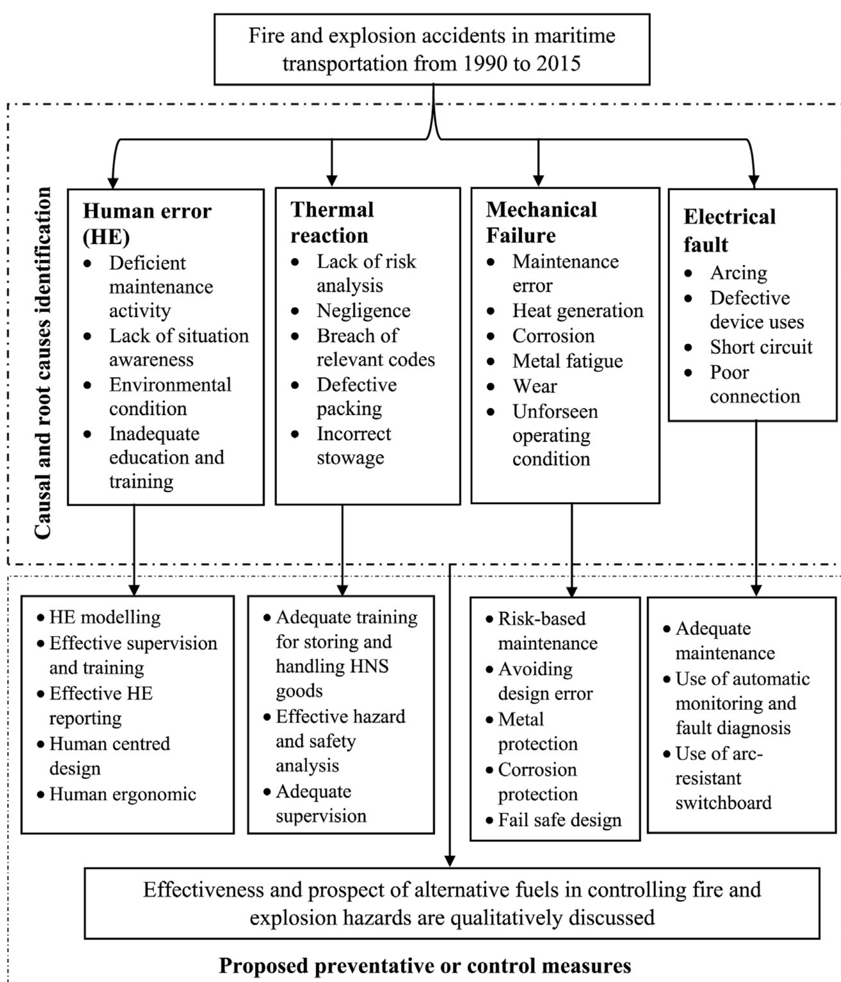

Fig. 3. Steps undertaken in this study.

Apostol-Mates and Barbu (2016), stated that human error is related to technology, environment, organisation, work practice and group. The Nippon Kaiji Kyokai - a classification society (ClassNK, 2010), broadly divided the factors related to the occurrence of human error into human element, hardware factors, and organisation and management factors. Baker and McCafferty (2005) categorised them into five broad groups including situation awareness group, management group, risk group, maintenance human errors and non-human error group and argued that failure of situation awareness and assessment, resulting from human fatigue and task omission, is predominant. Whittingham (2004) postulated two types of human error causation namely internal causes leading to endogenous error and external causes leading to exogenous error. An endogenous error relates to an internal cause arising from an individual such as a failure within the cognitive processes. An exogenous error has an external cause such as an unsuitable working environment. Reason (2000) discussed human fallibility using two approaches: the person and the system approaches. The person approach is related to errors of individuals, blaming workers for unsafe acts such negligence, forgetfulness, inattention, or moral weakness. The system approach focuses on the existing errors in the workplace and the organisational processes. Based on this concept, human failure is grouped into two categories namely active failures and latent failures. The active failures are the unsafe acts committed by frontline people such as drivers, control room staff or machine operators. The unsafe acts include a variety of practices such as slip ups, lapses, fumbles, mistakes, and procedural violations. The latent failures arise from decisions made by designers, builders, procedure writers, and top level management. Examples of latent failures are poor design of plant and equipment, ineffective training, inadequate supervision, ineffective communications, and uncertainties in roles and responsibilities. Latent failures often remain dormant within the system before they combine with active failures and local triggers to create an accident scenario. These failures can be identified and remedied before an adverse event occurs using proactive risk management strategy (Reason, 2000).

Rothblum (2000) stated that the maritime system is a people system where people interact with technology, environment, and organisational factors. Humans may not be the sole cause of an accident and in most accidents are involved in a complex interaction of several factors such as software, hardware, environmental conditions and other humans (Shappell and Wiegmann, 1997). Human interaction with other key factors is shown in Fig. 4. This shows that human factor depends on individual factors such as competency, health, stress and strength, workplace environment (such as site design, ease of use and working condition) and management (procedures, supervision and communications) under which he or she works.

In order to identify underlying causes of human failures, generic human error was functionally deconstructed into logical, mutually exclusive categories into skill based, rule based, and knowledge based errors, routine violations and singular violation as shown in Fig. 5.

Celik and Cebi (2009) identified various contributing factors of human errors in shipping accidents as given in Table 1 and priority weights were generated considering 4 levels of an analytical Human Factor Analysis and Classification System (HFACS). The study argued that skill-based errors, and personnel related factors such as coordination, communication, and planning are the primary causes of shipping accidents in first and second levels respectively. Moreover, inadequate supervision and failure to correct problems, and inadequate organisational processes are the root causes of shipping accidents in third and fourth levels of HFACS.

Among several causes of human error, deficient maintenance is one of the major causes of fire and explosion (Okoh and Haugen, 2014). This includes inadequate hazard analysis, violation of hot work and confined space entry permit guidelines. Some major accidents include an explosion and fire on the tanker Petrolab (TSB, 1999), boiler explosions on the bulk carrier Shirane (ATSB, 2007a) and cargo hold fire on BBC Baltic (ATSB, 2012a). Dhillon and Liu (2006) reviewed human error in maintenance and concluded that human error in maintenance was a pressing problem. Chang and Lin (2006) reviewed 242 accidents that occurred between 1960 and 2003 in storage tanks and revealed that fire and explosion accounted for 85% of these accidents and 30% of accidents were caused by human errors including poor operation and maintenance. Okoh and Haugen (2013) stated that about 30–40% of all accidents and

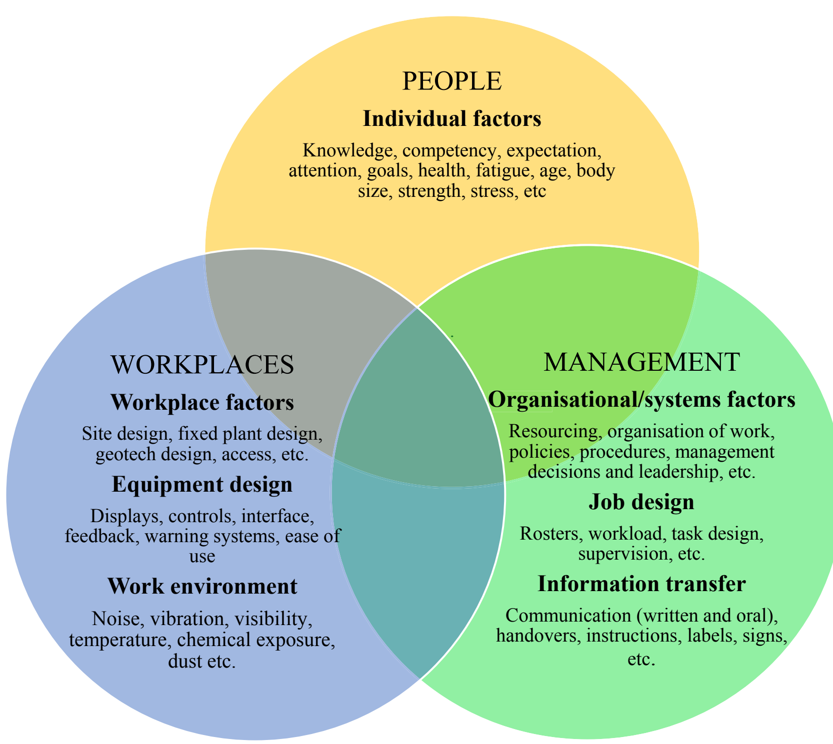

Fig. 4. Human interaction with other factors (WORKSAFE BC, 2017).

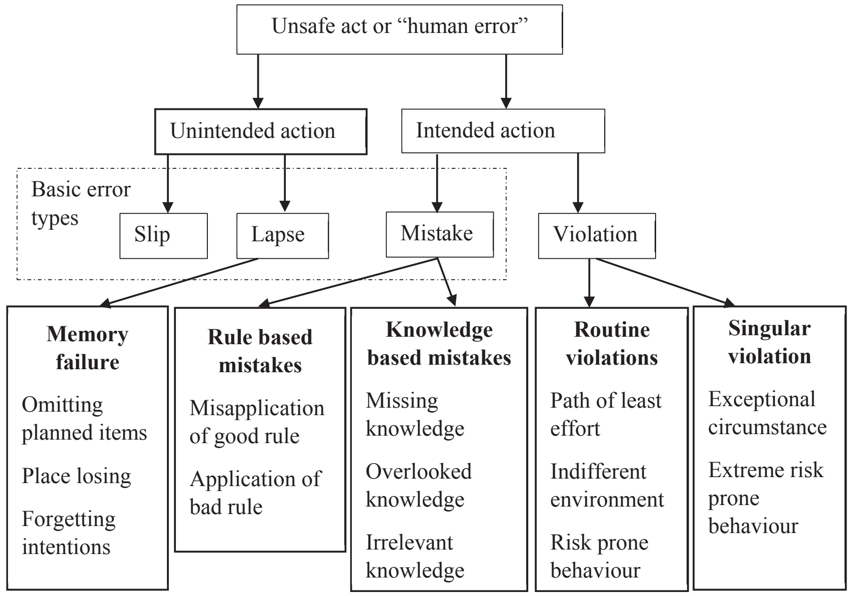

Fig. 5. Behavioural deconstruction of human error (Harrald et al., 1998).

Table 1
Contributing factors of human error on shipping accident.

Acts (level 1)	Preconditions (level 2)	Supervision (level 3)	Organisational influences (level 4)
1 Errors a Skill-based errors b Judgment and decision making errors c Misperception errors	1 Environmental a Physical environmental b Technological environmental c Cognitive factors d Psycho behavioural factors	1 Inadequate supervision	1 Resource management
2 Violations	2 Individuals condition a Adverse physiological states b Physical mental limitations c Perceptual factors	2 Inappropriate operation	2 Organisational climate
	3 Personnel factors a Coordination/communication/planning factors b Self-imposed stress	3 Failed to correct problem 4 Supervisory violations	3 Organisation process

precursor events in the chemical processing industry are due to maintenance-related factors. In another study conducted by Okoh and Haugen (2014) revealed that among 80 maintenance related major accidents, explosion was involved in 44% of these accidents followed by fire (34%). Hemmatian et al. (2014) also revealed that human error occurred mostly in general maintenance activities. In the current study, maintenance related errors were observed in 43% of human error accidents. The fire and explosion on the chemical tanker Bow Mariner in the Atlantic Ocean can be considered as an example of a major accident due to human error in a maintenance related activity. The accident occurred during the cleaning of residual Methyl Tert Butyl Ether (MTBE) by the crew. The accident caused 21 losses of life and the release of a large amount of MTBE, Ethyl Alcohol, heavy fuel oil and diesel into the environment (Manuel, 2011). Use of unskilled crew and lack of situation awareness was reported to be the cause of the accident (US Coast Guard, 2004). Another accident was the explosion of the Tanker Qian Chi in 2011 that led to the serious injury of three crew and caused severe damage to equipment (ATSB, 2012b). The improper installation of the thermal oil heater burner nozzle was reported to be the cause of this accident. Consequently, the fuel found its way to the burner and accumulated before the start of ignition. The furnace exploded when the igniter started. The IIWG report (Maritime Safety Committee 81st session, 2006) stated that the majority of incidents involved MARPOL Annex II substances (rather than oil) and were caused by tank cleaning, venting or gas freeing. Celik and Cebi (2009) HFACS investigated human errors in shipping accidents and argued that disorganisation in maintenance planning and management processes are significant factors in contributing to human error. Okoh and Haugen (2014) discussed failure scenarios associated with maintenance activities and argued that lack of barrier maintenance, deficient design, organisation and resource management and deficient planning/scheduling/fault diagnosis are the most frequent causes in terms of the active accident process, the latent accident process and the work process respectively. Deficient maintenance work also introduces new hazards particularly in safety-critical maintenance works and these are generated by application of new, invalidated procedures, processes, conditions and equipment or existing under validated ones. For example, an explosion and fire occurred in the Partridge-Raleigh oilfield in 2006 during welding of an open-ended piping left unisolated after a previous maintenance session (US Chemical Safety and Hazard Investigation Board, 2007).

Another factor responsible for human error is environmental conditions. Substandard physical working conditions may deter the effective performance of duties, causing stress and fatigue. One example of poor working conditions includes physical exhaustion due to high temperatures. High sea states, vibration, noises, and unsuitable temperature can also affect one's ability to work and can cause stress and fatigue. The environment refers not only to weather and other aspects of the physical work environment, but also the regulatory and economic climates

(Rothblum, 2000). Moreover, tight economic conditions may increase the probability of risk-taking and may put enormous pressure on one's working conditions. Ambient environmental considerations also include appropriate design of living spaces that assist in recovery from fatigue.

Every human error may lead to a condition necessary for an accident to occur which means that if there is no human error, a chain of events may break and the accident may not transpire. Hence, by employing appropriate means of preventing some human errors or increasing their detection probability in marine applications, one may provide a higher level of marine safety with fewer number of casualties (Rothblum, 2000).

2.2. Mechanical failure as a cause of fire and explosion accidents

Fire and explosion accidents initiated by mechanical failures have resulted in catastrophic consequences in the past. According to the Allianz Global Corporate and Specialty (2017) report, mechanical failure was the fifth highest reason for ship losses from 2007 to 2016. Darbra and Casal (2004) revealed that mechanical failure is the second highest grounds for general accidents followed by impacts. Vilchez et al. (1995) revealed that mechanical failures contributed 33% of accidents in a survey of 5325 accidents involving hazardous materials. The VVT research (Hakkarainen et al., 2009), found that fire and explosion events occurring in machinery spaces, cargo spaces and accommodation spaces of ships are 79%, 16% and 11% respectively. The influencing factors for mechanical failures (damage to mechanical equipment) are improperly selected material or its aging, extreme conditions of device operation, lack or malfunction of safety devices, bad quality of prepared safety mechanisms, connections or materials, spill of fuel or working fluids, and human error (improper use of tools or machines, negligence of maintenance work, and noncompliance with safety rules) (Bejger and Drzewieniecki, 2015). Similarly, Maleque and Salit (2013a) outlined that common causes of mechanical failure in a component or system are misuse, assembly errors, manufacturing defects, improper or inadequate maintenance, design errors/deficiencies, improper material or poor selection of materials, improper heat treatments, unforeseen operating conditions, inadequate quality assurance, inadequate environmental protection/control and casting discontinuities.

It is crucial to investigate the most vulnerable areas of any vessel or ship for mechanical failures. Studies of shipping accidents have shown that in most cases the fire originated in the engine room and was caused by oil or fuel coming into contact with hot exhausts. According to a research conducted by Det Norske Veritas (DNV) of 165 fires on board the DNV fleet from 1992 to 1997, 63% of fires occurred in the engine room and 56% of all engine room fires were caused by the combination of oil leakage onto a hot surface (Det Norske Veritas, 2000). Paula et al. (1998) presented the analysis of events involving fire and explosion from the database developed and maintained by Lloyd's Maritime Information Services Limited (LMIS) and found that the majority of fires or explosions are triggered by mechanical failures due to release of fuel oil and/or lube oil system onto hot surfaces in the engine room. This shows that spraying of fuel oil or lube oil on hot surfaces is one of the major causes of fire on board ships. The sources of oil or fuel leakage include damaged flexible hoses, couplings, piston ring, filters and fractured pipes (Det Norske Veritas, 2000).

In several past shipping accidents, various factors have caused mechanical failures and resulted in fires and/or explosions (ATSB, 2010; MAIB, 2007); NTSB (2013). For instance, on 10th March 2012, a roll on/roll off vehicle carrier, Alliance Norfolk, encountered rough weather resulting in damaged cargo and subsequent fire. The NTSB (2013) determined the probable cause of the fire to be due to ignition of flammable material by an undetermined ignition source due to shifting cargo while the vessel was rolling in heavy seas after losing power.

Another factor responsible for mechanical failure is that of an unsafe act such as failure to use the correct tool and procedure, negligence and inadequate supervision. For example on 10th December 2009, the containership Maersk Duffield in Moreton Bay, Queensland, Australia caught fire in an engine room. The ATSB investigation (ATSB, 2010) found that one or more of the connecting rod palm nuts or counterweight nuts had not been tightened sufficiently during recent overhauls and that the resultant failure of one of the retaining studs was the initiator of the catastrophic engine failure. Similarly, a fire broke out in the auxiliary engine room on board the containership Gunde Maersk on 8th December 2015. The NTSB (2015) determined that the fire was caused by fuel leaking from a dislodged O-ring in the fuel supply line and spraying onto the exhaust side of the engine. The leak occurred because the fitting had not been tightened with a torque wrench as prescribed in the manufacturer's written procedures. Likewise, on 13th of July 2014, the bulk carrier Marigold caught fire while loading a cargo of iron ore in Port Hedland, Western Australia. The ATSB (2016a) determined that the fire began on one of the generators after one of its fuel oil pipe fittings failed, resulting in sprays of fuel oil onto a hot surface on the generator. The investigation found that the compression fitting that failed had been used to connect a replacement pressure gauge that had a different pipe connection fitting size to that of the original pressure gauge. It is evident that human factor is one of the major contributing factors for mechanical failures that lead to fire and explosion in marine vessels.

Use of damaged filter or mechanical seals has been seen as another contributing factor for mechanical failure. For instance, on 19th of March 1999, the Multitank Ascania caught fire due to thermal oil leaking from a thermal oil pump mechanical seal and/or a nearby flange joint onto a pressure relief valve (MAIB, 2000). Similarly, on 11th March 1993, the oil tanker Irving Nordic experienced a main engine crankcase explosion due to piston ring failure contributed to by substantial wear on the cylinder liners and the ignition of lubricating oil (TSB, 1995).

Several mechanical failures occurred due to inadequate maintenances such as failure to follow procedure, inadequate inspection and deficient risk assessment during maintenance. For example, on 3rd February 1995, the Norwegian flagged containership Team Heina caught fire in the engine room due to a spray of hot fuel oil, from a failed compression fitting, onto the fuel rail of the starboard generator engine which was then ignited by the hot exhaust manifold (ATSB, 1995). The ATSB investigation found that the compression fitting failed due to prolonged fretting of the pipe caused by misalignment of the pipe with the fitting and also engine vibration. Similarly, on 9th of February 2007, the Bahamas registered general cargo ship Baltimar Boreas, whilst off Newcastle, New South Wales, caught fire in the engine room due to diesel oil spraying from a failed flexible fuel hose onto the very hot surface of the generator's engine (ATSB, 2008). The investigation found that some hoses were in poor condition and the manufacturer's instruction book and the vessel's safety management system provided no guidance for the maintenance or routine replacement of the flexible hoses. On 24th August 1998, the containership Repulse Bay caught fire in the engine room. The fire was caused by ignition of oil leaked from fractured bolts of the exhaust valve actuator (MAIB, 1999). The bolts fractured due to cyclic loads and fatigue and investigation found that there were no engine manufacturer's guidelines for maintenance or inspection.

Beside these aforementioned factors, there are other factors responsible for mechanical failures including malfunction of automatic controllers, failure of components in safety system and use of defective components. For example, on 2nd of October 2006, failure of the boiler's automatic controller overheated the auxiliary boiler furnace tube, causing a fire to break out on-board the containership Maersk Doha (MAIB, 2007). As a result, the auxiliary boiler fire tube, exhaust gas economiser tubes, uptakes and funnel casing were damaged due to direct, or radiant effect of excessive heat (Celik et al., 2010).

On marine vessels and offshore structures, corrosion is a leading factor for mechanical failures due to environmental conditions. Corrosion causes material degradation resulting in loss of mechanical properties such as strength and ductility and ultimately causes failure (Popoola et al., 2013). According to HID Statistics Report (HSR) (2003), about 66.3% of hydrocarbon releases were caused by equipment faults during the reported period and the most common cause was 'mechanical failure' which, in the majority of cases, was attributed to corrosion or other related degradation.

According to the causes of accidents, it is evident that mechanical failure may not be a standalone cause of a fire and or explosion in a marine vessel, rather it is associated with other contributing factors such as human error, harsh operating and environmental conditions, inadequate maintenance and mechanical fatigue.

2.3. Thermal reaction as a cause of fire and explosion accidents

In the shipping industry, reaction or auto-ignition of loaded Hazardous and Noxious Substances (HNS) is a contributing factor for some fire and explosion accidents. According to Munich Re Group (2002) report, container vessels can sometimes carry as much as 10–40% volume of hazardous goods. Violent reactions may occur when incompatible chemicals are mixed (Baltic Marine Environment Protection Commission (HELCOM), 2002). Chemical accidents originating from improper storage make up almost 25% of all chemical accidents (U.S. Chemical Safety and Hazard Investigation Board, 2002).

In order to avoid potential hazards while mixing or storing chemicals, the guidelines mostly used are from US Environmental Protection Agency's Chemical Compatibility Chart (Hatayama et al., 1980), U.S. Coast Guard's Cargo Compatibility Chart and Chemical Hazards Response Information System (CHRIS) (US Coast Guard, 1980) and National Oceanic and Atmospheric Administration's Chemical Reactivity Worksheet (Simmons et al., 2008). Shippers of dangerous goods on board ship are required to pack and mark the goods in accordance with the International Maritime Dangerous Goods (IMDG) Code (Ozcayir, 2007) and to provide necessary shipping documents and declaration that the dangerous goods are in all respects in proper condition for carriage (ATSB, 2007b).

Despite these guidelines and application of codes, fire and explosion has been reported while shipping dangerous and noxious goods due to chemical reactions or auto-ignition of goods (BSU, 2014; Sam, 2012; Schröder and Prause, 2016). Dangerous and noxious goods on board a ship increase the likelihood and consequences of fire and explosion accidents (Schuda, 1991). This has been supported by some major fire and explosion accidents involving goods carried on board container ships globally (ATSB, 2007b; Ellis, 2011; Haveman and Shatz, 2006). For instance, on 21st March 2006, an explosion and fire on board the container ship Hyundai Fortune in the Indian Ocean compelled the crew to abandon the vessel and it resulted in total constructive loss (Ellis, 2011; Sam, 2012). It is suspected and alleged that natural ignition of dangerous goods such as calcium hypochlorite or fireworks may have caused the initial explosions due to ambient temperatures and improper stowage (ATSB, 2007b; Ellis, 2011). Similarly, on 11th November 2002, the container ship Hanjin Pennsylvania, suffered a fire and explosion in the Indian Ocean with the loss of two lives. This was caused by undeclared dangerous goods, magnesium (Ellis, 2010). These incidents indicate the consequences of undeclared goods in shipping.

The main contributing factors for reaction or auto-ignition of loaded goods are defective packaging and incorrect stowage. The root causes of these are difficulty in chemical hazard identification and human error because of the complex nature of chemistry and the multitude of chemical regulations and their organisations relevant to their packing, storage and shipping (Simmons et al., 2009). Some chemicals such as methyl ethyl ketone peroxide (MEKP) are unstable and extremely flammable at ambient conditions. They readily cause fire and explosions if they are neither stored nor handled appropriately (2008a; 2008b). On 7th July 2010, a container ship, Charlotte Maersk, caught fire while en route from Port Klang, Malaysia bound for Salalah, Oman. Based on circumstantial evidence, the DMAIB (2012) pointed out that the fire probably originated from the container containing methyl ethyl ketone peroxide (MEKP).

Some chemicals such as calcium hypochlorite are prone to thermal runaway, a phenomenon in which the heat naturally produced by the chemical serves to heat itself further, thus generating more heat (Barton and Nolan, 1989; Clancey, 1987). According to the United States Court of Appeals for the Second Circuit ruling for the M/V DG Harmony explosion (2008c), on 9th November 1998, the ship was carrying approximately 160,000 kg of calcium hypochlorite below deck when an explosion occurred in the area where the calcium hypochlorite was being stored. Another explosion occurred on the vessel Contship France in October 1997, while the ship was carrying 512 drums of calcium hypochlorite (Tamburello, 2011). The explosion was caused by the self-heating of calcium hypochlorite contained in the area of the explosion. The United States Court of Appeals for the Second Circuit (2006) acknowledged that temperatures in the cargo area were high enough for the calcium hypochlorite to spontaneously ignite and recognised it as the cause of the explosion.

Additionally, defective packaging, such as loose lids on steel drums and loosely tied or damaged bulky bags can expose HNS goods to hazardous conditions and transporting them in large packages, such as bulky bags, increases the risk of auto-ignition and flammability (National Industrial Chemicals Notification and Assessment Scheme (NICNAS), 1995). Defective packaging and incorrect stowage are directly related to human and organisational errors. For example, on 14th July 2012, the German-flagged full container ship MSC Flaminia caught fire and exploded. The BSU (2014) stated, after analysing the physical and chemical properties of all the items of cargo in cargo hatch 4 of the damaged container, the most likely cause of the fire was either a release of car care products or leakage of dimethylaminoethanol from a tank container, which in turn reacted with surrounding items of cargo generating heat and ignition. In February 2007, the Nitrogen, Phosphorous and Potassium (NPK) fertilizer aboard the cargo ship Ostedijk underwent a chemical reaction and destroyed part of the cargo and compromised the ship (Babrauskas, 2003). This chemical is known to undergo self-sustaining decomposition reactions upon exposure to a heat source (Babrauskas, 2003).

Past shipping accidents confirm that the root causes of chemical reactions that lead to fire and explosion are mainly thermal runaway, auto-ignition and leakage due to defective packaging and incorrect stowage preceded by human and organisational errors, and inadequate safety analysis. This indicates that despite availability of regulatory requirements, databases/tables, codes and signage for chemical storage and handling, thermal reaction is still a major contributing factor to accidents in shipping. This demands a need for detailed study of properties of chemicals and the precautions that should be taken to avoid devastating losses.

2.4. Electric fault as a cause of fire and explosion accidents

Faults in electrical systems can be classified into a few groups such as poor electrical connections, short or open circuits, overloads, load imbalance and improper equipment installation (Jadin and Taib, 2012). Most commonly, an electrical fault on a ship causes three types of incident, being electrical shock, electrical fires and electrical failures. Electrical fire is a serious hazard aboard any ship and is most likely caused by faulty or improperly maintained electrical equipment. Electrical faults or malfunctions have resulted in several residential, industrial and shipping accidents in the past (Ahrens, 2016; ATSB, 2016b; Campbell, 2016). The National Fire Protection Association research report (Campbell, 2017) described electrical fires based on type of device that failed, type of malfunctions, location and origin, and time of occurrence. This report shows that electrical distribution, lighting and power transfer contributed to 57% of reported home fires involving electrical failure or malfunction. Babrauskas (2008) described electrical fires by grouping them into two categories, namely (1) according to the nature of the physical mechanism that led to ignition, and (2) according to causative factors which caused the failure mechanism to be triggered. Babrauskas (2008) stated that physical mechanisms causing electrical fires are poor connections, arcing across a carbonised path, arcing in air, excessive thermal insulation, overload, ejection of hot particles, dielectric breakdown in solid or liquid insulators and miscellaneous phenomena. Smith and McCoskrie (1990) outlined the causative factors for electrical fire as improper altercations, improper initial installation, deterioration due to aging, improper use, inadequate capacity, faulty product and unknown. The study found that improper altercations contributed to 37% of the reported residential electrical distribution system fires. Fires on ships are caused by electrical faults, ignition of spilled oils and fuels (Mouritz and Mathys, 1999). A research project on 165 fires on board the DNV fleet from 1992 to 1997 found that 9% of fires originated from electrical components (Det Norske Veritas, 2000).

Electrical faults or malfunctions have caused a number of fire accidents on marine vessels. For instance, on December 11th, 2015 a fire broke out in the electrical control room aboard the freighter Alpena 2015 and resulted in damage costs of 4 million dollars (Stuards, 2015). The NTSB (2016) determined that the probable cause of the fire was a fault in the electrical wiring providing power to the aft anchor winch.

In some fire and explosion accidents that occurred on shipping vessels, investigations could not conclusively find actual causes of accidents and thus, only provided likely or possible causes based on circumstances. For instance, on 28th April 1990, Val Rosandra was discharging refrigerated propylene at Brindisi in Italy when a violent explosion occurred in the cargo compressor motor room with a consequent fire due to ignition of escaping propylene. It is believed that the explosion most likely occurred because of ignition of released gas with electrical equipment in the compressor motor room (Niall and Roger, 2002). Similarly, on 7th August 1997, a fire was discovered on the lower bridge deck of the Taiwanese flag bulk carrier Ming Mercy. Based on circumstantial evidence such as the remainder of amateur wiring extensions found in the location of fire and other accommodation spaces, the source of the fire was identified as electrical fault (Marine Incident Investigation Unit, 1997).

On 9th of October 2014, a fire started in crew cabin 4 located on the upper deck of Ocean Drover's accommodation block. The investigations (ATSB, 2016b) could not identify the exact origin or cause of the fire because of loss of physical evidence. However, it was stated that electrical sources or smoking-related activities were likely origins of the fire. On 1st May 2013, heat and smoke were detected on the Swedish-flagged con-ro carrier Atlantic Cartier and the fire spread rapidly, resulting in cargo and material damages, i.e. cable routing beneath the ceiling and deck deformation (BSU, 2015). Due to preceding extinguishing works, smoke build up and the prolonged period of the fire, traces of evidences about the causes of the fire that might had been presented originally, were covered or destroyed, thus precise causes could not be identified. Based on circumstantial evidence, the BSU Report 99/13 stated that there were a number of conceivable causes, including a technical fault in the electrical system of a vehicle due to an overload or short circuit and partial overheating. Additional possible conceivable causes included negligent or malicious arson, inadequate wiring revealed by cable loops protruding from the protective sheath, traces of corrosion on cables, cable connections of inconsistent strength, existing damage to cables due to welding operations, damage due to abrasion caused by metal cables, forcibly bent cables inside the insulation, damage to the insulation due to overheating and traces of several earlier fires on deck 3 B.

Investigation of fire accidents can be complex and not as clear cut as other forms of investigation (Beland, 1984a; Hine, 2004). This is due to the possibility of omission of traces of evidence because of extinguishing works, smoke build-up, prolonged burning or fire damage, and the complex nature of fire scenarios. Beland (1984b) claimed that electricity is not as fire prone as generally believed and concluded that electrical fires are conceivable when different abuses such as overloading, combustible materials, high ambient temperatures and inadequate insulation are present. Due to the complexity involved in the justification of actual causes of fire or lack of precise physical evidence, a significant number of fires were mis-investigated and were assigned as electrical fires (Babrauskas, 2001; Beland, 1984b; Béland, 1992). Beland (1984b) further argued that electricity is a handy scapegoat because it is often difficult to defend it and electricity, as the cause of fire, is also defended on unconvincing evidence that electrical equipment was close to the point of origin. This later claim is not ruled out if the investigation reports of Atlantic Cartier fire, Ocean Drover fire and Val Rosandra fire and explosion accidents are referred to because their concluding remarks about cause of fire were all based on circumstantial evidence.

Despite such claims, there exists much evidence clearly justifying that electricity has contributed to fire and explosion accidents causing catastrophic consequences in residential, industrial and commercial spaces (Babrauskas, 2001; Campbell, 2016; Daeid, 2004; Troitzsch, 2016). This signifies a need for systematic research and investigation approaches in regard to causes of fires and explosions in order to improve accident investigations and to reduce fire and explosion accident losses.

In this study, it is found that about 9% fire and explosion accidents have unknown causes or definite contributing factors, and their underlying causes were not identified during investigation. Most physical evidence leading to fire and explosion is often damaged and destroyed during the accident (Beland, 1984a; Hine, 2004). This shows that investigation of fire and explosion accidents requires special attention and may need more effective approaches.

3. Preventative measures of fire and explosion accidents

The causal factors of fire and explosion accidents can be avoided or mitigated by adopting preventative measures. In order to prevent or mitigate the causes, identification of potential preventative measures is important. However, there is no silver bullet to identify solutions to all contributing factors. Due to this, some potential preventative measures are given in generic ways for each contributing factor.

3.1. Prevention and mitigation of human error

Humans are generally seen as error-prone as proved by numerous examples of human error. This signifies a need for design of human independent systems by replacing human performance with technology, specifically by automation, which is considered highly reliable because it is the result of a formal design process and is based on components with known failure rates (Hollnagel, 2008). Moreover, employing human centred approach may be effective to mitigate human error because it puts the human user at the centre of the design as shown in Fig. 6 (Midland Engineering, 2017).

In marine operations, human errors that lead to fire and or explosion generally occur in maintenance activities. In this study, it is found that 43% of human error results from maintenance related activities such as

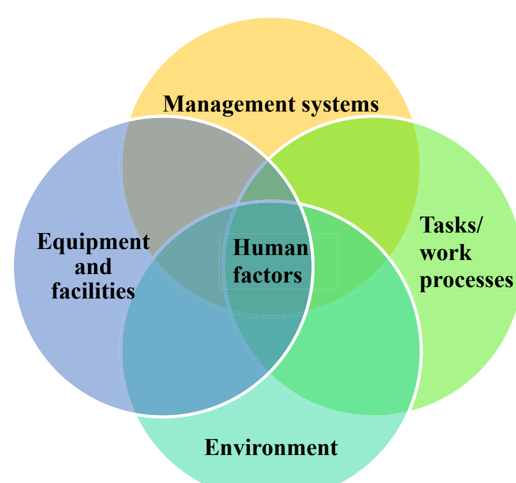

Fig. 6. Human centred approach for mitigating human error (Midland Engineering, 2017).

hot work, overhauls and inspections. Maintenance has been a subject of major interest in order to avoid or reduce human error. Pennie et al. (2007) introduced the issue of maintenance error considering the human factor in maritime maintenance and inspection and with emphasis on design for maintainability. Islam et al. (2016) determined human error probabilities in maintenance operations of marine engines and argued that the checking of fuel and lubricating oil filter pressure difference activity have high probability for accidents.

For human error likelihood assessments, different approaches such as the Human Error Assessment and Reduction Technique (HEART), the Technique for Human Error Rate Prediction (THERP) and the Success Likelihood Index Method (SLIM) are used (Abbassi et al., 2015; Noroozi et al., 2010). Islam et al. (2017) developed a monograph for assessing the likelihood of human error in marine operations and argued that the monograph can significantly decrease the time and resources required to estimate Human Error Probability (HEP) when decision making for marine operations involving different environmental and operational conditions. Applications of these methodologies can be helpful tools to reduce the potential of accident occurrence by assessing HEP.

Human error modelling (HEM) and an adoption of 'open culture' or confidential reporting system (CRS) are essential to better understand the causes and effects of human error (Whittingham, 2004). The HEM helps to explore the relationship between task and error, and helps to better understand the role of human error in accident sequences. Adoption of open culture encourages employees to report errors that they have made, or seen, so that the underlying causes can be investigated and corrected on time. A CRS enables error or other safety issues to be reported confidentially (without fear of litigation) by an employee to a concerned authority and the authority then communicates the information to the employer for necessary action (O'Leary and Chappell, 1996).

In most cases, human errors are caused by the growing imbalance between system reliability and human reliability. In order to overcome this imbalance, the science of ergonomics has evolved which focuses on addressing how the design of the interface between human and machine could take more account of human capabilities and maximize human performance thereby reducing the probability of human error (Karwowski, 2012). This helps to prevent human actions becoming out-of-tolerance in terms of exceeding some limit of acceptability for a desired system function (Whittingham, 2004).

According to Karwowski (2005), the current focus of the human factors and ergonomics (HFE) discipline is on the design and management of systems that satisfy human compatibility requirements. The design integration refers to interactions between hardware (computer--based technology), organisation (organisational structure), information system and people (human skills, training and expertise). Systems' management maintains the interactions between various systems' elements across process and product quality, workplace and work system design, occupational safety and health programmes and corporate environmental protection policies. The author further emphasised that emerging branches of HFE such as microergonomics, neuro-ergonomics and nanoergonomics would play a significant role in mitigating human errors. For instance, neuro-ergonomics focuses on the neural control and brain manifestations of the perceptual-physical-cognitive-emotional interrelationships in human work activities (Parasuraman, 2003). This aims to design a workplace to better match the neural capacities and limitations of human.

The American Bureau of Shipping (ABS), 2014 proposed a Human Factors Engineering/Ergonomics Model which contains four elements that influence safety and efficiency in job performance. They are vessel or offshore installation design and layout considerations, workplace ambient environmental conditions, management and organisational issues related to operations, and the personnel who operate the vessel or offshore installation as depicted in Fig. 7. In order to maintain safety, productivity and efficiency, sufficient attention needs to be given to these elements and these elements should be at the core of any HFE implementation effort (American Bureau of Shipping (ABS), 2014).

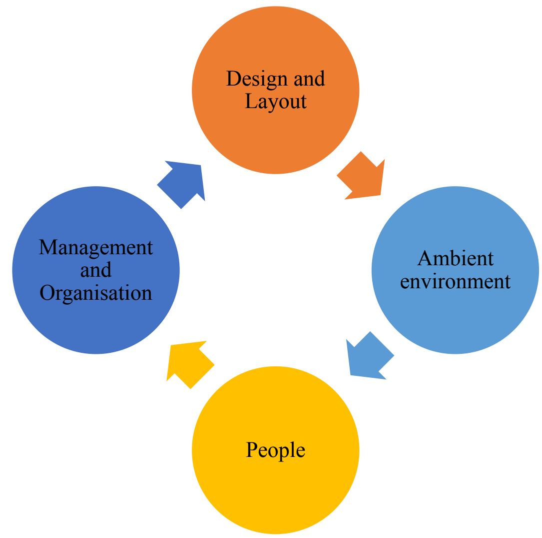

Fig. 7. ABS human factors engineering/ergonomics model.

People is an integral part of organisation and system as discussed in section 2.1. For prevention of both active and latent human failures, it should be looked at from a system approach which generally consists of defences, barriers, and safeguards. Maritime transportation has many defensive layers such as those which are engineered (alarms, physical barriers, automatic shutdowns, etc), people (control room operators, etc), and procedures and administrative controls. For prevention of fire and explosion accidents due to human factor, Swiss cheese model can be used as suggested by Reason (2000). The developed Swiss cheese model has three safety layers, equipment, processes and people, with direct influence of organisational safety culture as shown in Fig. 8. The presence of holes (errors, deficiency, flaws) in any one layer does not normally cause an accident. Usually, this can happen only when the holes in all layers momentarily line up allowing the hazards to pass through all layers. It is obvious that reducing the number of holes in each slice would play a key role in decreasing likelihood of accidents.

Equipment should be designed, located and modified in such a way that it contributes in reduction of errors during use, maintenance, inspection and testing thereby incorporating the effects of the environment in which they are operated. Workspace should be designed suitable for high human reliability. As far as possible equipment and its accessories need to be equipped with fire resistances and protections and flammable fluid inventories should have adequate leak prevention measures. Second safety barrier is processes which mainly comprise procedures, fire and explosion risk management, near misses and precursor's investigations, safety critical communication, staffing levels and workload. Procedures need to be clear and practical. Safety critical communications must be clear and unambiguous. Staffing levels and workloads must not compromise safety. The final barrier is people. Employees need adequate training and competence along with the correct level of supervision and leadership. Appropriate instructions for various operations (hot work permits, inspection and maintenance procedures, flammable gas monitoring) should be made available. Safety analysis should include human failures and behavioural safety including human interactions with other factors. Organisational safety culture needs to be appropriate such that it can play a central role to organise and co-ordinate safety barriers for prevention of accidents.

3.2. Prevention and mitigation of mechanical failure

Mechanical failures involve an extremely complex interaction of load, time and environment (Stephens et al., 2000). The complex nature of metal failures can only be understood by identifying different types of

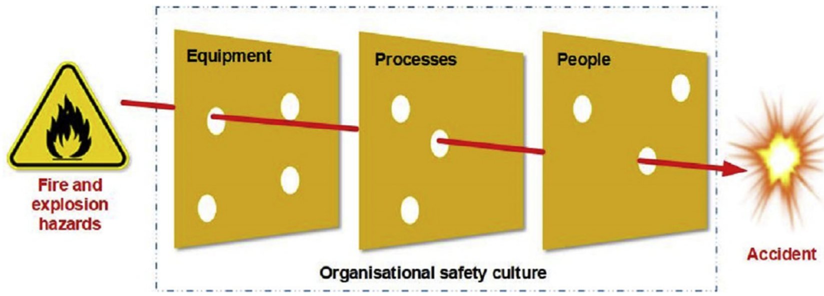

Fig. 8. Swiss cheese model for accident prevention due to human factor.

mechanical failures such as fracture, fatigue, creep, corrosion and wear (Maleque and Salit, 2013a). Vilchez et al. (1995) identified that leaking valve, overpressure, metallurgy failure, corrosion, flange coupling failure, hose failure, overheating, weld failure, leaking gland, relief valve failure, fatigue, overload, brittle failure, incompatible material use are specific causes of mechanical failure.

The causes of fatigue failure are identified as unintended stresses, misuse, design deficiencies, incorrect assembly, and deficient testing and inspection techniques (Scutti and McBrine, 2002). In this study, fatigue failure of a component is observed in 36% of accidents in mechanical failure category. Failure due to fracture can be prevented by avoiding stress concentration, reducing the speed of loading, avoiding ductile-brittle transition temperature and preventing thermal shock (Maleque and Salit, 2013a). The most effective method to prevent fatigue failure is in design improvement by avoiding sharp surface tears, surface discontinuities and tensile residual stresses and improving fabrication and fastening procedures (Maleque and Salit, 2013b). Creep occurs when the metal, under certain loads is heated normally over 40% of melting temperature of the material (Brnic et al., 2017). An understanding of behaviour of a material at high temperature with certain load over a period of time is a useful approach. It helps in evaluating failures of components due to creep (Dasgupta and Pecht, 1991). The fatigue failure and creep can be prevented by avoiding unintended stresses and strains and design deficiencies and using adequate coating, defect detection and testing techniques.

Corrosion is a very widespread problem in all engineering structures, especially those in harsh chemical environments such as chemical engineering processing equipment and in salty environments (Dasgupta and Pecht, 1991). Failure, due to corrosion, can be controlled or minimised by various means, such as correct material selection, galvanic protection, corrosion inhibitors, adequate corrosion monitoring and inspection and protective coating (Nalli, 2010). The various environmental conditions usually encountered by anticorrosive coatings are given in Fig. 9. In order to avoid material degradation due to corrosion, protection of anticorrosive coatings is essential. Anticorrosive coatings used in metals can be protected using barrier protection, passivation of surface (inhibitive effect) and sacrificial protection (galvanic effect) (Sørensen et al., 2009). Additionally, adoption of risk based inspection planning and integrity assessment methods may avoid failures due to material degradation (Khan and Howard, 2007).

It is important to understand the principles of corrosion in order to effectively select materials and to design, fabricate, and utilize metal structures for the optimum economic life of facilities because no particular material is the cure for all types of corrosion (Popoola et al., 2013). To understand the principles of corrosion, modelling of corrosion has been done considering experimental tests and probabilistic approaches such as Bayesian Networks (BN) (Bhandari et al., 2017a, 2017b). The Energy Institute (2008) proposed guidance model for improving corrosion management practices in oil and gas production and processing as shown in Fig. 10.

Wear is caused by the removal or displacement of material due to mechanical action of a contacting solid, liquid or gas. Failure due to wear can be controlled by preventing removal of material and reduction of dimension with proper material selection and design (Maleque and Salit, 2013b). Moreover, materials or parts vulnerable to wear need adequate maintenance and overhaul because wear cannot be totally eliminated. Therefore, the causes of failure of engineering components can be controlled or prevented by appropriate design, better materials selection, avoiding manufacturing defects and overloading, and adequate maintenance.

3.3. Prevention of thermal reaction in shipped goods

The shipping industry is involved with transporting goods ranging from non-hazardous to water reactive, corrosive, toxic and highly flammable. For maintaining safety during the transportation of hazardous goods, a number of international codes, such as international maritime dangerous goods code, construction and equipment of ships carrying dangerous chemicals in bulk (resolution A212 VII), Marine pollution convention, the revised guidelines of IMCO on hazardous chemical classification and the International Convention for the Safety of Life at Sea (SOLAS) Chapter VII (Carriage of Dangerous Goods) amendments (2002), are being implemented (Rao and Raghavan, 1996). Goods that are listed within the codes must be transported according to the

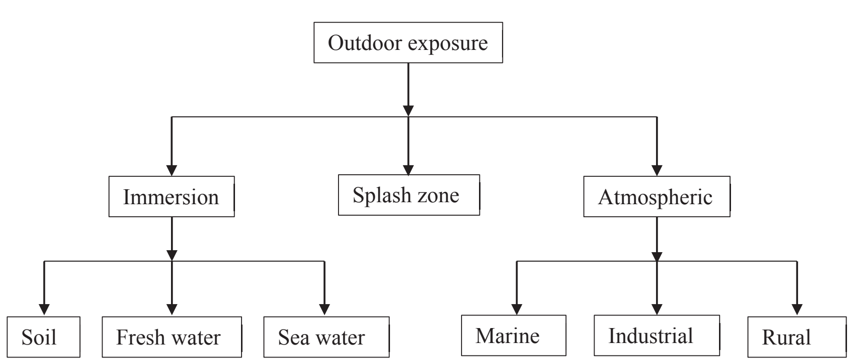

Fig. 9. Various environments encountered by anticorrosive coatings (Sørensen et al., 2009).

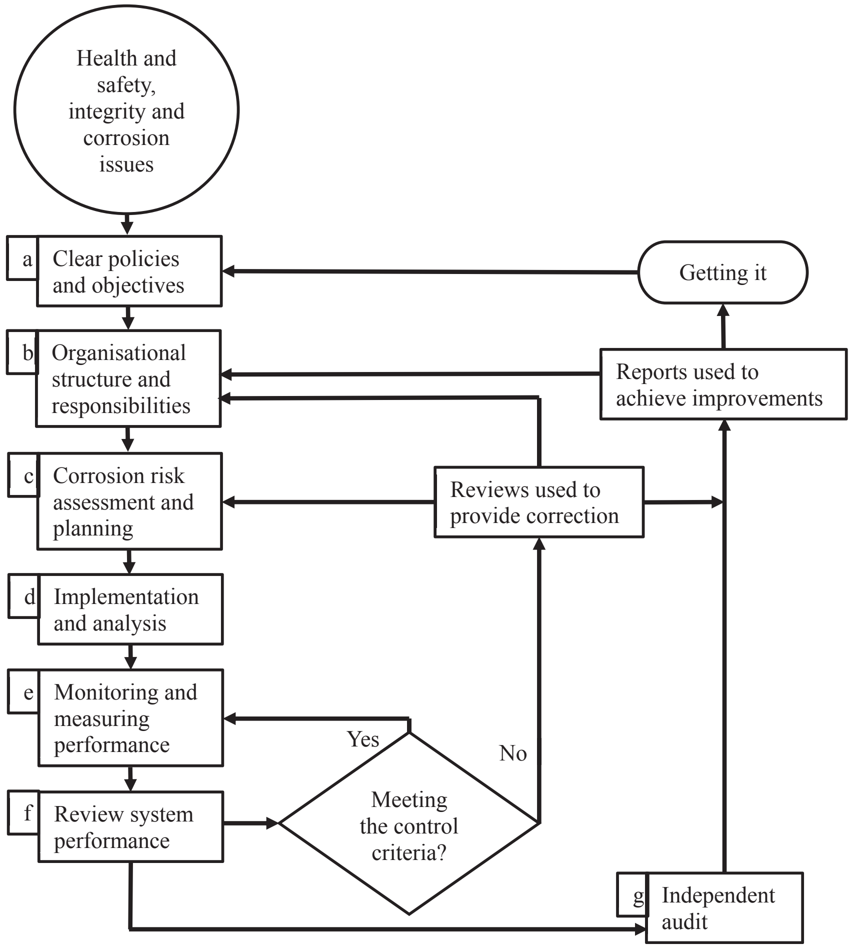

Fig. 10. The basic corrosion management process model (Energy Institute, 2008).

provisions which specify requirements for packing, consignment, and transport operations, including packaging to be used, marking, labelling, placarding, stowing, segregation, and transport documentation (Ellis, 2010). Despite these codes and regulations, the shipping industry has experienced many fire and explosion accidents in the past, mainly because of thermal runaway, auto-ignition and leakage due to defective packaging and incorrect stowage.

Some chemicals decompose rapidly on heating and under influence of light, and react violently with incompatible substances or ignition sources (acids, bases, reducing agents and heavy metals) to cause fire and explosion hazards (Wang et al., 2009). These properties of chemicals are required to be clearly identified, and more efforts are needed for reactive, self-reactive or incompatible chemicals. For instance, Wang et al. (2009) used a preliminary calorimetry approach to identify the effect of the incompatibility on the thermal hazards of *Tert*-butyl hydroperoxide (TBHP) to understand the safe design and precaution for the hazards of incompatibility of TBHP. The study found that TBHP solutions with alkaline have potential thermal instability and the aqueous TBHP can show more severe thermal and self-reactive hazards in the presence of contaminants. Hence, care should be taken in shipping, handling and storing. Due to this, Wang and Shu (2010) recommended reconsideration of the classification of thermal hazards of organic peroxide from the viewpoint of a proactive approach to an intrinsically safer design by incorporating safer process operating conditions, type and material of storage tanks for transportation, and firefighting via temperature control and pressure relief systems.

Thermal runaway is another contributing factor for fire and explosion accident. Gustin (2002) provided the case studies of thermal runaway reactions and stated that the study of accident case histories can greatly reduce the rate of occurrence of runaway reaction accidents. Similarly, Ho et al. (1998) analysed 65 incidents of runaway reactions and emergency relief in Taiwan and classified them into several categories according to their causes, material involved, equipment types, reaction types and ignition sources. The study found that heat of reaction was the main cause in initiating thermal or pressure runaway.

Chemicals with National Fire Protection Association (NFPA) reactivity ratings of 2 and above can be categorised as reactive and can undergo runaway reactions, decompositions, or self-polymerizations with resulting temperature or pressure increase (Rao and Raghavan, 1996). Hence, these chemicals should be stored or handled appropriately avoiding hazardous environments.

For safe handling of HNS, containerized cargo handling is gaining popularity. This has led to the design of various containers suited to hazardous substances. For instance, an insulated storage system with balanced thermal energy flow (McCormick, 2011) and shipping and storage system for exothermic materials (Fine and Kurtz, 2000) can be a better solution to mitigate thermal runaway and decomposition hazards of chemicals. Moreover, the specialised containers may prevent leakage and defective packaging. However, the container's contents need to be properly secured and braced.

Simmons et al. (2009) compared the chemical incident reports of the U.S Department of Energy (May 2005) and U.S. Chemical Safety Board (U.S. Chemical Safety and Hazard Investigation Board, 2002) and argued that in both reports about 70% of chemicals involved in incidents were either not regulated or had NFPA instability rating of “0” or “1”. Moreover, not all chemicals are rated and the NFPA rating system cannot be used for hazard identification of unrated chemicals. Likewise, Process Safety Management (PSM) regulation is not all-inclusive indicating that it does not regulate all chemicals. This indicates a need for more extensive hazard analysis approaches and more robust regulations.

Undeclared dangerous goods that entered the transport chain as a result of awareness, lack of regulations, mistakes/omissions during cargo transport booking, and deliberate non-declaration have caused a number of fire and explosion accidents. More extensive incident and inspection data is required to estimate the rates of undeclared dangerous goods and develop quantitative frequencies for the model (Ellis, 2010). All stakeholders in the transport chain, such as manufacturers, shippers, cargo brokers, freight forwarders and freight consolidators should be more accountable for ensuring that dangerous goods are correctly and honestly declared (Foster, 2007). Furthermore, appropriate training should be given to crew and personnel about regulations, precautions and packaging procedures in relation to handling and transporting dangerous goods. Simmons et al. (2009) proposed that academia, industry, and government join together and establish training and experience requirements to remedy risk of chemical hazards.

3.4. Prevention of electrical faults

In marine operations, electrical faults are caused by several factors, as discussed in section 2.4. Prevention of these causes is essential because a simple fault can be catastrophic in ships. For instance, a minor electrical spark may be an ignition source for an extreme fire and explosion event. Arcing fault is a common cause of electrical fires. Due to high-impedance, currents frequently fall within the range of normal working loads during arcing faults. Under this condition, circuit breakers frequently become ineffective against arcing faults (Land and Fowler, 2009). The use of arc-resistant switchboards and the use of arc-fault detection systems such as automatic arc-fault protection can significantly reduce the risk to personnel when arcing occurs (Land, 2008).

The ignition from poor connections (overheating or glowing connections) and external heating resulting in short circuit or arcing can be prevented by ensuring proper training to crew and fail-safe design of the system. Physical damage, voltage surges and deterioration of electrical insulation present hazards which can cause electrical fires and further research is required for physical mechanisms, minimum values, time frame for ignition, industrial fires and metallurgical issues relating to electrical fires (Babrauskas, 2008). Avoiding the use of defective or faulty electrical appliances may prevent short circuit ignitions. Moreover, very minor incidents such as static electricity, electric spark and arc can be sufficient to ignite accumulated combustible gas in confined or semi-confined areas and avoiding their sources will reduce likelihood of fire and explosion events.

Skjong et al. (2016) stated that characterization of the marine vessel electrical grid through real-time measurements, and the monitoring of fundamental parameters such as impedance, harmonic currents and voltages, would be essential to ensure the safety, integrity, and stability of the marine vessel power system. Since the intensive trend in use of electricity, the authors proposed that a smart grid similar to the modern land-based electrical system should be a necessity in marine vessels.

Using recent technologies, such as infrared thermography (IRT) in condition monitoring and inspection techniques, can enable identification of the presence of any thermal anomalies in electrical appliances (Jadin and Taib, 2012). The rapid development of computer programs, sensor, and signal processing technologies, and integration with artificial intelligence (AI) techniques, has made it possible to implement fault diagnosis and prognosis effectively (Liu et al., 2007). Previous researchers stated that the use of AI software agents will become essential for monitoring, diagnosing, and predicting system equipment faults, particularly important to critical systems and components such as engines, power generation, and thermal management.

For a fire to occur there must be the three basic components forming the fire triangle, oxidizer, flammable material and a source of thermal energy. These factors combined together result in the spread of fire and often lead to tragic consequences. In order to avoid or control a fire, one of these factors should be avoided. Investigating the root causes of the previous accidents reveals that the fuel leakage is the consequence of different fire and explosion accidents occurring in the engine rooms (ATSB, 2008, 2016a; MAIB, 1999). In a ship, fire occurs mostly in the engine room due to the high chance of having all three factors simultaneously. Air (oxygen) and hot surfaces exist constantly in the engine room. When fuel or lubricant oil sprays on hot surfaces, there is high chance of a fire and explosion event due to the high flammability of conventional fuel or oil. Several questions such as 'are there alternative fuels with less flammable property?' and 'does employing less flammable fuels or oils reduce the likelihood of fire and explosion events?' can be raised.

4. Alternative fuels

In this study, it is found that 31% fire and explosion accidents are caused by an accidental release of fuel or lubricating oil in the engine room. Replacing these highly flammable materials with other less flammable fuels may help to reduce the risk of ignition during accidental leakage. In the quest for less hazardous fuels, effectiveness of alternative fuels needs to be reviewed from safety perspectives. According to DNV report (Chryssakis et al., 2014), alternative fuels that are already used or could potentially be used in shipping in the future include LNG, Liquefied Petroleum Gas (LPG), biofuels, synthetic fuels (Fisher-Tropsch) (Takeshita and Yamaji, 2008), methanol and ethanol, Di-Methyl Ether (DME), biogas, hydrogen, biodiesel nuclear fuel and use of electricity for charging batteries and cold ironing. The EMSA report (2017) states that the currently considered alternative fuels in shipping such as LNG, electricity, biodiesel, and methanol and other fuels such as LPG, ethanol, DME, biogas, synthetic fuels, hydrogen (particularly for use in fuel cells), and nuclear fuel, could play a role in the future.

When analysing the viability and prospect of adoption of alternative fuels for use in shipping, safety considerations also need to be taken into account particularly the risks of fire and explosion accidents. In order to prevent or mitigate fire and explosion accidents in shipping, the effectiveness of alternative fuels needs to be assessed. The differences in chemistry and physical properties lead to different risks associated with transferring, dispensing, and handling alternative fuels. According to the EMSA (2017), one common challenge posed by the adoption of most alternative fuels is their physical and chemical characteristics, typically associated with low flashpoints, higher volatilities, different energy content per unit mass and in some cases toxicity.

In the current study, only fire and explosion related hazards that could be posed by alternative fuels are discussed. Inherently, all fuels present fire and explosion hazards if they are not stored or handled appropriately. Astbury (2008) explained the ignition and combustion properties of alternative fuels in relation to fire and explosion hazards such as gross calorific value, octane number, flash point, flammable limits, auto-ignition temperature, electrical resistivity, minimum ignition energy, boiling point and water solubility. A summary of ignition and combustion properties of some proposed alternative fuels is given in Table 2. The author stated that most alternative fuels have similar ignition and combustion characteristics as existing known conventional fuels except hydrogen, and additional hazards posed by alternative fuels are manageable. The author further stated that the use of many alternative fuels requires some adjustment or substitution of minor parts of existing burner or engine designs to allow for direct substitution of traditional fuels. If this adjustment or substitution does not occur properly, the alternative fuel may not be used or likely becomes uneconomical and or presents more hazards. Maggio et al. (1991) stated that alternative fuels do not present greater risks than conventional fuels, however their risks are simply different. Thus, with proper training, facility design and adequate precautions, alternative fuels can be handled safely.

The ignition and combustion properties of biodiesel are the same as those of conventional hydrocarbon oil-based diesel fuel, but it is a lower fire and explosion hazard than standard diesel because of a higher flash

Table 2
Ignition and combustion properties of some alternative fuels (Adopted from (Astbury, 2008)).

Material	Gross Calorific Value (MJ/kg)	Octane number	Flash point (°C)	Flammable limits (%,v/v)	Auto ignition temperature (°C)	Resistivity (Ωm)	Minimum Ignition Energy (mJ)
Ethanol	29.73	100	13	3.3–19	363	7.4×10^6	f
Methanol	22.72	99	11	6–36	385	3×10^3	0.14
LNG	19.98	>100	−188	5–15	537	Gas	0.28
CrNG	19.98	120	Gas	5–15	537	N/A	0.28
LPG (Propane)	50.49	104	Gas	2.1–9.5	450	Gas	0.25
LH_2	158.9	f	Gas	4–75	500	10^{17}	0.017
Hydrogen	158.9	f	Gas	4–75	500	N/A	0.017

f = No data available.

point. These properties make biodiesel and its blends with petroleum diesel safer to store, handle and use than conventional diesel fuel.

Methanol has a low rate of evaporation and low radiant heat energy which makes it a safer fuel because it is less likely to ignite in accidents and less harmful to people when it does (Nowell, 1994). Moreover, methanol is much less likely than gasoline to ignite in open air (well--ventilated areas) due to its low volatility. Methanol in a closed tank should be considered an explosion hazard because methanol fuel-air mixture in closed air tanks is within its ignition limits (Maggio et al., 1991). However, in the case of spontaneous combustion, methanol is classified between gasoline and diesel fuel (MacCarley, 2013). Additionally, due to the lower volatility and higher flammable limit, pure methanol (M100) is projected to result in as much as a 90 percent reduction in the number of automotive fuel related fires compared to gasoline (Machiele, 1990). According to Fort (2011), METHAPU project has successfully demonstrated that the on-deck methanol tank and fuel cell system did not present any greater risk to the ship, occupants, or environment than that associated with conventional fuels. Risk assessments are carried out in Stena Germanica, SPIRETH project and Waterfront Shipping chemical tanker and were approved for installation, demonstrating that safety considerations are not a barrier to the use of methanol fuel systems on ships (Ellis and Tanneberger, 2015). Similar to methanol, ethanol fires are less hazardous than gasoline and they can be readily extinguished with water (Bernton et al., 2010). It is safer than gasoline to store, transport and refuel (McWhorter, 2013). Thus, ethanol also presents a moderate fire and explosion hazard if handled incorrectly.

The main hazard related to CrNG is gross leakage from the fuel feed pipe work. The potential for ignition immediately after the accident (leakages) is greater for CrNG than petrol as the flammable atmosphere will be far greater and likely to spread further and more quickly (Astbury, 2008). However, natural gas is safer than gasoline and diesel in many respects such as its ignition temperature is higher than gasoline and diesel and it is more difficult to ignite accidentally in comparison to both (Kowalewicz, 1984). Additionally, it is lighter than air and any leaks disperse rapidly upwards while gasoline and diesel pool on the ground, increasing the danger of fire (Semin, 2008). Thus, natural gas presents fewer fire or explosion hazards in well ventilated areas because of high auto-ignition temperature and narrow explosive range.

LNG as a liquid is neither flammable nor explosive, but its vapour ignites when the vapour-air mixture is 5–15% (Baalisampang et al., 2017; Kolwzan and Narewski, 2012). Fire and or explosion hazards related to LNG are similar to CrNG though other hazards are different, for example, LNG has roll-over and cryogenic hazards. Use of LNG as an alternative fuel is promising and has the possibility of being a leading option in order to retain a substantial share of the world bunker market because it is proven technology (about 40 ships are currently running on LNG), and is meeting more than new emissions requirements and has less CO_2 emissions (Semolinos et al., 2013). Moreover, LNG is already providing an economic alternative to diesel in the heavy duty trucking industry, in port facility vehicles, and increasingly in marine and rail applications (Kumar et al., 2011; Litzke and Wegrzyn, 2001). Thus, similar to any flammable substance, appropriate design, regulations and personnel training are needed to maintain a safe environment for application of LNG as a fuel.

LPG is highly flammable and its leakage from a fractured pipe would form a large persistent flammable atmosphere, which would likely ignite (Astbury, 2008). As it is heavier than air, it tends to settle in trenches or maintenance pits increasing explosion hazards. Leak prevention measure is key to mitigating these hazards.

Hydrogen has a much lower minimum ignition energy (0.017 mJ) than any traditional hydrocarbon fuel and makes it far more sensitive to ignition than any other gaseous fuel (Astbury, 2008). Moreover, hydrogen has a much higher flame speed than any other gas and has wider flammable limits (4–75%) with higher explosion hazards (Astbury, 2008). Hydrogen ignition related accidents have occurred in the past resulting in severe consequences (Astbury and Hawksworth, 2007). Additional hazards may depend on its production and storage types.

This shows that there are certain properties which make some fuels more or less hazardous than others and the severity of risks posed by each alternative fuel may not be the same. In order to mitigate the fire and or explosion hazards of alternative fuels for commercial applications, necessary precaution measures should be put in place with appropriate fail-safe designs and their cost effectiveness needs to be assessed.

Existing studies on alternative fuels in shipping are mostly focussed on the possibility of emission reductions, however, secondary effects because of emission reduction measures are not extensively studied. Luo (2013) identified 8 possible side effects of emissions reduction measures, including both positive and negative impacts on emission reduction, world trade, economic efficiency, and the local environment. Maddox consulting (2012), identified 13 measures that have a negative marginal abatement cost (MAC) on emissions reduction in shipping, and analysed the six categories of barriers to their successful implementation, including technological, operational (or physical), regulatory, economic, market failure, and administrative barriers. Most cost effectiveness of alternative fuels is mainly assessed in relation to greenhouse gas reduction measures and not much emphasis is given to fire and explosion hazard reduction measures (Bouman et al., 2017; Hoffmann et al., 2012). Grahn et al. (2013), analysed cost effectiveness of LNG, fuel cells, hydrogen, synthetic fuels (gas-to-liquid (GTL)) and biofuel using the Global Energy Transition model (GET-RC 6.2). This was conducted based on global energy system modelling aiming to analyse fuel choices in the shipping sector under stringent Carbon dioxide (CO_2) constraints and reached the following conclusions;

1. A transition from oil-based fuels to an alternative fuel could be cost-effective in the next 10–20 years,
2. LNG could be a major fuel in the shipping sector between 2020 and 2070, depending on the cost of the storage tank,
3. After 2070, a variety of fuels; hydrogen, synthetic fuels and biofuels will be chosen depending on the characteristic of the ship,
4. Time of transition and fuel choices are affected by the chosen target of CO_2 concentration, energy demand scenarios and the total supply of oil and natural gas.

Findings of another study conducted by Taljegard et al. (2014) support these conclusions and state that (i) it is cost-effective to start the phase out of fuel oil within the shipping sector in the next decade; (ii) natural gas based fuels (liquefied natural gas and methanol) are the most probable substitutes during the study period; (iii) availability of carbon capture and storage (CCS), the CO_2 target, the liquefied natural gas tank cost and potential oil resources affect marine fuel choices significantly; and (iv) biofuels rarely play a major role in the shipping sector, due to limited supply and competition for bioenergy from other energy sectors. However, neither study incorporated all variables nor uncertainties such as engine efficiency, regulatory impact and cost of technology replacement or modification because some of the technologies are not yet commercial. This shows that there is a need for analysing cost effectiveness from safety perspective of alternative fuels incorporating adequate parameters in sensitivity analysis.

Regardless of inherent hazards and many uncertainties such as availability, cost and technology, some alternative fuels are already being used in marine vessels as a prime mover. Examples of marine vessels running on alternative fuels are (1) MS Bergensfjord (LNG fuelled RO-PAX), (2) Viking Lady (LNG Fuelled, also demonstrator project for Fuels Cells in the context of the FellowSHIP project) and (3) MV Stena Germanica (First Methanol fuelled ship conversion) (EMSA, 2017).

The proposed alternative fuels have both advantages and disadvantages at this stage in relation to fire and or explosion hazards and would demand further research in many aspects. Due to this, it is highly unlikely that any single technology or fuel has the potential to be the "silver bullet'' to be able to meet energy challenge and security, and mitigate the effects of climate change and other harmful environmental impacts, because all the options are subject to constraints of some kind (Ball and Wietschel, 2009).

From the initial stage of the development of alternative fuels and technologies, the consideration of fire and explosion hazard mitigation measures could play a significant role in reducing fire and explosion accidents in shipping. Comparing flammability properties of potential alternative fuels, some alternative fuels have favourable and safer properties than traditional fuels, which certainly minimise the risks of fire and explosion if adequate precautions are adopted.

5. Conclusions

Fire and explosion accidents are reported as a common accident type in maritime transportation. Fire and explosion accidents that occurred in maritime transportation between 1990 and 2015 are reviewed and analysed in order to identify causal and underlying causes of these accidents. The causal factors of fire and explosion accidents are identified and categorised as human error, thermal reaction, electrical fault, mechanical failures and unknown.

The general causes of fire and explosion accidents in shipping show that human error is the most common contributing factor accounting for 48% of accidents. In most cases, it is found that skill based error, inadequate supervision and inadequate organisational processes have resulted in mechanical failures, chemical reactions and electrical fault. Moreover, it is found that 43% of human error is arose from maintenance related activities. HEM, better safety culture, design integration and system management, and neuro-ergonomics design are seen as some key approaches in managing human failure.

In this study, it is found that mechanical failure contributed to 22% of fire and explosion accidents. Deficient maintenance activity and inappropriate overhauls have been the main contributors to leakage and mechanical failure. Mechanical failure can be prevented by controlling corrosion, fatigue failure, and wear and creep which are further mitigated by adequate design and safety systems. Investigations of shipping accidents have shown that in most cases fire originated in the engine room and was caused by leakage of oil or fuel coming into contact with hot exhausts. It is suggested that the failure of engineering components can be controlled or prevented by proper design, better materials selection, avoiding manufacturing defects and overloading, and adequate maintenance.

Hot metal surfaces, static electricity and electrical sparks and arcs are the major sources of ignition causing fire and explosion. In this study, about 7% of accidents are found to be caused by electrical fires. The main contributing factors for electrical fires are improper altercations, improper initial installation, and deterioration due to aging, improper use, inadequate capacity and faulty product. Some studies claimed that investigators considered a fire as electrical without definite evidence which led to the ruling out of other potential causes. Because of the complexity involved in investigation of fires, most fire accidents discussed in this paper are considered as electrical fires based on circumstantial evidences. Uses of arc-resistant switchboards and arc-fault detection systems such as automatic arc-fault protection can significantly reduce the risks of fire and shock. Moreover, application of smart grid similar to the modern land-based electrical system would help to better manage the electrical system in ships. It has been proposed that using recent technologies such as infrared thermography and AI in condition monitoring and inspection techniques may enable identification of the presence of any anomalies in electrical appliances or systems.

Thermal reaction has contributed 14% to fire and explosion accidents, and breach of guidelines or policies was found to be the main root cause of accident. Defective packaging, inadequate hazard identification and incorrect stowage have contributed to accidents in shipping. Additionally, undeclared dangerous goods due to lack of awareness of regulations, mistakes or omissions during cargo transport booking, and deliberate non-declaration, are also significant contributors to shipping accidents. In order to mitigate fire and or explosion from reaction, a robust and extensive hazard identification procedure or tool is needed and all stakeholders, including manufacturers and those involved in a transport chain, should be accountable for safe handling of commodities. Adequate safety analysis and effective training and education are found to be common recommendation in most accidents caused by thermal reaction. Moreover, it is found that in 9% of accidents, investigators could not conclusively identify causes of accidents. This shows that accident investigation may need more rigorous approaches and experts.

All fuels are prone to fire and or explosion risks, however, some fuels are less prone to risk of fire and explosion because of differences in flammability and combustion properties. In order to compare the fire and explosion hazards posed by different fuels, properties of some proposed alternative fuels are compared and it is found that at this stage, adoption of alternative fuels do not pose higher fire and explosion risks than conventional fuels. LNG, CrNG and methanol have suitable properties for mitigating fire and explosion hazards and appropriate management of their hazards could be safer than traditional fuels. The proposed alternative fuels have weaknesses and strengths in relation to fire and or explosion hazards and demands further studies in many aspects. Due to the lack of adequate studies and technological immaturity, at this stage, it is highly unlikely that any single alternative fuel has the potential to be able to mitigate fire and explosion risks, to meet energy challenge and security, and to mitigate the effects of climate change.

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