A hybrid model for human-factor analysis of engine-room fires on ships: HFACS-FFTA

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Abstract

Ships' engine rooms are areas with a high fire risk. Engine-room fires have a complex structure. Therefore, investigation and analysis of the impact of the human-factor effect on the occurrence of engine room fires is a challenging task. It is impossible to eliminate the factors that cause accidents. However, by taking precautions in each system, the risk of accidents can be minimised. The most effective way to achieve this goal is to identify the non-conformities that lead to the occurrence of accidents and to reveal the relationships between them. In this study, an analysis of fire-explosion accidents in ship engine rooms was conducted. For analysis, a hybrid method including the Human Factors Analysis and Classification System (HFACS) and fuzzy fault tree analysis (FFTA) was used. Using the HFACS method, the factors in the formation of engine-room fires were classified according to a hierarchical structure. The possible accident scenarios and probabilities were calculated using the FFTA method. In this study, it was observed that fire-explosion accidents were concentrated in ships over 20 years old and that mechanical fatigue affected accident formation. In particular, when the increased hot surfaces due to the operation of a ship's engines while it is in motion are combined with oil/fuel leakage, fire-related accidents become inevitable. Failure to provide proper insulation also triggers the occurrence of accidents. It has been observed that some of such accidents occur because the materials used in maintenance and repair work are not original to the ship. During this study, the causes of accidents were examined to prevent fire-related accidents from occurring in engine rooms, and suggestions were made to prevent similar accidents from happening in the future.

Keywords: Fire and explosion; marine accident; HFACS; FFTA; human-factor analysis

1. Introduction

Ship fires, which often occur unexpectedly, may have even more destructive consequences than other types of marine accidents (Kuo and Chang, 2003; Salem, 2010; Hassel *et al.*, 2011; Baalisampang *et al.*, 2018). According to data from the IMO (2019), 270 of the 1,400 accidents reported between 2000 and 2017 were fire- and explosion-related. This was the third most common accident category among marine accidents, accounting for 19.2% of those reported (IMO, 2019). It can be observed that the effect of such accidents on loss of life is about 132% greater than that of other types (Weng and Yang, 2015). Ship fires not only result in injuries and fatalities but may also cause considerable damage to a ship, the cargo being transported, and the environment. According to an AGCS (Allianz Global Corporate & Speciality) report (2019), 13% of the financial insurance claims resulting from marine accidents between 2013 and 2018 involved fires. Fires are the second most expensive type of marine accident, resulting in insurance claims of $1.26 billion from 2013 to 2018. In shipbuilding and operation planning, safety measures to protect against fires have become important when designing ships (Themelis and Spyrou, 2012). Therefore, many researchers have conducted studies to reduce ship fires and the damage they create (Darbra and Casal, 2004; Salem, 2010; Uğurlu, 2016).

Hakkarainen *et al.* (2009) emphasised that engine-room fires on ships account for 11% of ship fires. Ventikos (2013) examined 1,521 fire-related accidents that occurred between 2003 and 2010. He found that 642 of them occurred in the engine room or galley. He defined these areas as the ship compartments where ship fires were the most common, accounting for 42.21% of ship fires. McNay *et al.* (2019) emphasised that engine-room fires often occur when ships are in motion. According to a report issued by ClassNK (2010), the percentage of vessels damaged by engine-room fires was 75%, and 52% of these vessels became incapable of navigation. The PMA (2011) found that a ten-minute delay in fighting an engine-room fire can cost $200,000, and a twenty-minute delay can cost $2,000,000.

The engine rooms of ships are areas where additional safety measures are required because the main engine, generator, fuel tank, electrical units, and fuel circuits are located in a constricted area. The engine room is like the heart of the ship in terms of its power- and electricity-generating units. It is often difficult to extinguish fires in the engine room, and these fires can impair a ship's manoeuvrability and may cause collision-contact or grounding accidents (Su and Wang, 2013). Therefore, it is important to conduct studies discover ways to prevent engine-room fires. When looking at the relevant studies from the past, we observed that fire-related accidents on ships had been examined using various methods (Table 1).

Table 1. Similar studies related to ship fires

Technology and innovative applications of it have changed the ways in which ship accidents occur today. Investigation and analysis of the impact of human error on ship accidents with a variable nature is a difficult task. Human error may play a significant, and sometimes overriding, role in accident causation (Abbassi *et al.*, 2015; Keçeci and Arslan, 2014). For this reason, many studies on human factors and human reliability, to which the concept of human error is closely related, have been conducted by researchers from past to present. The Technique for Human Error Rate Prediction (THERP) method was developed for the quantitative and qualitative analysis of human reliability by Swain and Guttmann (1983). This method is considered one of the first-generation methods that are still valid today. The model evaluates human reliability by measuring human error probabilities as well as error definition and task analysis. THERPs have been widely used in maritime transport accident analysis (Amrozowicz *et al.*, 1997; Allal *et al.*, 2017). Zarei *et al.* (2019), to overcome the problem of human error, presented a hybrid dynamic human-factor analysis model, considering the Human Factors Analysis and Classification System (HFACS), intuitive fuzzy set theory, and Bayesian networks. Noroozi *et al.* (2014) developed the Human Error Assessment and Reduction Technique (HEART) method to evaluate the effects of cold working conditions on human performance. Islam *et al.* (2017) modified the HEART method and used it to evaluate and measure human errors in various marine, environmental, and operational conditions. Using this methodology, the aim was to make the maintenance and repair practices employed in maritime operations safer and more reliable.

In this study, a hybrid method consisting of the HFACS and fuzzy fault tree analysis (FFTA) was used to analyse fire-explosion accidents in ships' engine rooms. Investigation and analysis of the impact of the human-factor effect on the likelihood of occurrence of accidents is a challenging task. This type of analysis can entail a long process because human behaviour is not always easily predictable or interpretable (Uğurlu *et al.*, 2020). Ship fires, especially ones that occur in engine rooms, have a complex structure (Beland, 1984). There is a high risk that evidence may be destroyed in engine-room fires. The HFACS is a sophisticated method that makes it possible to analyse the effect of human error on accidents (Mirzaei Aliabadi *et al.*, 2018; Uğurlu *et al.*, 2018). This type of analysis not only reveals the apparent causes of an accident but also the latent factors contributing to it (Macrae, 2009; Chauvin *et al.*, 2013; Uğurlu *et al.*, 2018). Its reliability has been proven in many sectors, including maritime transport (Reinach and Viale, 2006; Patterson and Shappell, 2010; Olsen, 2011; Zhan *et al.*, 2017). However, the HFACS is inadequate for conducting a quantitative analysis of accidents (Jiang and Han, 2018). In this study, the FFTA method was used for quantitative analysis. The FFTA method enables both qualitative and quantitative evaluations (Wang *et al.*, 2013). In this study, a logical relationship has been established between the qualitative approach and the factors contributing to engine-room fires on ships (such as sources of combustible materials and heat-source materials) caused by unsafe acts. Using a quantitative approach, the combinations of accident factors were examined, and a numerical analysis of this logical relationship was performed.

2. Stages of the Study

This study is limited to fire-explosion accidents occurring in the engine rooms of ships of 500 GRT and above between 2000 and 2017. In this study, a detailed analysis of fire-related accidents in ships' engine rooms is conducted. The research consists of five stages (Figure 1).

Figure 1. Flow chart of the study

Step 1. Gathering accident data

The consistency and reliability of the results of a model depend on the data used. Access to reliable accident data forms the basis of accident analysis studies. Obtaining reliable data is the most important step in achieving reliable results. In this study, a total of 20 reliable accident databases, including those managed by the Marine Accident Investigation Branch (MAIB), European Maritime Safety Agency (EMSA), Australian Transport Safety Bureau (ATSB), Panamanian Maritime Authority (PMA), Bahamas Maritime Authority (BMA), and Marine Safety Investigation Unit (MSIU) were used. Forty-nine accident reports related to engine room fires, which constituted the basis of the study, were obtained. Seven of these accidents were considered ‘very serious’, and forty-two were ‘serious’. Such accidents resulted in loss of life, injury, structural damage to ships, or the loss of ships. The databases list the causes of the accidents as well as demographic information about them, such as ship names, ship flags, ship ages, and accident dates.

Step 2. Identification of accident causes

For an accident-formation process to be modelled, the reasons underlying its outcome must be fully and clearly laid out (Khan and Abbasi, 1999). The next step is to classify the reasons within the appropriate taxonomy. Classification allows us to understand accident formation in the context of stages and interpret the data by establishing a relationship between the reasons for an accident’s occurrence (Uğurlu *et al.*, 2020). At this stage of the study, the active causes and hidden defects related to the fire-explosion accidents occurring in the engine rooms of the ships were revealed, and they were made ready for classification using the system employed in the next stage, the HFACS.

Step 3. Classification of accident causes using the HFACS structure

The HFACS is a hybrid analysis method that enables the analysis of human errors within a systemic structure. Using this method allows the causes of accidents to be conceptualised as levels within a hierarchical structure (Chen *et al.*, 2013). In this study, the factors caused by human error within the HFACS structure detailing the causes of machine-room fires were classified. The classification process allowed us to understand and analyse the accidents in the context of stages. In this study, the HFACS-PV structure was used as a reference point for the classification process. Thus, organisational influences, unsafe supervision, preconditions for unsafe acts, and unsafe acts were the factors at the level including ‘unsafe acts and operational conditions’ (Uğurlu *et al.*, 2018). After the classification and analysis process of the HFACS structure was completed, FFTA applications were initiated.

Step 4. FFTA applications

In the last stage of the study, the relationships between the non-conformity factors at the level of 'unsafe acts and operational conditions' within the HFACS structure were analysed using the FFTA method. Fault tree analysis (FTA) is a logic-based method used to determine how non-conformities (basic events) are combined to formulate minimum 'cut sets' leading to the occurrence of the top event and how they affect the likelihood of the top event occurring (Miri Lavasani *et al.*, 2011; Uğurlu *et al.*, 2015a; Uğurlu, 2016). The top event of this study is 'engine room fire'. For a fire to occur, a source of combustible materials and heat-source materials must be present in an environment with sufficient oxygen. Since oxygen was found in every environment in the ship's engine room and will be included in all combinations within the fault tree that was created, it will not be investigated further. FTA involves two stages: qualitative and quantitative analyses. In the qualitative analysis stage, the causes of engine-room fires were classified, the occurrence probability values were determined (fuzzy logic applications with expert opinions), and the logical relationships (fault tree) between the causes were established. In the quantitative analysis stage, the minimum 'cut sets' (accident occurrence combinations) were determined, and the occurrence probabilities of engine room fires were evaluated. The experts in this study were selected from those who were relevant to the intended study. Experts may have different types of expertise and experience within a domain (Cheliyan and Bhattacharyya, 2018). Experts' opinions were evaluated based on their experience and knowledge of engine rooms and ship fires. In this study, expert opinions were weighted according to the experts' professional positions, qualifications, and ship-operation experience.

In this study, a hybrid method derived from the HFACS and FFTA was employed, which enabled the analysis of fire-explosion accidents in ships' engine rooms. Using this model, a detailed analysis of responses to engine-room fires was conducted. The application of the above-mentioned steps in the study's model is described under the 'Proposed Model (the

HFACS & FFTA)' heading, and the applications of the study are presented under the 'Case Study' heading.

2.1. Proposed Model (the HFACS and FFTA)

2.1.1. The HFACS

In Reason's 'Swiss Cheese' model, accidents are viewed as resulting from non-conformities between system components, causing undesirable consequences (Reason, 1990). Reason (1990) argues that the deficiencies in the first three levels of accident formation are the basis for unsafe acts at level four; as a result, accidents are ultimately caused by operators' unsafe acts and behaviours. Reason (1997) emphasises that latent factors in the system often go unnoticed until an accident occurs. The HFACS is an analytical method based on Reason's 'Swiss Cheese' Model, and it was created to determine the effect of human error on aviation accidents (Shappell and Wiegmann, 2000). It presents latent factors, active failures, and environmental factors within a hierarchical structure (Shappell and Wiegman, 2001; Uğurlu *et al.*, 2018). This makes it possible to understand the formation of an accident from its beginning. It is considered an effective method of conducting human-factor analysis (Chauvin *et al.*, 2013; Chen *et al.*, 2013; Macrae, 2009; Uğurlu *et al.*, 2018) and is adaptable to various industries. Many changes have been made in the structure of the HFACS from past to present, and it has been adapted to suit the industries to which it has been applied. A recent change was made by Uğurlu *et al.* (2018) to adapt it to maritime transport. They proved the accuracy of the HFACS structure they presented in two studies (Uğurlu *et al.*, 2018; Uğurlu *et al.*, 2020). In this study, the latent factors and active failures that cause engine-room fires on ships are coded according to a modified HFACS structure.

2.1.2. FFTA

The proposed framework consists of eight stages, as follows:

1. Fault tree development

2. Domain expert evaluations

3. Fuzzification

4. Aggregation

5. Defuzzification

6. Occurrence probability generation

7. Occurrence probability of the top event

8. Importance ranking

9. Validation

2.1.2.1. Fault tree development

The main elements of a fault tree can be classified as top events, basic events, intermediate events, and logical gates (Antao and Soares, 2006; Khan and Abbasi, 2000). In a fault tree, the 'top event' is an undesirable outcome, while the 'basic events' are the situations that lead to undesirable outcomes (Miri Lavasani *et al.*, 2011). The FTA method is used to determine the relationships between a system's non-conformities (Peeters *et al.*, 2018). A fault tree diagram starts with 'Top Event'. The 'top event' is connected to intermediate events, and the tree ends with basic events (Yuhua and Datao, 2005).

The FTA method is based on Boolean logic (Cheliyan and Bhattacharyya, 2018). The probabilities and probability theorems of all logic gates used in a logical diagram are calculated using Boolean mathematics (Mukherjee, 2019) (Table 2). The combinations of basic events in a fault tree are expressed as the 'minimum cut sets' (MCSs), which are defined as the irreducible pathways consisting of the basic events that cause the top event to occur (Ramamoorthy *et al.*, 1977; Ericson, 2005; Trucco *et al.*, 2008).

Table 2. Basic rules of Boolean mathematics

In the mathematical expression of logic gates, the top event (TE) indicated by T is connected to the basic events (BEs) indicated by X (X1, … Xi, …XN). In this expression, N is the number of basic events and Xi (i = 1, 2, ..., N) is the ith basic event. The occurrence probability of Xi is Q(Xi). Then, for the connection gates of 'AND' or 'OR', the occurrence probability of the top event, Q(T) is given below:

$$Q(T) = \prod_{i=1}^{N} Q(Xi) \quad (1)$$

$$Q(T) = 1- \prod_{i=1}^{N} (1 - Q(Xi)) \quad (2)$$

The occurrence probability of a top event in a fault tree is evaluated by obtaining the minimum cut sets.

Generally, the occurrence probability of the top event indicated by Q(T) is calculated as follows:

$$Q(T) = 1- \prod_{i=1}^{Nc} (1 - Q(Ci)) \quad (3)$$

where Nc is the number of minimum cut sets, Ci is the minimum cut set i (i = 1, 2, … Nc), and $Q(Ci)$ is the occurrence probability of Ci. When the occurrence probability of each associated basic event is much smaller than 1 (Q(Ci) much smaller than 1), the above value of Q(T) is calculated as:

$$Q(T) = \sum_{i=1}^{Nc} Q(Ci) \quad (4)$$

A typical minimum cut set is a collection of basic events (MCSj).

$$MCS_j = X_1, X_2, \ldots, X_{Nj-1}, X_{Nj} \qquad \text{where } X_i \in (X_1, X_2, ..., X_N) \quad (5)$$

'X' refers to basic events. 'Nj' is the number of basic events in 'MCS_j'.

In a traditional FTA, the occurrence probabilities of basic events are numerical values. Using this structure, obtaining a precise estimation of the occurrence probabilities of basic events is often impractical due to insufficient data and a high level of uncertainty (Liang and Wang, 1993). In such ambiguous cases, the 'fuzzy logic' approach is used. 'Fuzzy logic' is a mathematical tool used to model the uncertainty of human thought in the real world (Suresh *et al.*, 1996; Cheliyan and Bhattacharyya, 2018). In an FTA with a fuzzy approach, the probability value of each basic event is expressed in fuzzy numbers (Tanaka *et al.*, 1983). Expert opinions can be given in fuzzy numbers. The fuzzy numbers obtained from expert views form the probability values of the basic events (Misra and Weber, 1990; Harrald *et al.*, 1998; Rausand, 2004).

2.1.2.2. Domain expert evaluations

The fuzzy set theory proposed by Zadeh (1965) aimed to eliminate uncertainty by using linguistic values in the decision-making process. The FFTA method was established to determine the probability values of the events within an FTA structure in the absence of statistical data or in the presence of inadequate data. As in other industries, in the maritime industry, this is a practical method of obtaining the probability values of events from experts when there are deficiencies in the data. Many studies of human error estimation include expert opinion-based techniques. However, a single expert's view of an issue may be biased or incomplete. Therefore, expert opinions alone are not sufficient for constructing reliable human error estimates. A potential solution to this problem is to use multiple expert (multi-expert) knowledge and experience (Musharraf *et al.*, 2013). The opinions of each expert about the root causes of an event may be different. Therefore, evaluations are influenced by the importance of each expert from various perspectives. The reasons that experts may hold different opinions about the same event can include education level, work experience, and differences in their fields of expertise. Therefore, researchers use a weighting factor to represent the relative quality of the opinions of various experts (Yuhua and Datao, 2005). Various justification weights from 0 to 1 can be assigned to each expert to reflect differences in the impact of their assessments.

2.1.2.3. Fuzzification

In this study, a triangular fuzzy number (TFN) was used to determine the occurrence probability values of basic events. A TFN represents a triple set of fuzzy probability values (a_1, a_2, a_3) of a BE. For x϶A, $\mu_{\breve{A}}(x)$, A is a fuzzy number and R is in the range R→ [0,1]. Assuming that A is in the range $[a_1, a_3]$, the membership function $\mu_{\breve{A}}(x)$ is calculated as follows (Wang, 1997):

$$\mu_{\breve{A}}(x) = \begin{cases} 0 & x \leq a_1 \\ (x - a_1)/(a_2 - a_1) & a_1 \leq x \leq a_2 \\ (a_3 - x)/(a_3 - a_2) & a_2 \leq x \leq a_3 \\ 0 & x \geq a_3 \end{cases} \quad (7)$$

2.1.2.4. Aggregation

The various experiences and types of knowledge of experts within a heterogeneous group lead to multiple interpretations of, and decisions about, basic events. It is important to gather the data obtained from expert evaluations and reconcile the opinions. Hsu and Chen (1994) proposed an algorithm for combining views obtained from homogeneous and heterogeneous expert groups.

$\widetilde{R1}$, $\widetilde{R2}$: A pair of expert opinions

$S_{UV}(\widetilde{R1}, \widetilde{R2})$: Degree of agreement (similarity) of two distinct expert opinions

$S(\tilde{A}_1, \tilde{A}_2)$: Degree of similarity between two fuzzy numbers

$AA(E_u)$: Average degree of agreement of experts

$RA(E_u)$: Relative degree of agreement of experts

CC(E_u): Experts' consensus coefficient

$\tilde{R}_{AG}$: Aggregated results of expert opinions

Step (i): Calculate the degree of agreement (similarity) $S_{UV}(\widetilde{R1}, \widetilde{R2})$ of the opinions $\widetilde{R1}$ and $\widetilde{R2}$ of a pair of experts E_U (u =1 to M).

According to this approach, $\tilde{A}_1 = (a_{11}, a_{12}, a_{13})$ and $\tilde{A}_2 = (a_{21}, a_{22}, a_{23})$ constitute two triangular fuzzy numbers. Thus, the degree of similarity between these two fuzzy numbers can be obtained by using the defined similarity function.

$$S(\tilde{A}_1, \tilde{A}_2) = 1 - (1/3) \sum_{i=1}^{3} | a_{1i} - a_{2i} | \quad (8)$$

Step (ii): Calculate AA (average agreement) by M experts as follows:

$$AA(E_u) = \frac{1}{M-1 \sum_{\substack{U \neq V \\ V=1}}^{M} S(\tilde{A}_1, \tilde{A}_2)} \quad (9)$$

Step (iii): Calculate the degree of relative agreement (RA) by M experts as follows:

$$RA(E_u) = \frac{AA(E_U)}{\sum_1^M AA(E_U)} \quad (10)$$

Step (iv): Calculate the CC (consensus coefficient) of M experts as follows:

$$CC(E_U) = \beta . w(E_U) + (1 - \beta) . RA(E_U) \quad (11)$$

β (0≤β≤1) is the relaxation factor of the proposed method. This shows the importance of w (E_u) (weight factor of expert u) on RA (E_u). When β = 0, the weight factor of the expert is ignored; there is a homogeneous distribution among the experts. When β = 1, the expert has the same consensus coefficient (CC) and weight significance. In this study, β = 0.5 was considered (Lavasani *et al.*, 2015; Rajakarunakaran *et al.*, 2015).

Step (v): Finally, the aggregated result $\tilde{R}_{AG}$ value of the expert opinions is calculated as follows:

$$\tilde{R}_{AG} = CC(E_1) \times \tilde{R}_1 + CC(E_2) \times \tilde{R}_2 + \ldots + CC(E_M) \times \tilde{R}_M \quad (12)$$

2.1.2.5. Defuzzification

The purpose of defuzzification is to obtain measurable results from fuzzy numbers. Clarifying fuzzy numbers is extremely important when making decisions regarding uncertain issues. When fuzzy ratings are included in a fault tree analysis problem, the resulting ratings are, again, fuzzy numbers. To discover the relationship between these numbers, the fuzzy number must be converted to a crisp score called the 'fuzzy possibility score' (FPS). The FPS number of each basic event is derived from the obtained membership function, which is calculated during the expert opinion consolidation phase of calculating an FPS. Defuzzification methods include the mean-max membership, centroid method, weighted average method, centre of largest area, and centre of sums (Wang, 1997). In this study, the fuzzy possibility values of each basic event were calculated using the most frequently used 'centre of area' method because of its simplicity and comprehensibility. This technique was developed by Sugeno (1985).

Defuzzification equation: $X^* = \frac{\int \mu_i(x)\,dx}{\int \mu_i(x)}$ (13)

For the triangular fuzzy number $\widetilde{A} = (a_1, a_2, a_3)$ the equation is as follows:

$$X = \frac{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} x\,dx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} x\,dx}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1}\,dx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2}\,dx} = \frac{1}{3}(a_1 + a_2 + a_3) \quad (14)$$

2.1.2.6. Occurrence probability generation

In some cases, it is impossible to find the failure probability value due to uncertainties in the data. This problem can be resolved by converting the FPS to a 'failure probability' (FP) form. In this study, the function of converting an FPS to an FP form, which was proposed by Onisawa (1990), was used.

$$FP = \begin{cases} \frac{1}{10^K}, FPS \neq 0 \\ 0, FPS = 0 \end{cases}, K = \left[\left(\frac{1-FPS}{FPS}\right)\right]^{\frac{1}{3}} \times 2.301 \quad (15)$$

2.1.2.7. Occurrence probability of the top event

The components that generate any fault tree are basic events, and the ‘cut sets’ are formed by a combination of these basic events and the top event generated by these ‘cut sets’. If the probabilities of all basic events in the fault tree are known, the occurrence probability of the undesired top event is obtained.

2.1.2.8. Importance ranking

The FTA method is used to calculate the probability value of the top event and analyse the importance of ‘cut sets’. In the FTA method, the FV-I (Fussell-Vesely Importance Measure) method is frequently used to determine the significance value of the BEs and MCSs forming the top event (Wang *et al.*, 2016; Shafiee *et al.*, 2019). In this study, the FV-I method was used for significance calculations. According to this method,

$$I_{\mathrm{i}}^{FV}(t) = \frac{Q_{\mathrm{i}}(t)}{Q_S(t)} \tag{16}$$

where I_i = the importance degree of minimum cut set i, $Q_{\mathrm{i}}(t) =$ occurrence probability of minimum cut set i, and $Q_S(t) =$ occurrence probability of the top event.

2.1.2.9. Validation

Validation is defined as providing objective evidence that an item meets the specified requirements. The accuracy of a method is ensured by using another analysis method or by obtaining expert opinions. In this study, the formation of accidents (fire triangle) and expert opinions were used to verify the FTA.

2.2. Case Study

The proposed engine room fire-explosion analysis procedure can be briefly divided into two stages: (i) one in which engine-room fire-explosion identification and classification were conducted using the HFACS and (ii) one in which the FFTA was applied to fire-explosion accidents to conduct a comprehensive risk analysis. The model development and results are described as follows.

2.2.1. Application of the HFACS

A total of 275 factors were used in the classification process. The total frequency of these factors was 507. Figure 2 shows the distribution of these factors according to the main structure of the HFACS, and Figure 3 shows the distribution according to the HFACS sub-categories. In the following section, the coding for each level of the HFACS is given in Tables 3 - 6.

Figure 2. General distribution of factors according to the main levels of the HFACS

Figure 3. Distribution of fire-explosion accidents by HFACS sub-categories

Organisational Influences: These include errors are made during the operation-planning process; non-conformities in the management of human resources; deficiencies in risk analysis procedures; and non-conformities caused by top-level management, such as ignorance of safety assessments prior to operation. This level is divided into three sub-categories: resource management, organisational climate, and organisational process. Table 3 indicates the non-conformities and frequencies coded at the ‘organisational influences’ level in the HFACS structure created in this study. A total of 66 factors were coded at this level. These non-conformities were seen 173 times in total. The average number of observations of non-conformities per accident at the ‘organisational influences’ level was 3.53 (173/49).

Table 3. Accident factors and their occurrence frequencies at the 'organisational influences' level

Unsafe Supervision: This level includes the non-conformities related to the audit-control mechanism. When the audit-control mechanism fails, situations conducive to unsafe behaviours cannot be identified or prevented, creating favourable conditions for the formation of accidents. This level is divided into three sub-categories: inadequate supervision, inappropriately planned operations, and failure to solve a known problem. The non-conformities coded at this level for engine-room fires are indicated in Table 4. There were 36 non-conformities at this level. These non-conformities were seen (frequency) 70 times in total. Each engine-room fire had an average of 1.43 non-conformities at this level (70/49).

Table 4. Accident factors and their occurrence frequencies at the 'unsafe supervision' level

Preconditions for Unsafe Acts: This is the last level of latent factors. It includes situations and factors that negatively affect operators' decision-making abilities, such as mental fatigue, physical fatigue, lack of communication, intoxication, and the failure of ship equipment. Table 5 shows the non-conformities coded at this level. A total of 27 factors were coded at this level. These non-conformities were seen (frequency) 90 times in total. The average number of these factors per accident was 1.84.

Table 5. Accident factors and their occurrence frequencies at the 'preconditions for unsafe acts' level

Unsafe Acts: This level is the visible face of ship accidents. When the negative effects of latent factors are combined with unsafe actions, the system's defences are impaired, resulting in an accident (Reason, 1990; Reason *et al.,* 2006). This level includes incorrect or erroneous decisions made intentionally or unknowingly by human operators. This level is divided into two sub-categories: errors and violations. The non-conformities coded at this level are presented in Table 6. A total of 47 non-conformities were coded at this level. These non-conformities were seen (frequency) 75 times in total. The average number of these non-conformities per accident was 1.53.

Table 6. Accident factors and their occurrence frequencies at the 'unsafe acts' level

Operational Conditions: The environmental factors that comprise the final level of the HFACS are related to the internal and external environment of the ship, which plays a role in the prevention of unsafe acts. This level includes factors that cannot be completely eliminated by a ship's crew but can be controlled. Malfunctions, design failures, weather, and sea conditions are included in this level. In this study, the non-conformities at this level were classified according to FFTA and linked with accident occurrence. Therefore, the non-conformities under this heading are examined in the 'Application of FFTA' section.

2.2.2. Application of FFTA

2.2.2.1. Fault tree development

In this study, the 27 basic events that were instrumental in the realisation of the top event, their definitions, and the relationships between them within the FTA were identified by considering the following items:

- HFACS structure
- Accident reports
- Expert evaluations (a group of ten domain experts)

- Similar studies in the literature (Vassalos *et al.*, 2010; Schröder-Hinrichs *et al.*, 2011; Ventikos, 2013; Uğurlu, 2016; Baalisampang *et al.*, 2018; Puisa *et al.*, 2019) (Table 7). Definitions of the basic events are given below.

Table 7. Basic events in engine-room fires

Fuel Leakage (BE1): Fuel leakage is caused by malfunctions in fuel lines, fuel pumps, cylinders, and similar equipment connected to main engines or generators. Failures are mainly related to damaged flexible hoses, worn couplings, inappropriate filters, cracked lines, unsuitable bolts, loose studs, and the use of inappropriate parts (O-ring, pipe fitting, elbow, diaphragm, *etc*.). Because of insufficient maintenance or inspection practices, such parts may become fatigued under a load, stretch, and break, causing fuel leakage.

Oil Leakage (BE2): Damage to the lubricating pump or thermal oil line and issues with bearings' lubricating oils can cause oil leakage.

Oily Surfaces (BE3): Inadequate inspection or cleaning practices after maintenance of the main engine, generator, boiler, *etc*. in the engine room may result in the formation of oily surfaces. In addition, a small number of oil-fuel leaks may cause oil and fuel contamination of the compartment or equipment.

Bilge (BE4): 'Oil bilge' refers to oil, fuel, or leaked material accumulated on the floor near part of a ship's machinery, auxiliary machinery, tanks, cofferdams, or boilers. If the necessary inspections and/or cleaning are not performed, particularly in the bilge wells of the engine room, oil accumulation occurs, and this situation leads to the occurrence of fires.

Sludge (BE5): The waste left by the burnt oil or fuel sent to the sludge tank and the fuel sludge solidified at the bottom of a vessel's fuel tank are called sludge.

Non-Heat-Resistant Materials (BE6): This term refers to the materials in engine rooms that are not resistant to high temperatures. The most common non-heat-resistant materials encountered in engine-room fires on ships are the O-rings used in fuel lines.

Garbage and Waste (BE7): This refers to the domestic and operational solid wastes that are produced during of the normal operation of a ship and fall under the scope of the MARPOL (International Convention for the Prevention of Pollution from Ships) 73/78 Annex V. Plastics, paper products, rags, greasy clothes, thread waste, and operational waste pose high fire risks.

Soot (BE8): As is known, fuels such as gasoline, diesel, and fuel oil are hydrocarbon components, and, when they are burned in air, they form soot because of a chemical reaction. Incomplete combustion in the main and auxiliary machinery of a ship and the use of dirty fuel can cause soot accumulation within the exhaust system and turbo charger equipment. This soot is flammable.

Fuel Vapour (BE9): This term refers to the high-temperature fuel used in the main and auxiliary machinery when it is in the vapour phase. The presence of fuel vapour leakage implies a high risk of fire.

Gas Vapour (BE10): This term refers to the flammable vapour produced by gases such as oxygen, acetylene, and SF6 (sulphur hexafluoride), which are used in welding and cutting processes.

Main Engine Hot Surfaces (BE11): The main engine is the equipment that enables the operation of ships. During the operation of the main engine, the temperature of the inner and outer surfaces of the engine increases due to movement and creates a fire-friendly environment.

Main Engine Exhaust System Hot Surfaces (BE12): The exhaust system is called the 'unit' and ensures that hot exhaust gases formed because of the combustion of fuel in main machine cylinders are released into the atmosphere from the machine cylinders with minimum resistance. This creates a suitable environment for the formation of fires because of the high temperatures of the gases formed because of combustion and passage through the exhaust manifolds.

Main Engine Turbo Charger (BE13): This equipment uses the energy from exhaust gases to send clean air to the intake manifold and then to the combustion chamber. It increases the efficiency and power of the main engine.

Main Engine Hot Fuel Line (BE14): These are the circuits and connections that allow the fuel in the fuel tanks to be delivered to the main engine. The presence of high-temperature fuel in the circuits results in hot surfaces.

Generator Hot Surface (BE15): These are the auxiliary engines that provide the energy needed for ships while they are at port and underway. Hot surfaces result from hot fuel circulating within the circuit, and the interaction between the two factors may cause a fire.

Generator Exhaust System (BE16): This unit ensures that hot exhaust gases formed because of the combustion of fuel in the diesel generator (D/G) cylinders are removed from the cylinders with minimum resistance.

Generator Turbo Charger (BE17): Turbo chargers are engine parts that increase the combustion efficiency and performance of an engine by ensuring that the generator is supplied with excess air. The hot exhaust gases, fuel, and lubricating oil contained in the turbo charger (T/C) create conditions that are suitable for fire formation.

Boiler (BE18): Boilers are auxiliary engines used for the heating of cargo, fuel, bilge, water, and oil. The water or thermal oil in the boiler is heated with fuel. Because the combustion process takes place within the boiler, its surfaces become hot.

Thermal Oil System (BE19): This is a heating plant consisting of a thermal oil heater, circulation pump, expansion tank, storage tank, ventilator, pipe, and control panel. Once oil reaches the desired temperature, it is sent through the pumps to the lines to be used (cargo, fuel, *etc*.). As hot oil and exhaust gases circulate within the lines, the resulting hot surfaces create a fire risk.

Compressor (BE20): Compressors are auxiliary machines used to compress air or other gases at levels of pressure higher than the atmospheric pressure. Because of the hot oil they contain, they can result in a hot surface that is conducive to fire formation.

Electric Arc (BE21): The electric arc is a bluish electrical discharge. High temperatures in arc explosions cause the air around the point where the explosion occurs to heat up quickly and create high air pressure. Arc bursts occur suddenly, with an uncontrolled release of fire, light, and pressure waves. This instantaneous event causes damage to equipment and leads to fires.

Sparks (BE22): These are small particles in the fire phase that are caused by strong collisions and friction between metal parts. Hot sparks caused by improper use of the welding, cutting, and grinding motor become airborne, causing flammable materials in their vicinity to ignite.

Spontaneous Combustion (BE23): This is expressed as the minimum heat value that must be reached before fuel vapour or other combustible gases can burn without a source of fire or flame.

Hot Work (BE24): This type of work involves working with ignition sources or temperatures which can cause a flammable gas mixture to ignite. Some examples include welding and using burning or soldering equipment, blow torches, and some power-driven tools.

Static Electricity (BE25): This is caused by the contact and separation of various surfaces. It may be seen on solid-solid, solid-liquid, and liquid-liquid surfaces. Static electricity-induced sparks are a serious source of ignition.

Cigarette Smoking (BE26): Smoking by staff may cause a direct fire risk when a cigarette's flame makes contact with combustible materials, such as solid waste or oily clothes.

Naked Light/flame (BE27): This term refers to the fire or flame created by matches, lighters, and similar devices that are directly connected to flammable materials or containers.

There are two main event sets in the fault tree which lead to the top event of an 'engine-room fire'. These are the sources of flammability and the sources of heat. Using these two main sets, the undesirable events previously described were classified among themselves and the relationships between them were established through 'OR' gates (Figure 4). The sources of flammable material and the heat sources are connected to each other by 'AND' gates in the fault tree. This means that when the basic events of the two main event sets come together, the top event (*i.e*. a fire) occurs. The fault tree formation for engine-room fires on ships is presented in Figure 4.

Figure 4. a) Fault tree analysis structure of fire-explosion accidents, b) Flammable hot surfaces, and c) Sparks and heat sources

2.2.2.2. Domain expert evaluation

In this study, expert evaluations were constructed based on the opinions of ten experts. This expert group was a heterogeneous one that consisted of chief engineers, port state controllers, technical managers, accident investigators, and researchers. The experts assessing the effects of basic events on fire formation were professionals who had worked in the maritime sector for many years and had actively worked in various positions within the sector. At this stage, a weighting process considering the professional qualifications, operational experience, and training levels of the chosen experts was conducted. The weighting scores of the experts are presented in Table 8. To reflect the differences in the weight of their opinions, each expert was assigned a score from 0 to 5. Table 9 contains the data regarding the weighting calculations of the experts.

Table 8. Weighting scores of experts

Table 9. Total scores and weighting factors of the experts evaluating engine-room fire-explosion accidents on ships

The calculation of the weighting scores of the experts was based on Equation 6 (Rajakarunakaran *et al.*, 2015).

$$Weighting\ factor\ of\ expert\ (W_{\mu}) = \frac{Weighting\ score\ of\ the\ expert}{Sum\ of\ all\ experts'\ weighting\ scores} \quad (6)$$

where μ stands for expert μ within the group.

2.2.2.3. Fuzzification

In this study, a linguistic scale consisting of seven terms was used to solicit expert opinions of basic events with unknown error rates (Table 10). The occurrence probability of each basic event was scaled from the lowest to the highest. The linguistic scale used to evaluate the probability distribution of faults included the terms 'very high', 'high', 'medium high', 'medium', 'medium low', 'low', and 'very low' (*i.e.* VH, H, MH, M, ML, L, and VL). The results of the evaluation of the basic events in the fault tree by the expert group are given in Table 11.

Table 10. Linguistic measurement scale (Rajakarunakaran *et al.*, 2015)

Table 11. Linguistic results of expert evaluations of basic events

2.2.2.4. Aggregation

In the aggregation stage, BE14 was selected as an example. The similarity function values of the BE14 basic event (Table 12) were calculated using Equation 8, the average and relative agreement (Table 14) were calculated using Equations 9 and 10, and the consensus coefficient (CC) values (Table 13) were calculated using Equation 11. As a result of these calculations, the fuzzy possibility value of the BE14 basic event was found to be 0.641 (Table 15).

Table 12. Basic event BE14 similarity function value calculations

Table 13. Consensus coefficient (CC) findings

Table 14. The average and relative agreement values of experts

Table 15. BE14 expert opinion values in the 'aggregation' stage

2.2.2.5. Defuzzification

In accordance with the calculations, the fuzzy possibility scores of the basic events are presented in Table 16. The basic event with the largest fuzzy possibility value was BE1 (fuel leakage), with a value of 0.96. The basic events with the second and third most significant possibility values were BE11 (main engine hot surface) and BE12 (main engine exhaust system hot surfaces).

Table 16. Fuzzy possibility values for basic events

2.2.2.6. Occurrence probability generation

If the occurrence probabilities of all basic events are known, the occurrence probability of the top event can be calculated. The results obtained by applying this equation to each of the basic events are shown in Table 17.

Table 17. Calculations of fuzzy occurrence probability values of BEs

2.2.2.7. Occurrence probability of the top event

The probability values of the basic events obtained from the fuzzification to the probability-generation stages were placed in the fault tree, and the probability value of the top event was calculated. In this study, an open FTA program was used to calculate the probability value of the TE (Uğurlu *et al.*, 2015a). The occurrence probability value of the top event was found to be 7.401E-002 per vessel under investigation.

2.2.2.8. Importance ranking

At this stage of the study, the degree of importance of a 'cut set' was calculated. The FV-I values and rankings of the 'cut sets' are given in Table 18 according to Equation 16. In this study, there were a total of 170 'minimum cut sets' for the top event. Table 18 shows the 20 'cut sets' with the highest-ranking values.

Table 18. Fuzzy occurrence probability and FV-I calculations for MCSs

2.2.2.9. Validation

The fault tree in this study was created based on a fire triangle. The MCSs (accident occurrence combinations) obtained using the fault tree summarise the formation of engine-room fires. These MCSs exist in parallel with the factors affecting the likelihood of the occurrence of engine-room fires, which were examined in the accident investigation reports. The MCSs and their probability values were evaluated by a group of experts whose judgements were taken into consideration during the study. The accuracy of the established fault tree was verified.

3. Findings and Discussion

In this study, 275 factors (in 507 occurrences) causing fire-explosion accidents in ships' engine rooms were classified according to the HFACS structure. The prevalence of these factors according to the main levels of the HFACS was as follows: organisational influences (34.12%), operational conditions (19.53%), preconditions for unsafe acts (17.75%), unsafe acts (14.80%), and unsafe supervision (13.81%) (Figure 2). When the results were compared with those of the studies conducted by Baysari *et al.* (2008) and Schröder-Hinrichs *et al.* (2011), it was found that the results for 'organisational influences' and 'preconditions for unsafe acts' were similar. The sub-categories that stood out at the level of 'organisational influences' were equipment and facility resources (62), crew assignment (43), training and familiarisation (27), and oversight and control (22). The most important non-conformity in the 'equipment and facility resources' sub-category was uninsulated equipment (33 accidents). In this study, it was observed that engine-room fires that occurred due to lack of insulation were mostly caused by main engine surfaces, auxiliary engine surfaces, and fuel systems (Table 2). Most of the fuels used in ships are self-igniting when they make contact with surfaces at temperatures above 250°C. According to the requirements of SOLAS II-2 Reg. 4, 2.2.6, all surfaces above 220°C must be covered or insulated with protection shields. The results of this study showed that the isolation requirements of SOLAS II-2 were sometimes violated on merchant ships. Another important non-conformity at this level was ergonomic design flaws, which were observed 12 times. Kwiecińska (2015) emphasised that design flaws and equipment-related non-conformities have a significant impact on the likelihood of occurrence of fire-related accidents. The most common ergonomic design flaws are faulty/inappropriate design of the main engine's fuel pump unit, auxiliary engine's fuel line connections, thermal oil systems, and boiler systems. In many accident reports, it has been stated that the leakage that occurs in these lines resulting from oil/fuel lines directly connected to hot surfaces causes a fire. Another factor that stands out, with a frequency of 15 in the 'crew assignment' sub-category, is the presence of chief engineers who are unqualified to execute their duties effectively (Table 2). The chief engineer is responsible for all operations, routine maintenance, and the repair of the engine systems and equipment in accordance with the manufacturer's schedule (within the safety management system) while simultaneously guiding the engine crew appropriately. A chief engineer who does not have the skills to execute such tasks effectively may misdirect the crew under his or her guidance, leading to erroneous, incomplete, or sloppy work being carried out in the engine room. In addition, many accident reports emphasise that this situation leads to a lack of communication or coordination between the engine crew. The importance of an effective leadership style in promoting maritime safety was also clearly stated in the study by Sætrevik and Hystad (2017). Human resource-based non-conformities involve crew members who do not meet the requirements of their ranks, inadequate or ineffective crew-training programs, and the ineffective introduction of ship-specific systems.

Non-conformities are prominent at level 2, ‘unsafe supervision’, and include the latent factors of the HFACS, such as lack of internal audits (26) and lack of planned maintenance (19) in the sub-category of ‘inadequate supervision’. Both sub-categories refer to the routine maintenance and inspection of engines and equipment according to the Safety Management System (SMS) requirements (Table 3). The maintenance-repair of main engine fuel lines and equipment and D/G fuel lines and equipment has attracted attention as a source of non-conformities. Maintenance and inspections that are not performed in a timely or effective manner can cause the equipment under a load to become fatigued and malfunction. Puisa *et al.* (2019) examined fire accidents in the engine room of a Le Boreal passenger ship and found that routine maintenance-repair procedures and insufficient/inappropriate insulation were the most important factors in the occurrence of fires. Compliance with the requirements of a safety management system is the most important factor in safe ship operations. In this study, significant non-conformities contributing to the formation of fires related to the planning of ‘hot work’ in the sub-category of ‘planned inappropriate operations’ were found. The most frequently identified non-conformities related to ‘hot work’ included work areas that were not defined or cleaned, those where a lookout was not assigned, those where the lookout’s location changed during such work, and the use of equipment that generated sparks in an inappropriate area. Accidents become inevitable when a single non-conformity that is overlooked during 'hot work' is combined with other non-conformities. Baalisampang *et al.* (2018), in their study, stated that human errors that cause fire-explosion accidents generally occur during maintenance activities. In this study, it was observed that fires frequently occurred during maintenance activities, especially during 'hot work'.

The final level of the latent factors in the HFACS was 'preconditions for unsafe acts'. Non-conformities at this level resulted from a lack of situational awareness or communication and management activities. The factors related to lack of situational awareness that fell into the 'adverse mental state' sub-category referred to the current situation of the engine crew, developing conditions, and lack of awareness of environmental factors. In this study, 30 (61.2%) of fire-explosion accidents were found to have occurred due to lack of situational awareness.

Gruenefeld *et al.* (2018), in their study, stated that human error still has not been reduced in the last decade and that a lack of situational awareness prevails in most accidents caused by human error. In many accident reports examined in this study, it is emphasised that a lack of situational awareness causes accidents by contributing to poor decision-making processes (as in the M/V Thomson Majesty, M/V Arlott, M/V Arco Avon, and M/V Tai Shan fire-explosion accidents). Crew resource mismanagement in the sub-categories of 'substandard practices of crew members' stands out, with an occurrence frequency of 23. Crew resource mismanagement refers to non-conformities such as undisciplined team management, a chief engineer's errors in guidance (authority and misdirection), and failure to manage emergency situations. Another important non-conformity related to these sub-categories was 'lack of internal-external communication', which was a factor in 12 accidents (Table 4). Effective ship (in-team and inter-team) communication, which improves situational awareness, can be fostered by raising the awareness of the engine crew about the tasks and accident risks in the work area. For example, the third engineer, who noticed a fuel leak in the engine room of the Arco Avon, tried to stop the leak without notifying anybody else. Because of his faulty intervention, a fire occurred and he lost his life because of the fire spread to his coveralls (MAIB, 2016). The role of the team leader (chief engineer) is extremely important in ensuring effective communication between team members (Uğurlu *et al.*, 2015b; Sætrevik and Hystad, 2017). The effectiveness of the relationships between the crew members and the reporting of non-conformities by them are directly proportional to the positive attitude and motivation skills of the team leader.

The 'unsafe acts' at the last level of the HFACS were active failures that occurred because of interactions between the latent factors that caused accidents to occur. This level includes active failures, errors, and violations. Errors are undesirable behaviours, and violations are instances of deliberate non-compliance with rules and regulations. This study is focused on improper actions related to the main engines, auxiliary engines, and systems connected to them. The first sub-category under the level of 'unsafe acts' was the 'errors' category, and 48 non-conformities were observed. These included operating errors related to the main engine, auxiliary engine, and fuel systems. The most common faults in the operation of the main engine were failure to tighten the bolts/nuts/plugs of the fuel line and its associated components with the proper torque (7 accidents) and incorrect connection of the fuel line and its components (2 accidents) (Table 5). Kang (2017) examined the relationships between the levels of causal factors in his study, and the most prominent finding from the HFACS analysis was that latent factors were instrumental in the formation of all active failures. In most cases, the errors were found to have been due to inadequate supervision or organisational procedures, and the results obtained were found to be in line with this study when compared to similar studies from the past (Baalisampang *et al.*, 2018). On the other hand, the errors that were observed consisted of problems such as delayed responses by engine crews in operational situations related to the main and auxiliary engines and systems, indecision, and incorrect interventions when fuel leakage was present. These types of errors can be viewed as faulty behaviours or failures to take the correct actions in a timely fashion. Another category at this level was ‘violations’ (observed 27 times) (Table 5). The most common violations were related to procedures associated with ‘hot work’, fuel exchange, and planned maintenance. Doing ‘hot work’ does not necessarily lead to unsafe actions, but when such work is combined with unsafe actions, an accident is inevitable. Efficiently implementing safety procedures and fostering understanding of their requirements and importance is only possible when training that is deemed appropriate by shipping companies and ships’ flag states is provided. Uğurlu (2016) obtained similar results in his study investigating fire-explosion accidents between 1999 and 2013 in tankers carrying dangerous liquid cargo.

Active failures at the level of ‘unsafe acts’ in the HFACS reveal the causes of ship fires (fuel leakage, oil leakage, dirty and oily surfaces, and gas vapour accumulation). If these causes are combined with specific operational conditions (hot surfaces in the main engine or exhaust system, ‘hot work’, sparks, *etc*.), engine-room fires will occur. In this study, the relationship between these two categories was examined and evaluated using FFTA. It is impossible to eliminate the factors (accident-triggering factors and operational conditions) that cause accidents. However, by taking precautions in each system, the risk of accidents can be minimised. The most effective way to achieve this goal is to identify the non-conformities that lead to the occurrence of the top event and to reveal the relationships between them. The FFTA method makes it possible to analyse the interactions between fire-related non-conformities and operational conditions (accident occurrence combinations, or MCSs). According to the quantitative analysis in this study, BE1 (fuel leakage) was the most critical basic factor in the system. It was followed by BE12 (main engine exhaust system hot surfaces) and BE11 (main engine hot surfaces), respectively (Table 17 lists the other root factors and their rankings).

According to the analysis of the relationships established between the basic factors that were instrumental in fire-explosion accidents in ships' engine rooms, the most problematic accident scenario occurred when BE1 (fuel leakage) and BE12 (main engine exhaust system hot surfaces) were combined (Table 18). A good example of the outcome this combination is an engine-room fire caused by contact between a fuel leak and a hot surface (due to insufficient insulation), as occurred in the fire-explosion accident of the Ocean Star Pacific PMA (2011). In another similar accident, during the iron ore-loading operation at Port Hedland, Western Australia, fuel leakage caused by a fuel line failure (due to the use of non-original spare parts) was combined with the hot surface of a generator, and a fire occurred on the bulk carrier Marigold (ATSB, 2016). Other significant accident-friendly combinations include fuel or oil leakage (Table 18). This is consistent with the findings of previous studies, such as the one in which Paula *et al.* (1998) found that the majority of fire-explosion accidents occurred when fuel and/or lubricating oil leakage made contact with hot surfaces. Det Norske Veritas (DNV) found that 56% of fire-related accidents in engine rooms were due to a combination of oil/fuel leakage and hot surfaces (DNV, 2000). In many accident reports examined in this study, the factors leading to oil/fuel leakage were caused by damage to mechanical equipment or the use of inappropriate parts (such as hoses, couplings, filters, and pipe lines). This finding was in line with the safety bulletin issued by the DNV (2016). Oil/fuel leaks occurring in the engine room make contact with hot surfaces in the vicinity, causing fires. Insulation in the engine room is, therefore, a major issue. Thus, insulation materials damaged during maintenance-repair activities or after the passage of time should be replaced without delay, and adequate spare insulation materials should be kept on board. In addition, because fuel leakage in the main engine is close to a ship's exhaust system, more attention should be paid to leaks that occur in this area.

As in the study by Papanikolaou and Eliopoulou (2008), in this study, the prevalence (71.43%, or 35 accidents) of fire-explosion accidents occurring in ships with a hull structure over 20 years old showed that the risk of fire increases as a ship ages. The relationship between a ship's age and its fire risk arises because of the fatigue of mechanical parts under loads over time, structural abrasion, and the deformation of fuel systems.

4. Conclusions

In addition to being a relatively inexpensive mode of transport, maritime transport stands out because it is relatively safe and environmentally friendly. Despite its advantages, maritime transport can cause marine accidents, which can damage cargo, marine environments, and ship structures, leading to human injuries and/or deaths. Ship fires often draw the public's attention because they are one of the most common types of accidents, causing significant material losses and the loss of human lives. Many studies in the literature emphasise that fires in engine rooms are frequently involved in ship fires (Baalisampang *et al.*, 2018; Schröder-Hinrichs *et al.*, 2011; Uğurlu, 2016). Studies on marine accidents have indicated that fire-explosion accidents are concentrated in main and auxiliary engine systems. In this study, a hybrid model based on the HFACS and FFTA was presented, which enabled the analysis of engine-room fires on ships. The causes of engine-room fires were classified using the HFACS structure, and the formation process of accidents was revealed through the application of FFTA. The HFACS-based FFTA results showed that minor oversights in a ship's engine room can lead to major disasters. As in the case of the M/V Sea Dream I fire, an unsuitable tightened bolt can flex with great force and cause a fire, and a fire may cause the loss of a ship. Important results obtained from the study are presented below.

In this study, the accident-formation pattern for fire-explosion accidents is presented using fuzzy fault tree analysis based on an HFACS framework. This also reveals the relationships between the factors in such accidents. Thus, how accidents occur because of interactions between various factors can be discovered. The non-conformities discovered using the methods in the study can be used as a guide by accident investigators to understand the formation of accidents during the investigations carried out after engine-room fires.

- This study shows that fire-explosion accidents are concentrated in ships over 20 years of age and in association with mechanical fatigue in the main engine, auxiliary engines, and connected systems.
- Unqualified crew members and lack of training or familiarisation with equipment have been found to be the most important non-conformities underlying fire-explosion accidents. The engine rooms that are becoming modernised through the ongoing development of technology are designed to be equipped by specialists, and the systems that are housed in the machinery rooms today require qualified mechanical engineers and crew. It is impossible to maintain safe and secure engine rooms with an unqualified engine crew unfamiliar with ship-specific systems. The most common non-compliance factor in the category of 'inappropriate crew assignment' was found to be an unqualified chief engineer.
- Another non-conformity that was instrumental in the formation of engine-room fires was the presence of hot surfaces in the main engine, auxiliary engines, and connected systems. In particular, owing to the operation of such machinery while the ship is in motion, it is inevitable that a fire will occur if these increasingly hot surfaces make contact with oil/fuel leaks.
- There are too many potential sources in the engine room of fuel and oil leakage. In this study, it was found that the factors causing oil/fuel leakage were randomly distributed between flexible hoses, couplings, fractured pipes and broken studs, and worn gaskets. In most accidents, the materials used in maintenance and repair work were not original. Materials (bolts, nuts, pump

diaphragm O-rings, copper pipes used in the fuel line, *etc*.) that did not meet the specifications of the manufacturer's manual were more easily deformed when they made contact with cargo, hot fuel, or oil. These materials, which were not resistant to heat or chemicals, underwent mechanical deterioration, including abrasion, breakage, and fragmentation, causing fuel or oil leakage and facilitating the formation of fires.

- This study reveals that the engine room is a constricted area with a high risk of fire and that it must be kept under constant surveillance. In unmanned engine rooms, the absence of engine officers in the engine room, except during watch-keeping hours, caused an increased risk of fire (the M/V Boudicca, M/V Maribella, and M/V Seadream I are good examples of this point).

Accurate analysis and evaluation of accidents are crucial to avoiding similar accidents in the future. Accidents often appear to be the result of a single event, but, with proper examination, it often becomes apparent that they are caused by several factors. Therefore, an analysis of each accident should be conducted, considering the environment and conditions in which it occurred.

5. Recommendations

In the accident reports examined, it was observed that the procedures required by the International Safety Management (ISM) Code were either ignored or were not properly implemented. As shown by the results of the study, the existence of such procedures alone is not adequate to prevent accidents. The practitioners and ships' administrators should pay maximum attention to the implementation of such procedures. Fires can be prevented if the existing procedural steps are properly followed and such procedures are implemented in practice. The elimination of some nonconformities is also possible if proper shore-based training is given to staff by ship owners. For example, to mitigate non-compliance caused by factors related to main engines and generators, personnel must receive special training for their ship and its equipment. In addition, the personnel who are appointed to positions of authority should be made aware of the risks that may arise according to their rank and the ship's characteristics. ISM procedures, especially for planned maintenance, should be prepared with reference to manufacturers' manuals. The goal of a ship's operating company and staff should be not only to do what is required during inspections but to implement the ISM requirements adequately and effectively. Other recommendations based on this study are as follows:

- In aged ships, it is inevitable that mechanical parts will become fatigued under loads, structural abrasions will occur, and fuel lines and systems will become deformed with time. In the planned maintenance systems created by companies, the aim must be to ensure that a ship's materials can be used for the longest time and in the most efficient manner possible. Possible related non-conformities can be prevented by timely and effective maintenance-repair operations on ship equipment (in accordance with the requirements of the planned maintenance system). Therefore, it is necessary to establish policies that prevent the planned maintenance system and its requirements from being ignored by the ship's crew.
- Today, new environmentally friendly practices, such as the installation of exhaust emission systems and ballast water treatment equipment, are being implemented. These innovative applications have inspired new regulations, which often provide exemptions for old ships. To ensure the efficacy of new laws and their enforcement, the modified systems or new parts that must be installed do not generally work well on old ships. In addition, such equipment, which is incompatible and, in some cases, not produced by the original manufacturers of ships' machinery, entails risks of accidents and malfunctions. Therefore, international maritime policies should be adopted, and ships that have reached a specific age should be removed from operation by providing appropriate incentives to ship owners to replace their existing ships with new ones.

- Another non-conformity that attracts public attention in the category of ‘organisational influences’ is lack of insulation. The insulation materials on an engine’s equipment deteriorate with time (for reasons such as maintenance, repair, and overhaul). Such materials may not be suitable for reuse. Because most ships do not have spare insulation materials on hand, the continuity of insulation cannot always be ensured. Therefore, policies should be developed to ensure the continuity of insulation in ships’ engine rooms. If ships’ administrators meet the insulation requirements in accordance with the SOLAS II-2 requirements, it becomes possible to prevent fire-explosion accidents caused by a lack of proper insulation.
- Owing to the design of engine rooms, the location of the equipment and rig is not always suitable for monitoring or surveillance. For this reason, infrared thermometers and cameras (with a measuring range of -50 to 1,000°C), which are used for the measurement and monitoring of hot surfaces in many areas in land facilities, should also be used in ships’ engine rooms. In this way, in places like engine rooms, where hot surfaces are too high to reach and space is limited, these thermometers and cameras can be used to regularly control and monitor temperatures.

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Table 1. Similar studies related to ship fires

Name of the study	Methodology	Journal name	Author(s) - Year
Accident investigation reporting deficiencies related to organizational factors in machinery space fires and explosions	HFACS	Accident Analysis and Prevention	Schröder-Hinrichs *et al.*, 2011
Numerical computation and characteristic analysis on the centre shift of fire whirls in a ship engine room fire	Fire Dynamics Simulator (FDS)	Safety Science	Shichuan *et al.*, 2012
Safety in maritime oil sector: Content analysis of machinery space fire hazards	Summative Content Analysis Approach, Computer Assisted Qualitative Data Analysis Software (CAQDAS)	Safety Science	Ikeagwuani and John, 2013
Use of HFACS–FCM in fire prevention modelling on board ships	HFACS, Fuzzy Cognitive Mapping (FCM)	Safety Science	Soner *et al.*, 2015
Analysis of fire and explosion accidents occurring in tankers transporting hazardous cargoes	FTA, Fuzzy Extended Analytic Hierarchy Process (FAHP)	International Journal of Industrial Ergonomics	Uğurlu, 2016
Fault Tree Analysis of fire and explosion accidents for dual fuel (diesel/natural gas) ship engine rooms	FTA	J. Marine Sci. Appl.	Guan *et al.*, 2016
Effect of human behaviour in shipboard firefighting decisions: The case of fire in engine rooms	Analytic Hierarchy Process (AHP)	Journal of Contingencies and Crisis Management	Karahalios, 2017
A probabilistic model for fatality estimation of ship fire accidents	FDS, Available Safe Egress Time (ASET), Required Safe Egress Time (RSET)	Ocean Engineering	Wu *et al.*, 2018
Review and analysis of fire and explosion accidents in maritime transportation	Review	Ocean Engineering	Baalisampang *et al.*, 2018
Analysis of effectiveness of fire safety in machinery spaces	Formal Safety Assessment(FSA), Dynamic Barrier Management	Fire Safety Journal	McNay *et al.*, 2019
Towards an explanation of why on board fires happen: The case of an engine room fire on the cruise ship "Le Boreal"	Systems-Theoretic Accident Model and Processes (STAMP), Causal Analysis based on Systems Theory (CAST)	Applied Ocean Research	Puisa *et al.*, 2019

Table 2. Basic rules of Boolean algorithms

Associative Laws	$(A + B) + C = A + (B + C)$ $(A \cdot B) \cdot C = A \cdot (B \cdot C)$
Commutative Laws	$A + B = B + A$ $A \cdot B = B \cdot A$
Distributive Laws	$A \cdot (B + C) = A \cdot B + A \cdot C$ $A + (B \cdot C) = (A + B) \cdot (A + C)$
Absorption Laws	$(A \cdot B) + A = A$ $(A + B) \cdot B = B$
Redundancy Laws	$A \cdot (A + B) = A$
Idempotent Laws	$(A + A) = A$ $A \cdot A = A$
De Morgan Laws	$(A + B) = A \cdot B$ $(A \cdot B) = (A + B)$

Table 3. Accident factors and their occurrence frequencies at the 'organisational influences' level

		Factors	Frequency
Resource Management	Human Resources	**Lack of Training and Familiarity with the Ship**	
		Level alarm system (main engine, auxiliary engine, fuel tanks)	4
		Filter replacement (fuel pump, lubricating oil)	2
		Planned maintenance of diesel generator	4
		Thermal oil system (maintenance and emergency response)	2
		Company International Safety Management (ISM)system and applications	5
		Main engine fuel pump	5
		Shipyard workers unfamiliar with the ship	1
		Ship-specific electrical system (electrical officer)	1
		Main engine turbo charge (T/C) maintenance-engine crew	1
		Steam boiler – engine crew	2
		Crew Assignment	
		Minimum crew manning	-
		Incompatible with the rank (insufficient) - master	2
		Incompatible with the rank (insufficient) - chief engineer	15
		Incompatible with the rank (insufficient) - 1.engineer	9
		Incompatible with the rank (insufficient) - 2. or 3.engineers	8
		Incompatible with the rank (insufficient) - electrical officer, oiler, fitter	6
		Unqualified non-ship personnel (Shipyard, service team)	3
	Equipment/facility Resources	**Deficient Equipment and Facility**	
		Spare parts for main engine	1
		Spare parts for auxiliary engine	-
		Purchasing of Unsuitable Equipment	
		Engine Room	
		Use of heat resistant hose in ventilation duct	1
		Main Engine	
		Fuel line stop valves	1
		Heat and fuel non-durable gasket	1
		Turbo charger RPM counter	1
		Pressure relief equipment	1
		Non-original fuel supply line	1
		Insulation of insufficient Low sulphur diesel oil (LSDO) lines	1
		Lubricating oil filter air release screw	1
		Rubber diaphragm fuel pump	1
		Non-original fuel system flange connection protection caps	1
		Uninsulated main engine surface	3
		Uninsulated turbo charger	5
		Uninsulated exhaust manifold	8
		Uninsulated fuel line	1
		Auxiliary Engine and Diesel Generator	
		Diesel Generator (D/G) manometer equipment	2
		D/G unsuitable hose	1
		D/O fuel line pressure and fuel non-durable gasket	1
		LSDO fuel line isolation valve gasket	1
		Uninsulated turbo charger	6

		Uninsulated exhaust manifold	7
		Uninsulated auxiliary engine and diesel generator surface	3
		Previously used O-ring in the fuel line	1
Resource Management	Equipment/facility Resources	**Ergonomic Design Flaws**	
		Engine Room	
		Thermal oil system (pressure meter connection, line)	2
		Boiler (furnace cooling system, burner)	2
		Hydraulic oil tank ventilation line	1
		Main Engine	
		Fuel pump (pressure relief valve, lubricating oil-filter handle)	2
		Fuel line (pipe connections, isolation valve)	2
		Auxiliary Engine and Diesel Generator	
		D/G fuel line emergency system designed for low pressure	1
		D/G manometer connection (connecting directly to the T/C)	1
		D/G stop valves without non-return	1
Organizational Climate	Structure	**Communication and Coordination**	-
		Chain of Command	-
		Delegation of Authority	-
	Policies	**Promotion**	-
		Drugs and Alcohol	-
	Culture		-
Organizational Process	Operations Management	Failure to meet the spare parts demand on time by the company	1
	Legal Deficiency	**Procedure-Based**	
		Scavenge cleaning	1
		Lubricating oil filter change	2
		D/G and fuel lines maintenance	3
		Generator start (failure to determine the amount of load that should work)	1
		Maintenance of fuel line stop valves	1
		Fuel exchange	2
		Thermal oil system maintenance and emergency operation	2
		Routine alarm tests of the compressor (temperature)	1
		Hot work - use of grinding motor	1
		Main engine fuel line maintenance	1
		Legislation-Based	
		LSDO line installation plans	1
		Unspecified training to introduce the ship-specific electrical system	1
		Use of spare parts is not enough explained in the user manual	1
	Oversight and	**Risk Analysis**	
		Planned maintenance - D/G, boiler, hydraulic line, main engine, fuel line, fuel Pump, fuel pump filter cleaning	11
		Repair-boiler, D/G, fuel line	3

			Fuel transfer	2
			Hot work - welding, grinding motor	5
			Safety Assessment	
			Ignored risk assessment	1

Table 4. Accident factors and their occurrence frequencies at the 'unsafe supervision' level

	Factors	Frequency
Inadequate Supervision	**Lack of Internal Audit**	
	Main engine working hours	1
	Line and valve pressures of the LSDO system	1
	Auxiliary engine working hours/working performance monitoring	4
	Main engine fuel lines and equipment	6
	D/G instrument panel and equipment	1
	Boiler working performance monitoring	1
	Compressor (instrument panel/operating performance)	2
	Auxiliary engine fuel lines and equipment	5
	Boiler water	1
	Engine room bilge wells	1
	Fuel tanks instrument panel	1
	Fuel filter isolation handle	2
	Lack of Planned Maintenance	
	Main engine fuel lines and equipment, T/C	2
	Main engine fuel pump	3
	Auxiliary engine fuel line and equipment/ T/C	3
	D/G fuel line system and equipment	5
	Lubricating oil lines and equipment	1
	Thermal oil system	2
	Boiler system	1
	Scavenge cleaning	1
	Incinerator cleaning	1
Planned Inappropriate Operations	**Hot Work**	
	Workspace boundaries	3
	Work area cleaning	2
	Change of the location of the fire watcher	1
	Use of grinding motor	1
	Work Planning	
	Inadequate Crew (lacking)	
	Hot work	3
	D/G repair	5
	Repair of boiler	1
	Repair of fuel tank	1
	Working resting hours- port period workload	1
	Inappropriate	
	Repair of boiler	1
	Task distribution	1
	Fuel exchange	1
	The main engine exhaust manifold covers are disassembled	2
	LSDO system installation planning	1
Fai led to	Unsafe storage of garbage in the engine room	1

	Factors	Frequency

Table 5. Accident factors and their occurrence frequencies at the 'preconditions for unsafe acts' level

	Factors	Frequency
Substandard Conditions of Crew Members	**Adverse Mental States**	
	Lack of Situational Awareness	
	Engine crew	22
	Chief engineer	3
	Engine officer	5
	Lack of Attention	
	Engine crew	5
	Engine officer	1
	Repair team	1
	Overconfidence and Comfort	
	Engine crew	4
	Chief engineer	4
	Engine officer	3
	Others	
	Sleeplessness - engine crew	1
	Stress	1
	Mental fatigue of the officer	1
	Adverse Physiological States	
	Physical fatigue-engine officer	1
	Physical fatigue-engine crew	1
	Physical/Mental Limitations	
	Excessive workload - watchkeeping engineer	1
	Excessive workload due to lack of team members	1
Substandard Practices of Crew Members	**Personal Readiness**	-
	Engine Resource Management	
	Crew Resource Mismanagement	
	Undisciplined team management (failure of leadership)	3
	Chief Engineer's error of guidance - working plan	6
	Chief Engineer's error of guidance - maintenance	10
	Chief Engineer's error of guidance - management of hot work	2
	Chief Engineer's error of guidance - feedback	1
	Chief Engineer's error of guidance - assignment	1
	Lack of Communication	
	Chief Engineer - engine officers	5
	Between engine team members	4
	Shipyard - ship	1
	Fitter-lookout	1
	Company-ship	1

Table 6. Accident factors and their occurrence frequencies at the ‘unsafe acts’ level

	Factors	Frequency
Errors	**Main Engine**	
	Faulty connection of the fuel line and components	7
	Fuel line and components - failure to tighten bolts/nuts/plugs with proper torque	2
	Incorrect response of the chief engineer to leakage in the manometer connection pipe	1
	Misinterpreting the operating principle of its and fuel system	2
	T/C maintenance-repair operations	1
	Manometer maintenance-repair operations	1
	Temporary stop of fuel leak detected in the fuel injector on the main engine	1
	Stopping the circulation pump without determining the cause of sudden low pressure in the fuel system and taking the necessary measures	1
	The chief engineer loosening the air vent screw instead of the normal screw	1
	Chief Engineer loosening wrong screw due to failure to mark air release screw	1
	Failure to detect fuel tank alarm indicator malfunctions	1
	Auxiliary Engine	
	Not to dominate the work done (Unfamiliarity to the task)	
	Fuel line and components - failure to tighten bolts/nuts/plugs with proper torque	1
	Incorrect closing of the incinerator air flaps	1
	Loosening the D/O fuel pump cover bolts under pressure	1
	The chief engineer loosening the wrong screw (air release screw)	1
	Loosen the D/G fuel filter cover bolts without opening the relief valve	1
	Maintenance of ship hydraulic line	1
	All equipment connected to the thermometer was disconnected from the line	1
	Improper response to fuel leakage at D/G	1
	Intervention to hydraulic oil line on ship trimmed to aft	1
	D/G temporary- incorrect response to fuel leakage	3
	Re-commissioning of the D/G, although it has shut down several times	1
	Temporary response to fuel leakage from the copper connection pipe of the manometer	2
	Late decision on decommissioning of D/G	1
	Temporary resolve of failure of the flexible hose used in D/G	1
	Improper Maintenance-Repair Operations	
	Boiler system	3
	Compressor	1
	D/G	3
	T/C	3
	Thermal oil system	2

Violations	**Violation of Regulations**	
	Complete removal of the protective covers of the main engine F/O fuel lines (unprotected against fuel leakage and fire) (Canada Shipping Act, Safe Working Practices Reg., item 9)	1
	Use of non-original protective covers for flanged connections of the M/E fuel system (SOLAS II-2 Reg., item 4)	1
	Use of unsuitable parts in the fuel isolation valve when installing the LSDO system (Flag State and Classification Society)	1
	Directing fuel pipes and lines directly to heat sources (SOLAS II-2 Reg., 4 - Canada Shipping Act, Marine Machinery Reg., Schedule XII, item 21)	1
	Manometer (SOLAS II-2 Reg., item 4)	1
	Violation of the Instruction Manual	
	Failure to install the T/C oil thrower by the repair team	1
	Inappropriate used spare part - O-ring (pre-used material)	1
	Running the T/C at a higher speed than necessary	1
	The use of non-original material for maintenance and repair of A/E	3
	Violation of Company Safety Procedures	
	Hot work	8
	Fuel exchange	2
	Scavenge cleaning	1
	Incinerator operation and cleaning	1
	Opening the main engine rotor cover while the main engine is running (maintenance)	1
	Boiler burner service	1
	Work permit before using the grinding motor	1
	Smoking in restricted areas	1

Table 7. Basic events in engine-room fires

Intermediate Events				Basic Events	Frequency	Abbreviation of Basic Event
Sources of Flammable Materials	Fluid material source	Leakage		Fuel-diesel leakage	31	BE1
				Lubricating oil leakage	6	BE2
		Waste product	Oil/fuel residue	Oily surfaces	1	BE3
				Bilge	2	BE4
				sludge	1	BE5
	Solid material source			Heat non-resistant materials	3	BE6
				Garbage and wastes	1	BE7
				Soot	1	BE8
	Gas material source			Fuel vapour	2	BE9
				Gas vapour	1	BE10
Heat Source Materials	Hot surface	Main engine		Main engine hot surface	8	BE11
				Main engine exhaust system hot surfaces	12	BE12
				Main engine turbo charger	6	BE13
				Main engine hot fuel line	1	BE14
		Auxiliary engine		Generator hot surface	4	BE15
				Generator exhaust system	2	BE16
				Generator T/C	2	BE17
				Boiler	3	BE18
				Thermal oil	2	BE19
				Compressor	1	BE20
	Spark and fire (heat) source	Inappropriate equipment		Spark	1	BE21
				Electric arc	1	BE22
				Spontaneous combustion	1	BE23
		Inappropriate work		Hot work	5	BE24
				Static electric	-	BE25
		Inappropriate crew		Cigarette	1	BE26
				Naked light/flame	-	BE27

Table 8. Weighting scores of experts

Constitution	Classification	Score
Professional position (PP)	Port State Control Officer	5

	Technical Manager	4
	Professor	3
	Lecturer	2
	Shipping company owner-engineer	1
Competency (Comp.)	Chief Engineer	5
	1st Engineer	4
	2nd Engineer	3
	Oceangoing Master	3
Professional experience in years (PE)	Greater than 15 years	5
	10 to 15	4
	5 to 10	3
	3 to 5	2
	1 to 3	1

Table 9. Total scores and weighting factors of the experts evaluating engine-room fire-explosion accidents on ships

Expert no.	Professional position	Competency	Operational experience (year)	Weight score: Professional position (Score)	Competency (Score)	Professional experience in years (Score)	Total score	Weight factor
1	Professor	Oceangoing master	19	3	3	5	11	0.096
2	Lecturer	1st engineer	11	2	4	4	10	0.088
3	Technical manager	Chief engineer	14	4	5	4	13	0.114
4	Lecturer	Chief engineer	16	2	5	5	12	0.105
5	Shipping company owner	1st engineer	12	1	2	4	7	0.061
6	Technical manager	Chief engineer	16	4	5	5	14	0.123
7	2nd Engineer	2nd engineer	9	2	2	3	7	0.061
8	Lecturer	Chief engineer	11	2	5	4	11	0.096
9	Port state control officer	Chief engineer	27	5	5	5	15	0.131
10	Port state control officer	Chief engineer	12	5	5	4	14	0.123

Table 10. Linguistic measurement scale (Rajakarunakaran et al., 2015)

Measurement Scale	TFN a_1	a_2	a_3
Very low (VL)	0.00	0.04	0.08
Low (L)	0.07	0.13	0.19
Medium low (ML)	0.17	0.27	0.37
Medium (M)	0.35	0.50	0.65
Medium high (MH)	0.63	0.73	0.83
High (H)	0.81	0.87	0.93
Very high (VH)	0.92	0.96	1.00

Table 11. Linguistic results of expert evaluations of basic events

		Experts									
BE No	Basic Events	1	2	3	4	5	6	7	8	9	10
1	Fuel leakage	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
2	Oil leakage	H	MH	MH	H	H	H	MH	MH	H	MH
3	Oily surfaces	M	M	ML	M	L	H	ML	M	MH	H
4	Bilge	MH	L	L	MH	L	L	VL	ML	M	M
5	Sludge	MH	VL	L	MH	ML	M	L	ML	L	M
6	Heat non-resistant materials	M	MH	ML	M	ML	MH	M	H	M	H
7	Garbage and wastes	ML	M	M	H	L	M	ML	H	MH	H
8	Soot	ML	M	L	ML	L	M	MH	MH	MH	MH
9	Fuel vapour	ML	M	ML	H	M	MH	H	MH	ML	L
10	Gas vapour	L	L	L	L	M	L	L	L	MH	VL
11	Main engine hot surface	H	VH	MH	H	MH	H	H	MH	H	VH
12	Main engine exhaust system hot surfaces	VH	VH	VH	VH	VH	VH	VH	VH	VH	H
13	Main engine turbocharger	MH	MH	H	H	MH	H	M	H	VH	M
14	Main engine hot fuel line	ML	MH	L	ML	M	H	MH	H	H	VH
15	Generator hot surface	MH	L	MH	H	ML	M	M	M	MH	H
16	Generator exhaust system	MH	M	H	VH	M	H	VH	H	VH	H
17	Generator turbo charger	M	M	MH	H	ML	H	M	MH	VH	ML
18	Boiler	MH	MH	MH	H	M	H	MH	H	VH	M
19	Thermal oil system	M	H	M	M	MH	H	MH	MH	H	H
20	Compressor	L	VL	L	L	L	VL	VL	VL	VL	L
21	Spark	ML	MH	M	MH	L	H	L	MH	MH	VH
22	Electric arc	M	L	ML	H	L	ML	VH	MH	VH	MH
23	Spontaneous combustion	L	L	VL	L	VL	L	ML	VL	VL	ML
24	Hot work	H	MH	VH	H	MH	MH	ML	H	H	H
25	Static electric	L	VL	VL	VL	L	VL	L	VL	VL	L
26	Cigarette	L	M	L	L	ML	MH	M	MH	M	L
27	Naked light/flame	VL	VL	VL	VL	VL	VL	VL	VL	L	VL

Table 12. Basic event BE14 similarity function value calculations

Expert No	Membership Function			Similarity Functions	Similarity Functions Value	Similarity Functions	Similarity Functions Value	Similarity Functions	Similarity Functions Value
	a_1	a_2	a_3						
E1	0.17	0.27	0.37	S(1,2)	0.540	S(2,9)	0.860	S(5,6)	0.630
E2	0.63	0.73	0.83	S(1,3)	0.860	S(2,10)	0.770	S(5,7)	0.770
E3	0.07	0.13	0.19	S(1,4)	1.000	S(3,4)	0.860	S(5,8)	0.630
E4	0.17	0.27	0.37	S(1,5)	0.770	S(3,5)	0.630	S(5,9)	0.630
E5	0.35	0.50	0.65	S(1,6)	0.400	S(3,6)	0.260	S(5,10)	0.540
E6	0.81	0.87	0.93	S(1,7)	0.540	S(3,7)	0.400	S(6,7)	0.860
E7	0.63	0.73	0.83	S(1,8)	0.400	S(3,8)	0.260	S(6,8)	1.000
E8	0.81	0.87	0.93	S(1,9)	0.400	S(3,9)	0.260	S(6,9)	1.000
E9	0.81	0.87	0.93	S(1,10)	0.310	S(3,10)	0.170	S(6,10)	0.910
E10	0.92	0.96	1.00	S(2,3)	0.400	S(4,5)	0.770	S(7,8)	0.860
				S(2,4)	0.540	S(4,6)	0.400	S(7,9)	0.860
				S(2,5)	0.770	S(4,7)	0.540	S(7,10)	0.770
				S(2,6)	0.860	S(4,8)	0.360	S(8,9)	1.000
				S(2,7)	1.000	S(4,9)	0.400	S(8,10)	0.910
				S(2,8)	0.860	S(4,10)	0.310	S(9,10)	0.910

Table 13. Consensus coefficient (CC) findings

Expert No	CC
E1	0.093
E2	0.100
E3	0.092
E4	0.097
E5	0.083
E6	0.116
E7	0.087
E8	0.102
E9	0.120
E10	0.109

Table 14. The average and relative agreement values of experts

Expert No	Experts Average Agreement (AA)	Expert No	Experts Relative Agreement (RA)
E1	0.580	E1	0.089
E2	0.733	E2	0.113
E3	0.456	E3	0.070
E4	0.576	E4	0.089
E5	0.682	E5	0.105
E6	0.702	E6	0.108
E7	0.733	E7	0.113
E8	0.698	E8	0.108
E9	0.702	E9	0.108
E10	0.622	E10	0.096

Table 15. BE14 expert opinion values in the 'aggregation' stage

Aggregation of Basic Event14			BE14 Fuzzy Possibility Score(FPS)	BE14 Occurrence Probability Generation	Occurrence Probability	BE14 FV-I Index	BE14 FV-I Ranking
a_1	a_2	a_3					
0.560	0.641	0.721	0.641	1.90	1.265E-02	1.709E-07	10

Table 16. Fuzzy possibility values for basic events

BE No	Aggregation Results of Basic Events			Fuzzy Possibility Score (FPS)
	a_1	a_2	a_3	
BE1	0.920	0.960	1.000	0.960
BE2	0.722	0.801	0.881	0.801
BE3	0.425	0.534	0.644	0.534
BE4	0.240	0.330	0.420	0.330
BE5	0.248	0.341	0.435	0.341
BE6	0.402	0.500	0.598	0.500
BE7	0.134	0.202	0.269	0.202
BE8	0.468	0.581	0.694	0.580
BE9	0.472	0.574	0.675	0.574
BE10	0.379	0.482	0.586	0.482
BE11	0.782	0.849	0.916	0.849
BE12	0.908	0.950	0.992	0.950
BE13	0.690	0.775	0.860	0.775
BE14	0.560	0.641	0.721	0.641
BE15	0.505	0.608	0.712	0.608
BE16	0.754	0.826	0.898	0.826
BE17	0.538	0.638	0.737	0.638
BE18	0.669	0.759	0.848	0.759
BE19	0.625	0.723	0.820	0.723
BE20	0.035	0.085	0.135	0.085
BE21	0.529	0.618	0.707	0.618
BE22	0.481	0.565	0.648	0.565
BE23	0.060	0.120	0.179	0.120
BE24	0.732	0.804	0.876	0.804
BE25	0.026	0.073	0.121	0.073
BE26	0.271	0.369	0.467	0.369
BE27	0.008	0.050	0.092	0.050

Table 17. Calculations of fuzzy occurrence probability values of BEs

BE	Aggregated Fuzzy Numbers			Fuzzy occurrence Probability	Rank
	a_1	a_2	a_3		
BE1	0.920	0.960	1.000	1.593E-01	1
BE2	0.721	0.801	0.881	3.582E-02	6
BE3	0.425	0.534	0.644	6.340E-03	17
BE4	0.240	0.330	0.420	1.220E-03	22
BE5	0.248	0.341	0.435	1.363E-03	21
BE6	0.402	0.500	0.598	4.992E-03	18
BE7	0.134	0.202	0.269	2.286E-04	23
BE8	0.468	0.581	0.694	8.640E-03	14
BE9	0.472	0.574	0.675	8.231E-03	15
BE10	0.379	0.483	0.586	4.411E-03	19
BE11	0.782	0.849	0.916	5.076E-02	3
BE12	0.908	0.950	0.993	1.379E-01	2
BE13	0.690	0.775	0.860	2.996E-02	7
BE14	0.560	0.641	0.721	1.265E-02	10
BE15	0.505	0.608	0.712	1.031E-02	13
BE16	0.754	0.826	0.898	4.275E-02	4
BE17	0.539	0.638	0.737	1.242E-02	11
BE18	0.669	0.759	0.848	2.686E-02	8
BE19	0.625	0.723	0.820	2.128E-02	9
BE20	0.035	0.085	0.135	8.306E-06	25
BE21	0.529	0.618	0.707	1.097E-02	12
BE22	0.481	0.565	0.648	7.769E-03	16
BE23	0.060	0.120	0.179	3.337E-05	24
BE24	0.732	0.804	0.876	3.657E-02	5
BE25	0.026	0.073	0.120	4.330E-06	26
BE26	0.271	0.369	0.467	1.771E-03	20
BE27	0.008	0.050	0.092	7.312E-07	27

Table 18. Fuzzy occurrence probability and FV-I calculations for MCSs

MCs	Fuzzy occurrence Probability	FV-I Measure Index	Rank
BE1-BE12	2.197E+04	2.968E-01	1
BE1-BE11	8.087E+03	1.092E-01	2
BE1-BE16	6.811E+03	9.203E-02	3
BE1-BE24	5.827E+03	7.873E-02	4
BE2-BE12	4.940E+03	6.674E-02	5
BE1-BE13	4.773E+03	6.449E-02	6
BE1-BE18	4.280E+03	5.783E-02	7
BE1-BE19	3.391E+03	4.582E-02	8
BE1-BE14	2.016E+03	2.724E-02	9
BE1-BE17	1.978E+03	2.673E-02	10
BE2-BE11	1.818E+03	2.457E-02	11
BE1-BE21	1.748E+03	2.362E-02	12
BE1-BE15	1.642E+03	2.218E-02	13
BE2-BE16	1.532E+03	2.069E-02	14
BE2-BE24	1.310E+03	1.770E-02	15
BE1-BE22	1.238E+03	1.672E-02	16
BE8-BE12	1.191E+03	1.610E-02	17
BE9-BE12	1.135E+03	1.533E-02	18
BE2-BE13	1.073E+03	1.450E-02	19
BE2-BE18	9.623E+02	1.300E-02	20

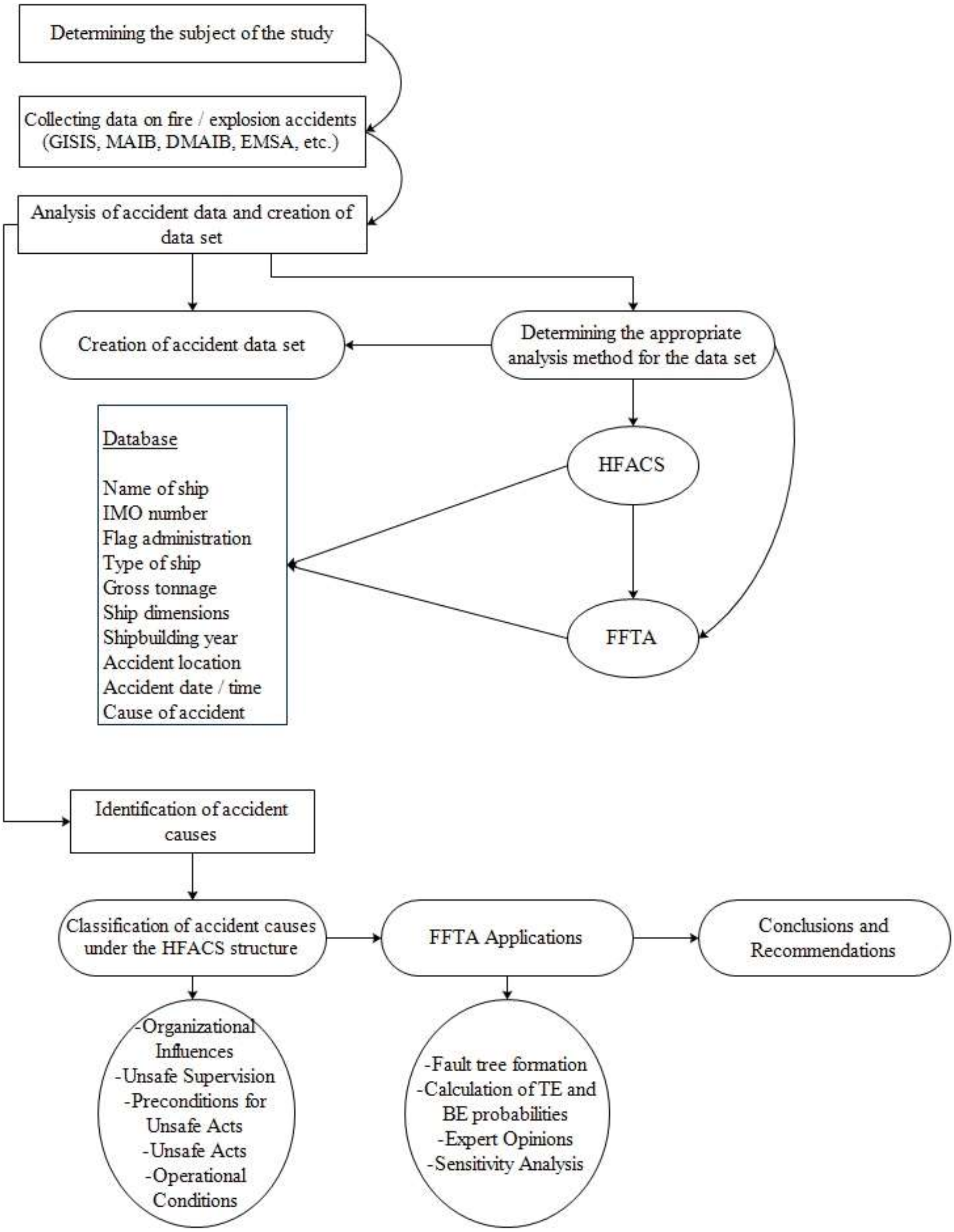


Figure 1. Flow chart of the study

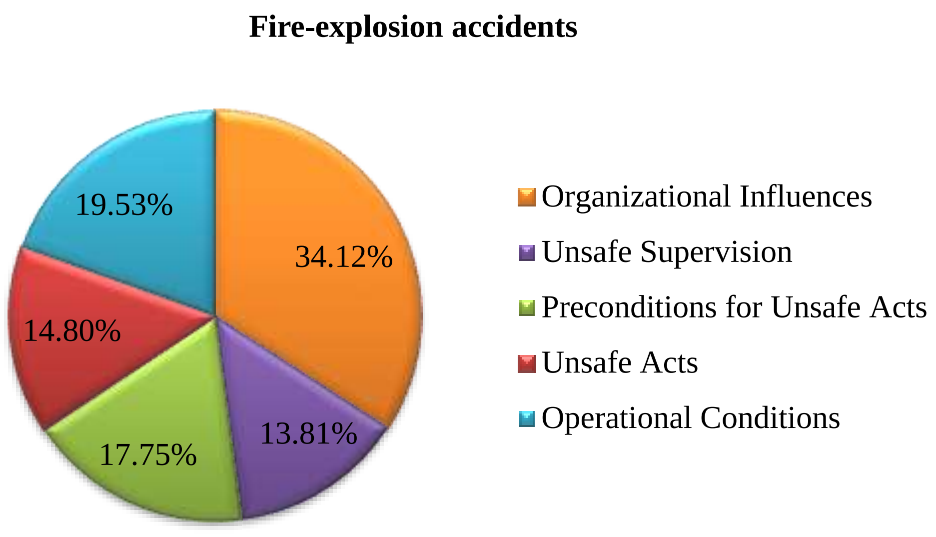


Figure 2. General distribution of factors according to the main levels of the HFACS

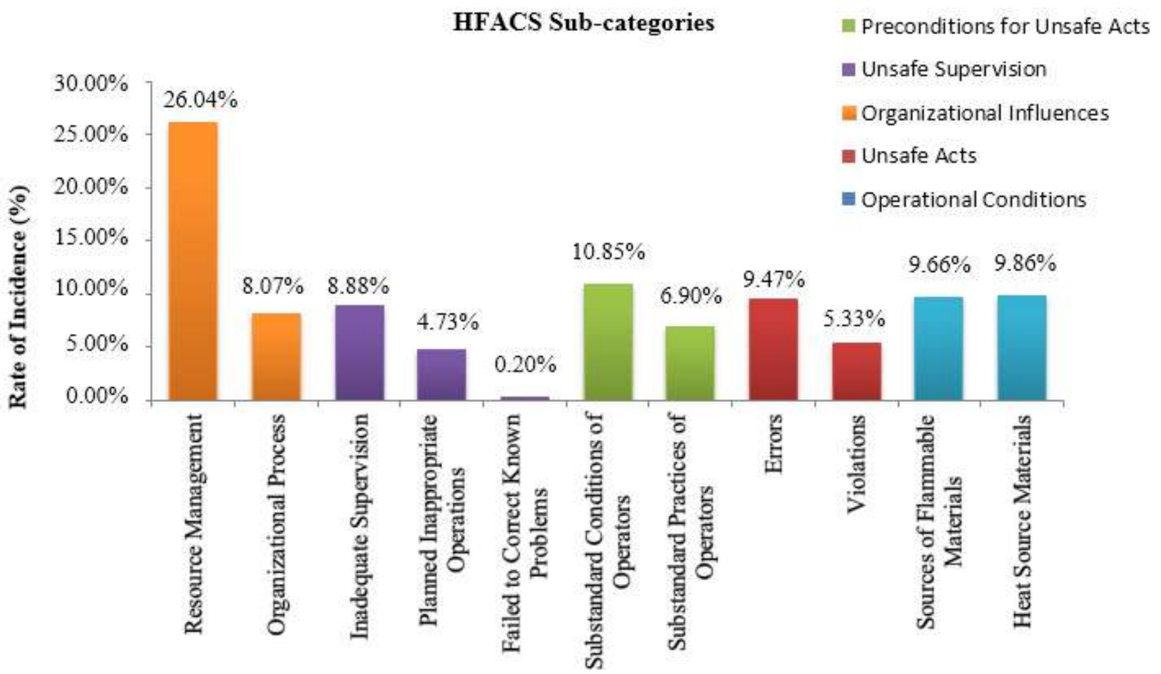
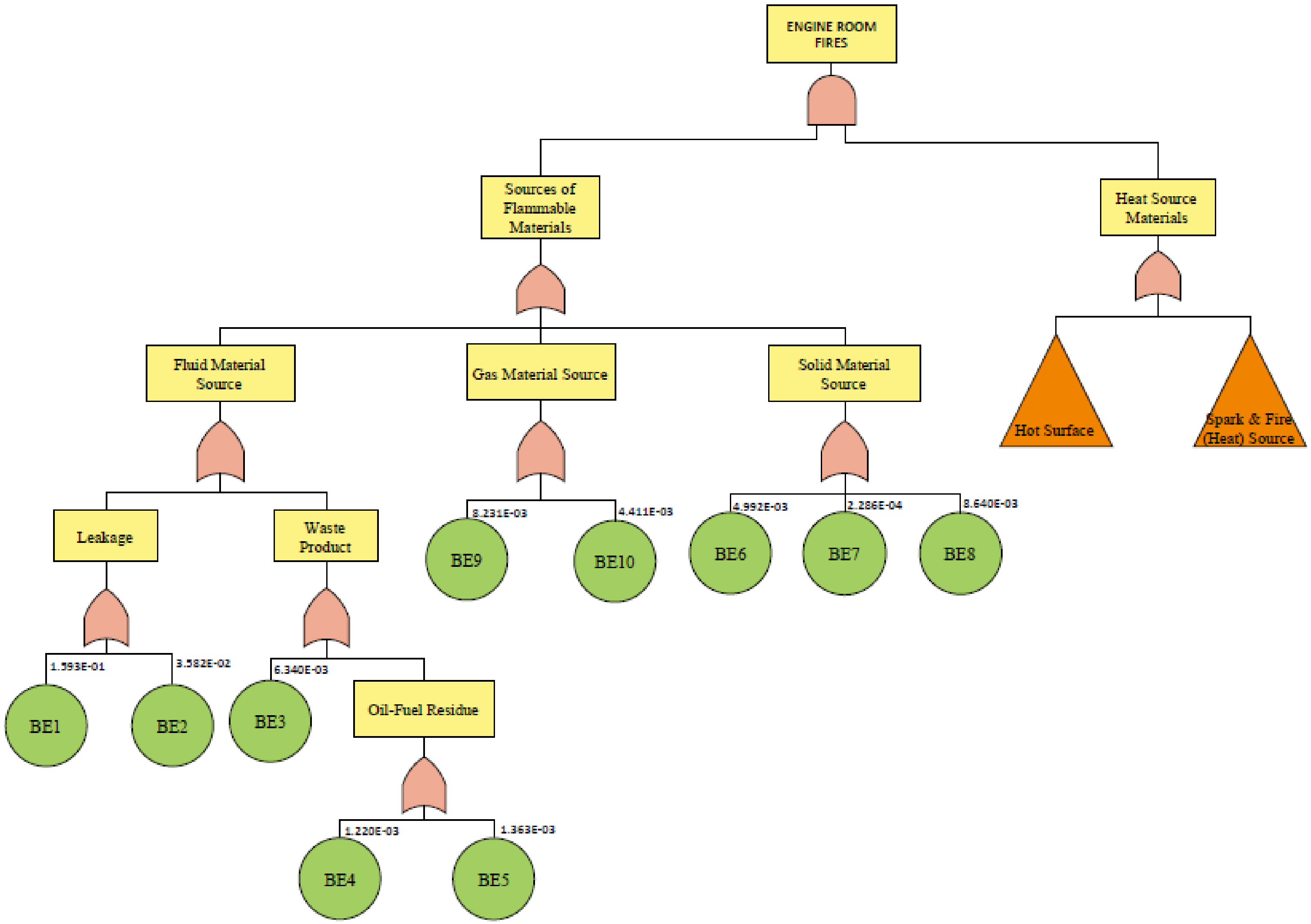
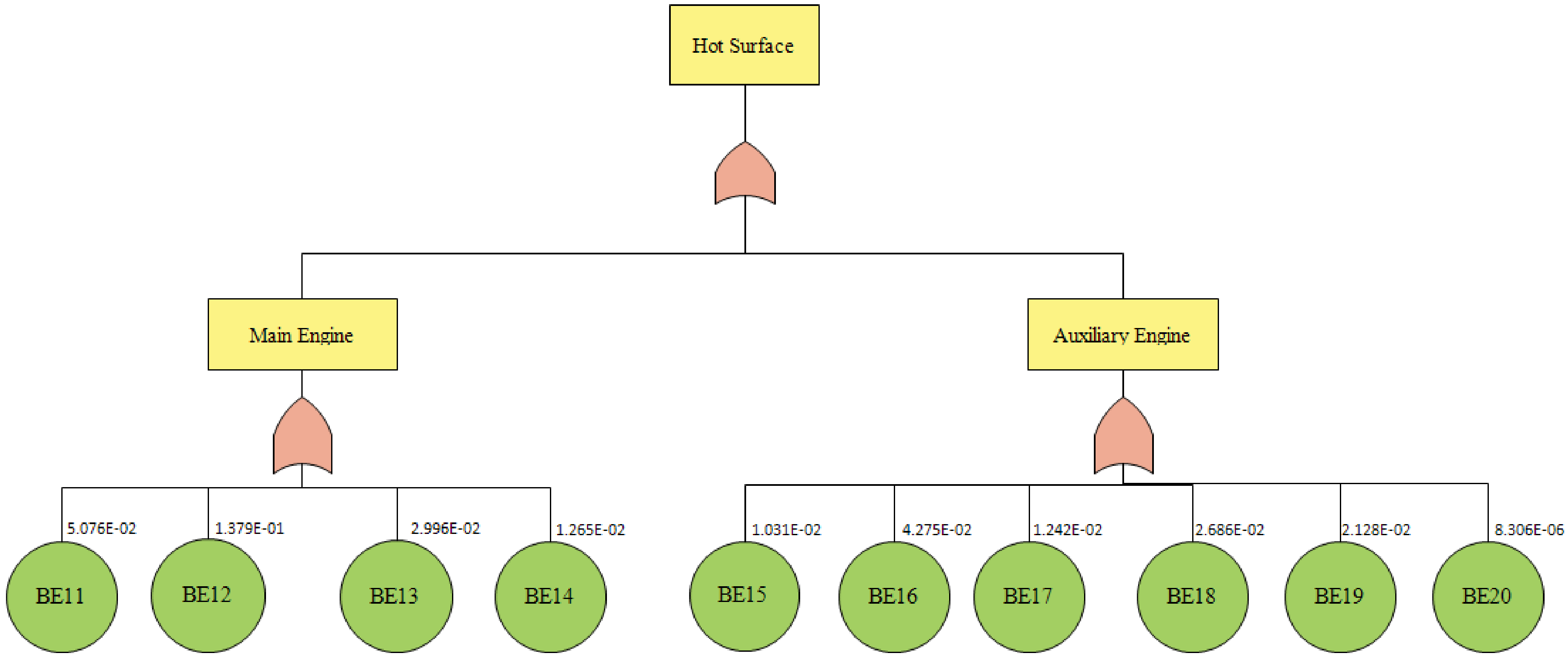


Figure 3. Distribution of fire-explosion accidents by HFACS sub-categories

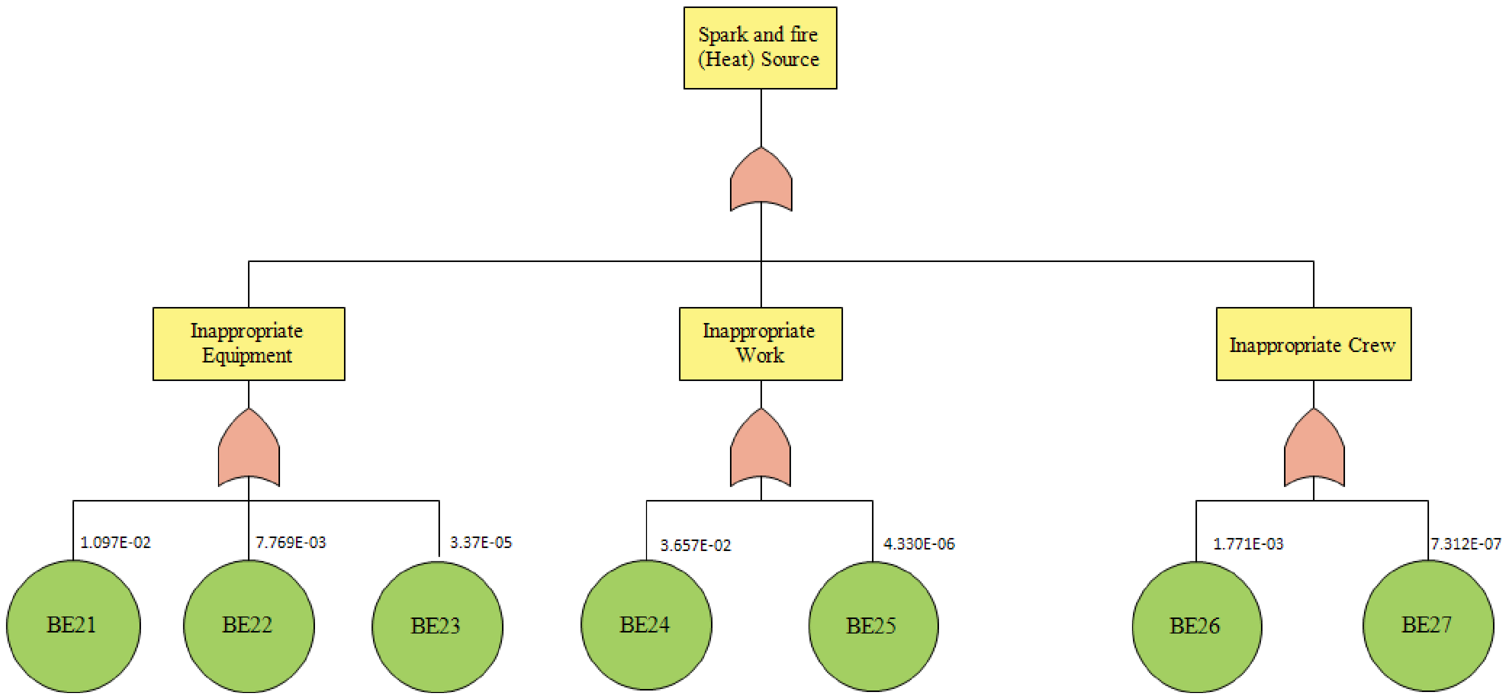


ENGINE ROOM FIRES
Sources of Flammable Materials
Heat Source Materials
Fluid Material Source
Gas Material Source
Solid Material Source
Hot Surface
Spark & Fire (Heat) Source
Leakage
Waste Product
8.231E-03
4.411E-03
4.992E-03
2.286E-04
8.640E-03
BE9
BE10
BE6
BE7
BE8
1.593E-01
3.582E-02
6.340E-03
BE1
BE2
BE3
Oil-Fuel Residue
1.220E-03
1.363E-03
BE4
BE5

a)


Hot Surface
Main Engine
Auxiliary Engine
5.076E-02
1.379E-01
2.996E-02
1.265E-02
1.031E-02
4.275E-02
1.242E-02
2.686E-02
2.128E-02
8.306E-06
BE11
BE12
BE13
BE14
BE15
BE16
BE17
BE18
BE19
BE20

b)



c)

Figure 4. a) Fault tree analysis structure of fire-explosion accidents, b) Flammable hot surfaces, and c) Sparks and heat sources