The evolution of the HFACS method used in analysis of marine accidents: a review

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ABSTRACT

The importance of accident investigations carried out in every field where operators play a vital role is increasingly recognised. Many researchers argue that understanding accident formation is the most important way to prevent future disasters. In this research, an analysis of the modified Human Factor Analysis and Classification System (HFACS) structures developed for use in the analysis of marine accidents was conducted. These structures include HFACS-PV (Passenger Vessels), HFACS-MA (Maritime Accidents), HFACS-Coll (Collisions), HFACS-SIBCI (ship collision accidents between assisted ships and icebreakers in ice-covered waters) and HFACS-Ground (Groundings). In this study, revisions in HFACS structures were examined. It was found that the accident factors were classified at different levels to facilitate the application of the original HFACS framework. The first of the remarkable differences among the basically developed methods is the level of external factors (first level), where the accident factors arising from national and international rules are classified. The second is the level of operational conditions (last level). It has been observed that the precondition for the unsafe acts level has been revised in all methods examined. This study will guide researchers in choosing an HFACS structure suitable for the area they will study, as well as revealing different aspects of the modified methods examined in marine accident analysis.

Keywords: HFACS, Marine accident, Accident analysis, Human factor

1. Introduction

Accidents are a combination of undesirable events that often lead to losses (Grabowski et al., 2007; Uğurlu et al., 2020a). They occur as a result of actions or omissions that are not intentional (Harrald et al., 1998). The effects of accidents vary from mild injuries to deaths, from environmental damages to significant financial losses (Mullai and Paulsson, 2011; Uğurlu et al., 2015a).

Transportation, which affects the development of the world economy, is considered one of the most important connections of international economic relations (Bulut and Yoshida, 2015). The most crucial part of commercial transportation is carried out by maritime transportation. It is observed that there is a growth in the volume of the world maritime transport fleet based on the increasing trade activities. This growth in the sea fleet indirectly causes an increase in marine accidents (Uğurlu, 2016).

Despite innovative safety measures and practices implemented by the maritime industry, marine accidents have a high potential for disasters (Hetherington et al., 2006; Uğurlu et al., 2015b). In addition, marine accidents adversely affect people, the marine environment and, activities on board and land (Arslan and Turan, 2009; Uğurlu et al., 2016). Today, despite many best practices implemented in ship operation, marine accidents still exist as an important phenomenon that must be dealt with. Not only are personal or financial losses experienced as a result of the accidents, but they also affect corporate business success and motivation.

The basis of maritime transportation is human. Human error is a wrongly made decision or action. Accidents occur as a result of improper actions of the human factor (Antão and Soares, 2008; Celik et al., 2010; Uğurlu et al., 2018). Understanding the human factors in accidents is the key in maritime transport (Macrae, 2009). In recent years, the shipping industry has aimed to increase efficiency and ensure maritime safety. Therefore, the concept of the human factor in maritime transportation has been a subject frequently mentioned within the scope of accident analysis (Uğurlu et al., 2015c; Akyuz, 2017; Yang et al., 2019).

Uğurlu et al. (2015b), stated that approximately 77-81% of sea losses are caused by human error, and if only one of these human errors does not occur, the chain of events will be broken and the accident will not occur. Hemmatian et al. (2014) revealed that human error is mainly seen in general maintenance activities. Baalisampang et al. (2018) observed that 43% of human errors in accidents were related to maintenance. Nippon Kaiji Kyokai (ClassNK) has categorized the factors regarding the occurrence of human error into human element, hardware factors, organization and management factors (ClassNK, 2011). Apostol-Mates and Barbu (2016), stated that human error is associated with technology, environment, organization, business practices and group. Therefore, it has become a critical situation to take necessary measures to examine, interpret and minimize human errors that are effective in marine accidents (Hetherington et al., 2006).

There are various systematic methods of accident analysis that have been used to examine and evaluate the human error factor so far. Table 1 illustrates other human factor analysis methods frequently used in the literature and descriptive information about them.

Table 1. Human factor analysis methods

2. Literature Review

It is crucially important that accident investigators choose the appropriate methods for their field of study. Most of the review studies of human factor analysis in the literature are related to the interaction of the methods, advantages, disadvantages and usage areas.

The study conducted by Kirwan (1996) for the comparison of Technique for Human Error Rate Prediction (THERP), Human Error Assessment and Reduction Technique (HEART) and Justification of Human Error Data Information (JHEDI) methods was one of the preliminary studies to examine the human factor analysis methods. This study introduces analysis methods and compares human reliability measurement methods. Another study by Kirwan (1997) made recommendations for developing these analysis methods and improving their use.

Hulme et al. (2019a) examined 73 studies of applying AcciMap, the Human Factors Analysis and Classification System (HFACS), the Systems Theoretic Accident Model and Process method including Causal Analysis based on (STAMP-CAST), and the Functional Resonance Analysis Model (FRAM) between 1990 and 2018. They indicated that these methods were used together with analytical techniques such as Chi-square, Bayesian Network, and Fuzzy AHP (Analytic Hierarchy Process) in most of the studies examined. Furthermore, in the study, recommendations were made regarding the necessity of developing accident reporting systems and new accident analysis approaches. They emphasized that the HFACS method is one of the most widely used reliable analysis methods for human factor analysis.

Salehi et al. (2021) reviewed 52 studies of using the FRAM method published between 2010 and 2020. Their study shows that the FRAM method is mainly used in the health sector. They found that the mixed data collection method such as interview through a focus group was used in 52% of the studies. They evaluated the shortcomings of FRAM in their studies and stated that additional methods should be used to assist researchers who will use the method.

Hulme et al. (2019b) reviewed 43 studies of using the HFACS analysis method in different fields. They found that the HFACS method is widely used in the airway, railway and maritime transportation sectors. They stated that in more than 60% of the studies examined, the

HFACS method was used by modifying it. The rationale for the modification is the adaptation of HFACS to the area in which it is used and a clearer understanding of the structure.

Salmon et al. (2020) reviewed 23 studies of using the AcciMap analysis method. In each of the studies, it was aimed to create a typical AcciMap diagram by determining the factors defined within the framework of AcciMap analysis and the interrelationships of the factors. Therefore, the causes of accidents obtained from the studies were coded according to the thematic classification scheme. The resulting AcciMap contains 79 distinct contributory factor types covering 5587 accident causes. They recommended using the AcciMap method developed to identify and classify contributing factors to accidents.

The need to investigate the effect of the human factor on the realization of accidents has become more noticeable day by day (Liu et al., 2018). Unfavourable situations such as the inability of people to adapt to technological applications and being affected by the conditions they are in bring with accidents. Over time, accident researchers needed a reliable human factor analysis method to determine human errors and the relationships between them.

HFACS is a reliable and comprehensive method within the scope of accident analysis (Hsieh et al., 2018; Illankoon et al., 2019). It enables in-depth analysis of accidents and reveals all the causes of accidents at each level. Therefore, HFACS has become a rising trend in accident investigations for the last decade (Omole and Walker 2015; Liu et al., 2019). The HFACS method has been effectively used by the researchers because it could be used together with different techniques, enabling qualitative and quantitative analysis, and providing a detailed analysis of the accidents. In this study, the keywords "accident, maritime and human factor" were scanned in databases (PubMed, Scopus, ScienceDirect and Web of Science) to examine the studies conducted within the scope of human factor analysis, and a total of 72 studies were listed. It was observed that the HFACS method was used in 15 of the listed studies. In this study, maritime modifications of the HFACS method have been examined.

2. Methodology

In this study, modified HFACS methods developed for use in the analysis of marine accidents were examined. The study consists of 4 stages:

In the first stage of the study, information was given about the content of the main HFACS framework put forward by Wiegmann and Shappell (2003). In the second stage, the methods developed by revising the main HFACS framework were introduced. These include HFACS-PV (Passenger Vessels), HFACS-MA (Maritime Accidents), HFACS-Coll (Collisions), HFACS-SIBCI (ship collision accidents between assisted ships and icebreakers in ice-covered waters) and HFACS-Ground (Groundings). At this stage, the general features, development methods, differences and nonconformity examples of the frameworks were examined.

In the third stage of the study, the categories and sub-categories within all modified HFACS frameworks were tabulated and coded under 8 main headings. In this step, firstly, accident factors in the main frameworks were examined and the distinguishing features of the frameworks were compared. Then, the causes of accidents (nonconformities) were detailed for each HFACS level and the coding was applied by referring to the tables produced in the first step of this stage. The causes of the accident are based on data from the modified HFACS frameworks examined (HFACS-PV: 70 accidents, HFACS-MA: 1 accident, HFACS-Coll: 27 accidents, HFACS-SIBCI: 17 accidents, HFACS-Ground: 115 accidents). In this study, a total of 949 nonconformities (accident causes), including modified HFACS frameworks, were examined and tabulated. The aim of this stage is to reveal different-similar aspects of the classifications made in HFACS categories and to interpret the different perspectives of the researchers. This study was conducted to guide researchers about the content of modified HFACS frameworks introduced in maritime transportation. Through this study, researchers will be able to choose an HFACS framework that is most suitable in the marine accident analysis being conducted.

3. HFACS

HFACS is a comprehensive analysis method designed to analyse the underlying causes of human error (Wiegmann and Shappell, 2003; Shappell et al., 2007). In the Swiss Cheese Model (Reason, 1990), which forms the basis of the original HFACS framework, the factors that cause an accident are divided into two groups as latent factors and active failures. These two groups are divided into four sub-levels (Reason, 2016). The first three levels (pre-conditions for unsafe acts, unsafe supervision and organizational influences) represent latent factors while the last level (Unsafe acts) represents active failures. This model argues that latent factors are effective in the formation of active failures.

HFACS was first used by Shappell and Wiegmann (2000) for the analysis of aviation accidents. HFACS is a proven method for identifying human errors and enables the examination of accident occurrences in a hierarchical structure. It has been used for accident analysis in the analysis of civil and military aviation accidents (Shappell and Wiegman, 2001; Wiegmann and Shappell, 2003; Shappell and Wiegmann, 2004; Dambier and Hinkelbein, 2006; Omole and Walker 2015) in maritime transport (Chen et al., 2013), rail transport (Baysari et al., 2008), mining industry (Patterson and Shappell, 2010; Lenne et al., 2012; Liu et al., 2018), oil and gas industry (Theophilus et al., 2017; Zhang et al., 2020), medical and health sciences (Judy et al., 2019) and many other fields. With this method, it is possible to systematically examine the effects of human factors on accidents and to identify sub-causes. The most important feature that distinguishes HFACS from other accident causality methods is its ability to define the role of administrative and organizational factors in complex systems such as accident occurrences (Wiegmann and Shappell, 2003; Ergai et al., 2016; Uğurlu et al., 2018). Another advantage of the HFACS hierarchical structure is that it provides accurate identification and correlation of factors related to human error in accidents (Chauvin et al., 2013; Akhtar and Utne, 2014; Uğurlu et al., 2018). In addition to this advantage, HFACS makes it possible to analyse complicated systematic causes (Jiang and Han, 2018). HFACS does not require expert opinion on the classification of accident causes and causal factors. Therefore, researchers who master the main structure and infrastructure can gradually reveal the occurrence of accidents (Uğurlu et al., 2018). Explanatory information about original HFACS levels is given below (Figure 1).

Figure 1. The overview of the HFACS framework (Wiegmann and Shappell, 2003)

1. Level (Organizational Influences): It includes negative situations such as weak and faulty organizational framework and lack of team culture. These situations may not be an accident factor alone, but they prepare the ground for the occurrence of accidents. It is often described as the most challenging latent factors to detect (Wiegmann and Shappell, 2003; Shappell et al., 2007). This level is divided into three sub-categories: Resource management, organizational climate and organizational process.

i- Resource management: Resource management covers the processes related to the management, allocation and maintenance of organizational resources. It is defined as the erroneous behaviours made in corporate decisions regarding the proper management of human, equipment and budget resources. Factors such as inappropriate crew assignment, lack of personnel training, insufficient equipment, and design flaws can be given as examples of this category.

ii- Organizational climate: Organizational climate refers to the working environment of the organization. It is defined as the changes that occur within the organization and affect the individual's performance. Factors such as chain of command, authority and responsibility, recruitment, dismissal, promotion, use of drugs and alcohol are examples of this category.

iii- Organizational process: Organizational process covers formal processes, methods and oversight issues within the organization. Each of the shortcomings in top management and decisions indirectly negatively affects team members' performance and system security. It includes process components such as working commitment, time pressure, incentive systems, watchkeeping systems, creation of safety programs, performance standards, creation of company procedures and instructions.

2. Level (Unsafe Supervision): This is the level where nonconformities arising as a result of inadequate or inappropriate audits are defined. Unsafe supervision is examined under four sub-categories: Inadequate supervision, planned inappropriate operations, failure to correct known problems and supervisory violations (Wiegmann and Shappell, 2003; Shappell, et. al., 2007; Patterson and Shappell, 2010; Chauvin et al., 2013).

i- Inadequate supervision: It refers to failures arising from the control chain of command. The aim of the supervision is to ensure success in the process that operates within the existing system. Therefore, team members are required to receive appropriate guidance, adequate training, oversight and operational leadership. In the absence of these factors, risk increase and failure related to the operations is inevitable. Oversight failures, failure in performance monitoring and failure to provide training are typical examples.

ii- Planned inappropriate operations: It is a situation where a pre-planned operation is faced with an unpredictable risk due to deficiencies in the planning process. Factors such as improper matching of crew members, lack of proper rest time for the crew, and failure to manage emergencies operations can be given as examples.

iii- Failure to correct known problems**:** It is expressed as the fact that the existing deficiencies or inappropriate situations associated with individuals, equipment, training, *etc*. are known by the manager, but corrective or preventive action is not taken. Failure to correct the problem in documents, failure to initiate corrective action and failure to determine the risk are typical examples of such incompatibilities.

iv- Supervisory violations: These are violations by the supervisor mechanism. It is the intentional violation of rules, regulations, instructions or procedures by administrators. Ignoring the rules by administrators can also cause employees to violate the rules. Allowing unauthorized personnel to flight, accepting unnecessary dangers are examples of such non-compliances.

3. Level (Pre-conditions for Unsafe Acts): It is the mental-physical conditions and inappropriate practices of operators that cause the emergence of unsafe actions. This level is divided into three sub-categories: Environmental factors, conditions of operators and personnel factors.

i- Environmental factors: It is defined as environmental conditions that adversely affect the performance of operators. It is examined under two sub-categories as the physical and technological environment.

- ***Physical environment:*** It is expressed as the operational external environment and conditions of the working environment. Factors such as weather, altitude, temperature, noise, vibration and lighting can be given as examples.

- ***Technological environment***: It is the technological environment that has an impact on the performance of operators. Examples include the design of equipment and control units, display/interface features, checklist layouts, and automation.

ii- Conditions of operators: It is expressed as mental conditions that negatively affect the performance of the individual. Conditions of operators are examined under three sub-titles: Adverse mental states, adverse physiological states and physical and mental limitations. Factors such as lack of situational awareness, mental fatigue, stress, extreme self-confidence, relaxation and motivation are a few examples.

- **Adverse mental states:** It is defined as medical or physiological conditions that are equally important with adverse mental states and negatively affect performance. Conditions such as illness, drunkenness, intoxication, physical fatigue, insomnia and side effects of the drugs used are typical examples.

- **Adverse physiological states:** It refers to the fact that individuals do not have the necessary talent, skills and time to manage the current situation. These factors include mental ability, visual limitations, insufficient reaction time, learning ability, memory capacity, and lack of general knowledge.

- **Physical /mental limitations:** It is expressed as confusion and incorrect decisions due to lack of coordination among team members. These are insufficient situations that go beyond routine practices. This category is examined under two headings: Crew resource management and personal readiness.

iii- Personnel factors: It is expressed as confusion and wrong decisions made due to a lack of coordination among team members. They are inadequate situations that go beyond routine practices. The crew is studied under two categories: Resource management and personal preparation.

- ***Crew resource management*:** It is expressed as the failure of team members to act in harmony as a team. It covers the nonconformities caused by the lack of effective communication between the team members. Ineffective and inadequate communication, inadequate information and inadequate team management are examples of these situations.

- ***Personal readiness:*** It is defined as off-duty activities that prevent team members from working efficiently. Alcohol use, taking medications, inadequate rest, and doing activities that may cause physical and mental fatigue are examples.

4. Level (Unsafe Acts): It is defined as actions by individuals or operators that directly lead to an accident (pilot, co-pilot, air traffic controller, *etc*.). Unsafe acts are divided into two categories as errors and violations.

i- Errors: Errors are actions that are carried out unintentionally and may cause an accident. Errors are analyzed in three sub-categories: Decision errors, skill-based errors and perceptual errors.

- ***Decision errors:*** They cover inappropriate and insufficient decisions of the operators and mistakes they make while making decisions. They are inadequate or inappropriate selections made by operators (pilots) during any planning activities. This group, also called "honest errors", can be exemplified by lack or poor implementation of methods and procedures, wrong choices of operators, making improper decisions, misinterpretation or misuse of information (overloading, not checking fuel level indicators and not asking for a forecast before flight, *etc*.).
- ***Skill-based errors:*** They can be defined as errors made in situations that do not require any state of consciousness or thought, that is, constantly experienced. These errors occur mostly in practical or routine practices related to the procedure, training or qualification. They include skill-based errors associated with professional experience and tendency. Errors such as unsuccessful lookout, turning the wrong button or buttons on and off, and skipping some steps in routine operations are examples of this group.
- ***Perceptual errors:*** These errors usually occur at night, in bad weather conditions and in environments that weaken the sense of vision, that is, when the sensory inputs are impaired. In the direction of the wrong or incomplete information obtained, they can be expressed as situations where the aircraft crew responds incorrectly to various visual and audio illusions. Examples of this include the incorrect feedback given due to miscalculated distance, and altitude or visual errors.

ii- Violations: They are actions that are intentionally made against rules and regulations. They are divided into two sub-categories: Routine and exceptional violations.

- ***Routine violations:*** It can be defined as the situation in which rules and procedures that have become habits are ignored over time and not applied by individuals. They are violations known and often tolerated by the organization or authority. Such violations, which are also referred to as flexing the rules, are generally carried out by the personnel working under the managers who violate the rules. Steps skipped in the departure-arrival checklists, flying with extreme manoeuvres and pilots flying in adverse weather conditions are examples of such violations.

- ***Exceptional violations:*** Violations made in unusual circumstances. The situation that makes exceptional violations unusual is that they occur outside of rules and laws. These are situations that are not tolerated by managers and not permitted by law. Flying in forbidden airways and passing under a bridge by plane are examples of such violations.

4. Use of HFACS in the Marine Sector

It is emphasized by many accident researchers that human and organizational factors play a role in the occurrence of marine accidents (Hetherington et al., 2006; Chauvin et al., 2013; Ugurlu et al., 2013). Human error and organizational factors contain many uncertainties (Qiao et al., 2020). Therefore, many researchers in the maritime sector have adopted HFACS based on the systematic analysis framework that has been put forward in order to eliminate the uncertainty in human factors. HFACS has undergone several changes depending on the field of study and the needs of the researchers. Although the basic framework is kept constant by most researchers, various sub-categories related to the study area have been added and some categories have been adapted. The first use of HFACS in the investigation of marine accidents was proposed by Rothblum (2002). Over the last decade, it has also been used by various researchers to investigate accidents in the maritime industry (Uğurlu et al., 2020b). Celik and Cebi (2009) have developed an analytical HFACS method based on the Fuzzy Analytical Hierarchy Process for use in the analysis of marine accidents. Schröder-Hinrichs et al. (2011) proposed the HFACS-MSS (for machinery spaces on ships) method for the analysis of fire-explosion accidents occurring in the engine rooms of ships. Chauvin et al. (2013) developed the HFACS-Coll framework by modifying the main HFACS framework for the analysis of collision accidents at sea. Akyuz and Celik (2014) formed the HFACS-CM framework by integrating the Cognitive Map (CM) approach and HFACS to evaluate human factors that are effective in marine accidents. Table 2 shows the modified HFACS frameworks examined in this study.

Table 2. An overview of HFACS methods related to maritime safety

4.1. HFACS-Coll

The method was developed by Chauvin et al. (2013) for the analysis of collision accidents. It was created with reference to 27 collision accidents (230 Nonconformities). They defined HFACS-Coll as a method that provides systemic and multi-factor analysis of accidents. Unlike the original HFACS structure developed by Wiegmann and Shappell (2003), it includes modifications at the pre-conditions for unsafe act level (Figure 2). In addition, the outside factors level was added to the main framework by taking the HFACS-MI (Mining Industry) structure as a reference (Patterson and Shappell, 2010). Revisions on the framework are shown in red. The method consists of 5 levels and 14 sub-categories. The following is a description of the distinguishing features of the framework that are not included in the classical HFACS framework.

Figure 2. The overview of the HFACS-Coll framework

4.1.1. Revisions Included by HFACS-Coll

4.1.1.1. Outside Factors

It is defined as the first level of HFACS-Coll, aiming to analyse the impact of external factors in the occurrence of an accident. This level is divided into two sub-categories: Regulatory factors and others. Regulatory factors include organizing factors such as COLREG (Convention on the International Regulations for Preventing the Collusions), ISM (International Safety Management Code) and STCW (Standards of Training Certification and Watchkeeping) in the maritime industry. Others are the rules set by official or civil regional authorities outside the vessel such as VTS (Vessel Traffic Service) stations, harbour masters and pilotage organisations.

4.1.1.2. Pre-conditions for Unsafe Acts

This level is separated from the original HFACS structure with the revision made in the personnel factors category. The personnel factors category is divided into two as ship resources mismanagement and personnel readiness. The ship resources mismanagement sub-category includes nonconformities such as crew members not working together properly and ship internal-external communication errors (pilot-pilot, pilot-bridge crew and mobile phone usage between pilots, *etc*.). The personnel readiness sub-category is expressed as the one in the original HFACS structure.

4.2. HFACS-MA

Chen et al. (2013) created the HFACS-MA with reference to the Herald of Free Enterprise accident and the IMO (International Maritime Organization) accident investigation guidelines. As a result of the investigation of the accident, 27 nonconformities were found. The features that distinguish HFACS-MA from other human factor analysis and classification systems are that it can be listed as meeting the IMO guidelines, defining human factors in maritime accidents, and is based on the HOF (Human and Organization) framework. In HFACS-MA, unlike the original HFACS structure, the pre-condition for unsafe act and unsafe act levels have been modified. In addition, the level of external factors was developed by taking the HFACS-MI structure as a reference (Patterson and Shappell 2010). The proposed HFACS-MA framework contains 16 sub-categories at 5 levels (Figure 3).

Figure 3. The overview of the HFACS-MA framework

4.2.1. Revisions Included in HFACS-MA

4.2.1.1. Unsafe Acts

This level differs from the original HFACS framework with the revision made in the errors category. Sub-categories that differ from the original structure are rules-based errors and knowledge-based errors. The researchers stated the reason for this change that the framework was created with reference to the IMO guidelines. The IMO guidelines refer to the Generic Error Modelling System (GEMS) to identify errors. Errors in this framework are divided into 3 sub-categories: Rules-based errors, knowledge-based errors and skill-based errors. Rules-based errors classify the factors resulting from the action not being in accordance with the rules. In the knowledge-based errors sub-category, when the problem-solving routines of the individuals are exhausted, the errors caused by unconscious action are categorized. Skill-based errors include the factors that result from memory, attention and technical deficiencies.

4.2.1.2. Pre-conditions (SHELL)

HFACS-MA is significantly different from the original HFACS framework due to the adoption of the SHELL (Software, Hardware, Environment, Liveware and Liveware/Human) model at the level of pre-conditions for unsafe acts. In HFACS-MA, the SHELL model has been used to identify incompatibilities between the human and workspaces in the work system. The categories recommended for this level are: Condition of operator (mental and physical limitations), software (non-physical part of the system), hardware (physical parts of the workplace), environment (weather and sea conditions, positional constraints) and liveware (human-human relations). In this way, the researchers stated that they provide a clear method for distinguishing pre-conditions, management and organizational factors as well as fulfilling the requirements of the IMO guidelines (IMO, 2000; Chen et al., 2013).

4.2.1.3. External Factors

It is the first levels of HFACS-MA and prepares the source for the formation of nonconformities at the organizational influences level. This level consists of three sub-categories: Legislation gap, administration oversight and design flows. Legislation gap is a sub-title that classifies the shortcomings of existing rules and laws that guide the shipping industry. In the administration oversight sub-category, possible deficiencies made by the administration authorities during the implementation of the rules and codes are classified. In addition, the deficiencies that the management made during the fulfilment of its duties are examined under this sub-category. Under design flows, incompatibilities related to ergonomics and the design of system components are classified.

4.3. HFACS- Ground

Mazaheri et al. (2015) have created the HFACS-Ground method for the investigation of grounding accidents. The method was created with reference to the main HFACS-Coll framework and 115 grounding accidents (147 nonconformities). Outside factor and pre-condition for unsafe act levels have been modified in the HFACS main structure, as in HFACS-Coll. The model consists of 5 levels and 14 categories (Figure 4). In the following, the distinctive features of the framework, which differ from the original HFACS framework, are described.

Figure 4. The overview of the HFACS-Ground framework

4.3.1. Revisions Included by HFACS-Ground

4.3.1.1. Outside Factors

It is the first level of HFACS-Ground. This sub-category was created with reference to the HFACS-Coll and HFACS-MI frameworks (Patterson and Shappell, 2010; Chauvin et al., 2013). It aims to analyze the effect of external factors on accident occurrence.

4.3.1.2. Preconditions for Unsafe Acts

The categories of personnel factors, environmental factors and operator conditions differ from the original HFACS framework. In the category of personnel factors, personnel's individual preparation sub-framework remained the same, BRM (Bridge Resource Management), and coordination/communication planning subframes were added. In the sub-category of the conditions of the modified operator, in addition to the main framework of HFACS, accident factors were examined in 5 sub-categories adding cognitive factors, behavioural factors and perceptual factors (Figure 4). In the environmental factors category, it was modified by adding an "infrastructure" sub-framework.

4.4. HFACS- SIBCI

It is a method developed by Zhang et al. (2019) to analyse collision accidents that occur on the icebreaker ships. The HFACS-Ship-Icebreaker Collision in Ice-covered waters (HFACS-SIBCI) method is proposed to identify and classify conflict risk factors during icebreaker aid in icy waters. It was created with reference to 17 collisions accidents (28 nonconformities) between 1989 and 2017. The proposed HFACS-SIBCI method consists of 5 levels and 17 sub-categories (Figure 5). The main HFACS framework includes external factors added at the first level and modified pre-conditions for unsafe acts and unsafe act levels. The descriptions of the levels added and modified in HFACS- SIBCI are as follows.

Figure 5. The overview of the HFACS-SIBCI framework

4.4.1. Revisions Included by HFACS- SIBCI

Unlike the original HFACS structure, the external factors were added as the first level, and organizational influences and pre-condition for unsafe act levels were modified. The descriptions of the modified and added levels in the HFACS-SIBCI are as follows.

4.4.1.1. External Factors

While creating the external factors level, the HFACS-MA was taken into account, and, unlike this structure, the social factors subframe was added (Zhang et al., 2019). It is divided into 4 subcategories as legislation gaps, administration oversights, design flaws and social factors. Legislation gaps express the incompatibilities caused by deficiencies in the regulations and policies and differences between the countries prepared for the ships sailing in icy waters. Russia (Sailing Directions of Russia), Finland (Finnish Transport Agency), Canada (Transport Canada), and China (Guidance on Arctic Navigation in the Northeast Route) have different arctic navigation rules. This can affect icebreaker assistance operations, resulting in poor management and the unsafe acts of operators. Administrative oversights include the erroneous behaviour and negligence of icebreaker services, ship management companies or ship officers during the implementation phase of the rules. Design flaws are defined as defective design of the icebreaking or navigational vessel. Social factors include deficiencies in economic, political, legal, safety culture and other social-environmental factors.

4.4.1.2. Organizational Influences

This level consists of 4 sub-categories different from the original HFACS framework. The emergency process sub-category added to this level refers to the emergency process that will occur during icebreaker operations. In this sub-category, the requirements for emergency training are defined for the icebreaker and other ship crew members on the escort. It covers situations such as the absence of an effective emergency procedure to reduce the risks of collision and damage caused by collision.

4.4.1.3. Pre-conditions for Unsafe Acts

This level has been modified, taking into account the HFACS-Ground. Condition of operators and personal factors categories were revised difference from the original HFACS framework. Condition of operators, cognitive factors, perceptual factors, psycho-behavioural factors, adverse physiological states are divided into sub-classes. Cognitive factors include factors that lead to unsafe conditions such as misperception of the characteristics of the icebreaker operation, the decision or behaviour of the vessel and icebreaker crew. Perceptual factors are unsafe situations caused by misunderstanding or misjudgement. Psycho-behavioural factors include crew characters, psychological problems, psychological barriers, or risk factors such as inappropriate motivation. Adverse physiological states include negative physical conditions similar to the main framework (physiological events that cause poor performance, such as lack of sleep and dizziness caused by ice-covered conditions).

Personal factors are divided into coordination-communication planning, personal readiness, and ship resource mismanagement sub-categories. Coordination-communication planning indicates deficiencies encountered in communication. It represents the ineffective communication between the icebreaker and the vessel due to language barriers, misunderstandings and disagreements. These risk factors have been shown to affect aid operations and emergency operations. Personal readiness represents factors related to human behaviour and decisions, similar to the main framework. Ship resource mismanagement is defined as an insecure situation caused by incomplete or erroneous decisions made by the icebreaker or vessel crew regarding the use of the equipment.

4.5. HFACS-PV

The HFACS-PV model was developed by (Uğurlu et al., 2018) for the analysis and classification of passenger ship accidents. It was created by referring to 70 vessel accidents (570 nonconformities) from 22 accident investigation organizations. This model consists of 5 levels and 12 sub-categories. The difference between the HFACS-PV framework and other methods is that it takes into account the characteristics of accidents occurring on the passenger ship. The differences exist both at the main level and in the associated sub-categories. The most important difference that distinguishes the method from the original HFACS framework is that it contains the level of operational conditions at the final level. Even if all the necessary factors for the accident come together, it is stated that the accident will not occur in the absence of an operational condition (Sarıalioğlu et al., 2020; Uğurlu et al., 2020b; Yıldız et al., 2021). The other modified HFACS levels are pre-condition for unsafe acts and unsafe acts (Figure 6).

Figure 6. The overview of the HFACS-PV framework

4.5.1. Revisions Included by HFACS-PV

4.5.1.1. Precondition for Unsafe Acts

Unlike the original HFACS method, this level is subdivided into sub-standard team members, and technology and interface failures. The substandard team members category includes accident factors from team members' inappropriate management activities and personal situations. This category combines two categories in the main HFACS framework under one group. The term operator has been updated as team members. Substandard team members are divided into two as substandard conditions of team members and substandard practices of team members. The reason for this modification is to emphasize that during the accident analysis, it is necessary to focus on the substandard conditions and practices of all crew members on board, not just the captain. The substandard conditions of the team members category is divided into three sub-categories: Adverse mental conditions, adverse physical conditions, and physical and mental conditions. This category generally covers incompatibilities such as lack of situational awareness, fatigue, insomnia and stress. The substandard practices of the team members category is divided into two as readiness for operation and bridge team management. This category, which is located in the main framework of HFACS as the sub-standard applications of operators, has been applied to passenger ship accidents without any change in the framework.

On the other hand, technology and interface failures are the categories in which the accident factors are classified as hardware and software failures, and defects in vessel systems. This category does not exist in the original HFACS framework (Wiegmann and Shappell, 2003; Shappell et al., 2007) and is divided into 3 subclasses. These are electronic navigation aids malfunctions, interface malfunctions and other technological malfunctions. In general, this category is defined as failures of devices such as GPS (Global Positioning System), AIS (Automatic Identification System), Radar, and electronic interface.

4.5.1.2. Unsafe Acts

This level contains revisions in the sub-category of violations. Violations are divided into three sub-classes: Rules, procedures and abuse of authority. Rule violations are related to deliberate negligence or non-enforcement of legal regulations issued by the IMO, flag states or competent authorities. Procedure violations are violations of internal rules of shipping companies. Abuse of authority is defined as deliberate violations.

4.5.1.3. Operational Conditions

Uğurlu et al. (2018) found that operational conditions (environmental factors) played an important role in most of the accidents they examined. For this reason, they aimed to reveal the role of operational conditions in accident formation in detail in their study (Uğurlu et al., 2020b). The factors under the human condition structure related to human error in the HFACS framework differ from the factors at other levels. Operational conditions include uncontrollable or partially controllable factors. As a result of the study, the researchers stated that accidents can be prevented by considering these factors in the decision-making process (Uğurlu et al., 2018).

Operational conditions according to HFACS-PV represent the final stage of the occurrence of a marine accident. It plays a role as a complementary element for unsafe action resulting in an accident. It is argued that every vessel accident involves at least one operational condition. This category is divided into two sub-categories, internal and external conditions. Internal conditions include factors related to ship structure and accident factors that affect ship movement and are partially controlled by operators. This sub-category is divided into two sub-classes: Nonconformities and failures preventing ship motion, and vessel structural defect. External conditions include natural conditions and non-ship factors that are not related to the ship's structure or not arising from human contribution and intervention. This sub-category is also divided into two sub-categories: Weather conditions and local restrictions.

5. An Overview of the Methods

The importance of accident investigations carried out in every field where humans are effective is increasing day by day. Many researchers argue that understanding accident occurrence is the most important way to prevent future disasters (Chen et al., 2013; Uğurlu et al., 2020b). Therefore, it has become crucial to understand the human reactions and behaviours in the chain of accident occurrence. The original HFACS framework has been developed for use in the analysis of aviation accidents. In this study, an analysis of modified HFACS methods was carried out. When the studies in the literature are examined, it is seen that the HFACS method has been modified over time according to different accidents or ship types. Each of the modified HFACS methods, which form the basis of this study, has been designed to remain faithful to the original HFACS framework (Wiegmann and Shappell, 2003; Shappell et al., 2007). A total of 230 marine accidents were examined in the modified HFACS structures included in the study, and 949 nonconformities (accident reasons) that were effective in the realization of these accidents were determined. The distribution of these nonconformities according to the modified versions is HFACS-Coll (230), HFACS-MA (27), HFACS-Ground (147), HFACS-SIBCI (28) and HFACS-PV (517) as shown in Table 2.

The relationship between the obtained 949 nonconformities was examined, and it was seen that they contain similar features. For this reason, 949 nonconformities were grouped as 44 distinct contributory factors. For example, lack of training and familiarization distinct contributory factor covers all nonconformities due to lack of training familiarity with the use of ship equipment (ECDIS, ARPA *etc*.) and lack of training familiarity with the manoeuvring characteristics of the ship (turning circle, stopping distance *etc*.). In the study, a coding method was used to compare the modified HFACS levels and sub-categories (Table 3).

Table 3. Comparison of the modified methods developed with the original HFACS framework

It was observed that organizational influences, as the first level of the original HFACS, were only revised in the HFACS-SIBCI method. According to Hulme et al. (2019b), not much change was needed at this level as accident investigators mainly focus on active failures. 13 of the 44 distinct contributory factors classified within the scope of the study are at the organizational influence level. It was observed that distinct contributory factors (ergonomic design, regulatory-based, safe manning, unsuitable and inadequate equipment) classified at this level in the original framework were classified differently in modified frameworks.

Table 4. Distribution of distinct contributory factors according to HFACS organizational influences level

Modified HFACS developers (Coll, Ground, MA, SIBCI) stated that ergonomic design, inappropriate and insufficient equipment factors are not due to organizational or individual deficiencies and therefore should be evaluated at a different level from the organizational influence level (Chauvin et al., 2013; Chen vd. 2013; Mazaheri et al., 2015; Zhang et al., 2019). The developers of the HFACS-MA framework have classified the related distinct contributory factors at the pre-conditions level (SHELL level) under the hardware sub-category (Table 4). In the HFACS-SIBCI framework, it is considered that the ship's equipment and operational standards should comply with SOLAS (Zhang et al. 2019). For this reason, the researchers classified design and inappropriate, and insufficient equipment under the sub-category of legislation at the external factor level. It has been determined that minimum safe manning nonconformities, considered at the first level in the original HFACS framework, are classified under the planned inappropriate operations sub-category only at the unsafe supervision level in the HFACS-MA framework.

Table 5. Distribution of distinct contributory factors according to HFACS unsafe supervision level

Unsafe supervision, the second level of original HFACS, has a similar structure in modified HFACS frameworks. This level, consisting of 4 categories in the original HFACS framework, has 3 categories only in the HFACS-PV (Table 3). Two of the nine types of distinct contributory factors classified under this level were classified at different levels in the modified HFACS structures (Table 5). These are lack of external audit and supervisory violations. Lack of external audit was classified in external factors or outside factor levels in structures other than the original HFACS and HFACS-PV. Researchers defined the lack of external audit nonconformity as the deficiencies made by the national and international management during the implementation of the existing rules and codes. Administrator violations were classified under violations, which is a sub-category of the unsafe acts level in HFACS-PV (Table 7). This category defined as passive factors in other HFACS frameworks was categorized as active failures in HFASC-PV. HFACS-PV developers stated that failure to follow safe navigation procedures, instructions and checklists directly affects the occurrence of the accident. Therefore, this type of nonconformities that may directly lead to the accident have been classified into active defects.The third level of the original HFACS structure, the pre-conditions for unsafe acts, has remained unchanged only in HFACS-Coll. In HFACS MA, the SHELL method is integrated to this level. At this level, ten distinct contributory factors are classified. Among these, it has been observed that physical environment and lack of situational awareness are classified at different levels in the modified frameworks (Table 6). Physical environment is included in the HFACS-PV framework at the operational conditions level, unlike other HFACS structures. This situation is explained in a way that even if all the factors necessary for the development of the accident come together, the accident will not occur unless the operational condition is present (Uğurlu et. al., 2018). For example, it is not possible for a ship to run aground unless it sails in shallow waters. Therefore, the physical environment is not a precondition that plays a role in the emergence of an unsafe act, but a complementary factor that plays a role in accident occurrence. Another accident factor (nonconformities) classified differently at this level was the lack of situational awareness. In the HFACS-SIBCI method, the lack of situational awareness was evaluated as perceptual errors at the level of unsafe acts. Unawareness of dangerous situations (towing distance, speed, *etc*.) between the icebreaker and the assisted ship may directly cause the accident (Zhang et al., 2019). For this reason, the lack of situational awareness was categorized at the level of unsafe acts.

Table 6. Comparison of methods developed at the level of preconditions for unsafe acts

Eleven distinct contributory factors are classified at the level of unsafe acts (Table 7). Improper route selection among these distinct contributory factors is at a different level in the HFACS-SIBCI method. Improper route selection is classified under decision error sub-category in all methods except HFACS-SIBCI. The HFACS-SIBCI method states that choosing an improper route may make navigation difficult or dangerous, but this nonconformity will not directly cause an accident. For this reason, it is classified under the pre-conditions for the unsafe acts level.

Table 7. Distribution of distinct contributory factors according to HFACS unsafe acts

When the outlines of the studies are examined, it is seen that the most remarkable difference between the other studies developed with reference to the original HFACS framework is the environmental (operational) conditions. The location and content of this new level differ from the other modified HFACS structures (Table 3). This new level was evaluated as passive accident factors in all methods except HFACS-PV. It was placed after the level of unsafe acts in the HFACS-PV framework.

When the level of external factors added in HFACS-Coll and HFACS-Ground methods were examined, it was seen that the original HFACS (Wiegmann and Shappell, 2003) framework coincides with the factors it contains. Distinct contributory factors (Legislation Based Shortcoming) that were in the organizational process sub-category of the organizational impact level in the original HFACS structure were classified in the regulatory factors subcategory at the external factors level in the modified methods (HFACS-Coll and HFACS-Ground). Considering the laws and rules as a whole in the national and international area, the lower level in the original HFACS framework will be sufficient. These deficiencies, defined as external factors, can be considered as part of the organizational process (onboard or offboard) as stated in the original HFACS framework and can be evaluated as latent factors. The external factors level, which is similarly defined in HFACS-MA and HFACS-SIBCI, also has factors covered by the main framework. Legislation gaps and design flaws sub-categories defined under this level are located at the level of organizational influences in the main framework. The new levels added in all five specific methods described are similar. The level of operational conditions defined in HFACS-PV seems to be an option that can be adapted for different types of accidents due to the factors it contains (*e.g.* weather conditions, local restriction, and ship structural defects).

6. CONCLUSION

In this research, the analysis of modified HFACS frameworks developed for use in the analysis of marine accidents was conducted. Revisions in HFACS frameworks were examined in the study. It was found that the researchers classified the accident factors at different levels, keeping true to the original HFACS structure. The reason for this was given as ensuring the applicability of an accident analysis method in a different area. After the modifications, the hierarchical structure of the factors that caused the accidents could be revealed and accident occurrences became much easier to understand. Among the methods developed, the first of the remarkable differences is the level of external factors (first level) in which accident factors are classified due to national and international rules, and the second is the level of environmental (operational) conditions (final level). The importance of the management system and environmental conditions is taken into account in the occurrence of an accident. This shows that the researchers take into account the importance of the management system and environmental conditions in the occurrence of accidents. These newly defined levels make it possible to define detailed causes of accidents not originating from the vessel and bridge team. When the common behaviours of the researchers are examined, in all the methods examined, the pre-condition for unsafe act level was created differently from the original HFACS structure. At the end of the study, it was seen that those modifications of the main HFACS frameworks were needed to be suitably applied in maritime accident investigation, taking into account the IMO circular, accident type and ship type. The research findings reveal that these developed methods are specific for accident analysis. This study was conducted to provide researchers with the selection of a specific HFACS framework with the associated content in marine accident analysis.

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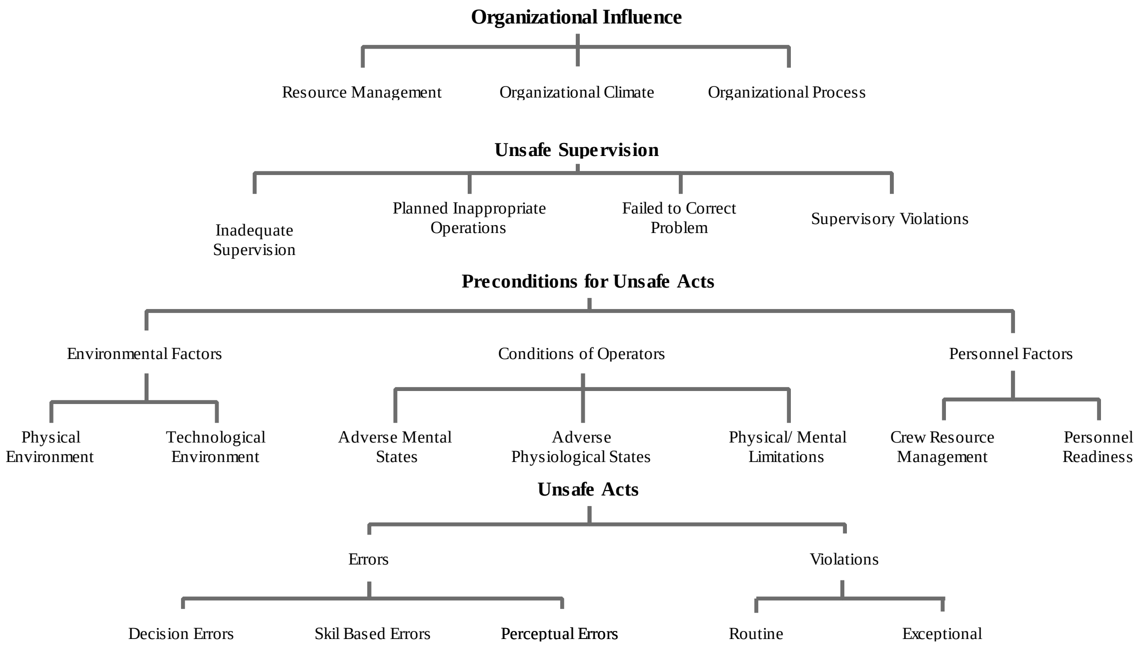

Figure 1. The overview of the HFACS framework

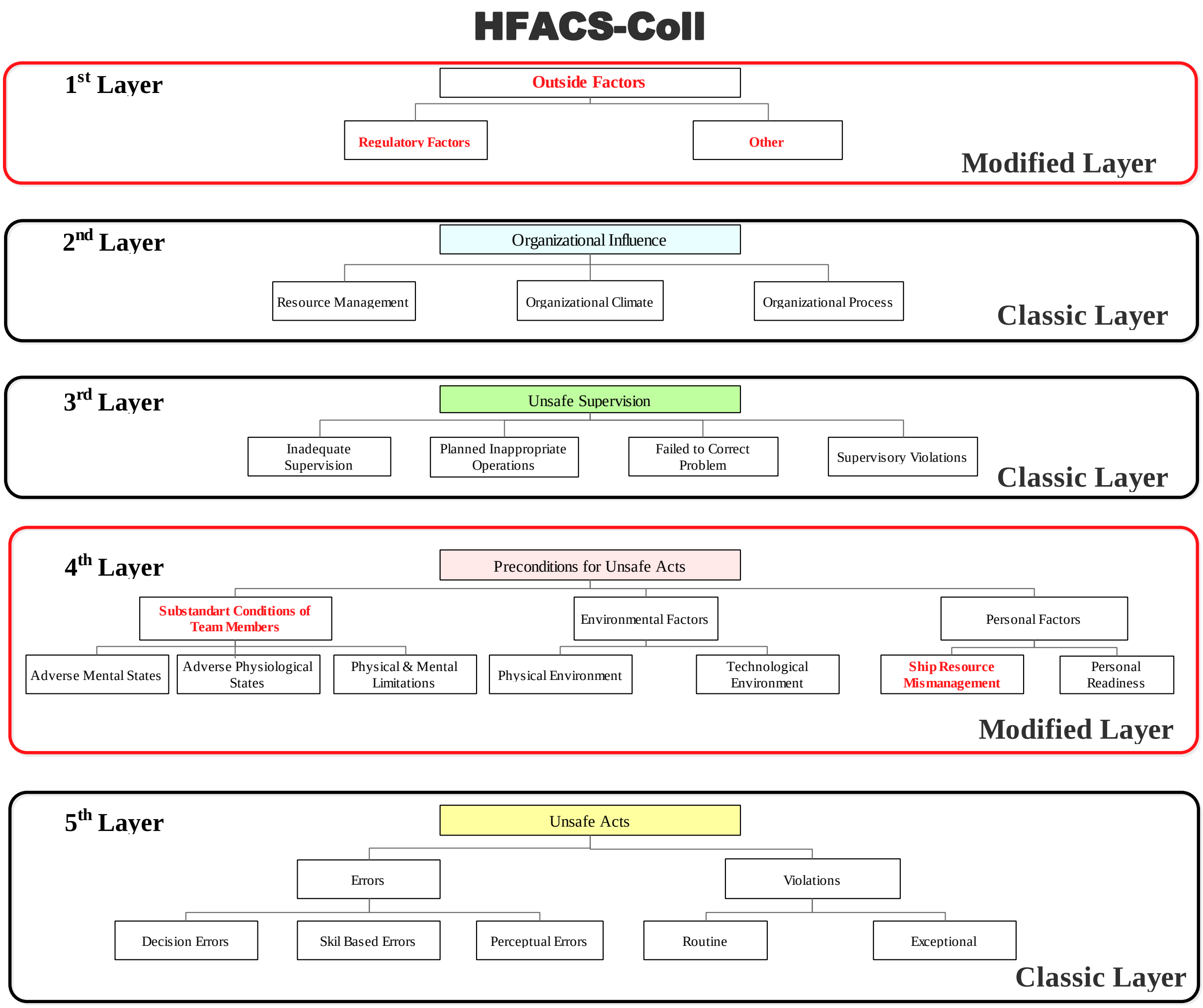

Figure 2. The overview of the HFACS-Coll framework

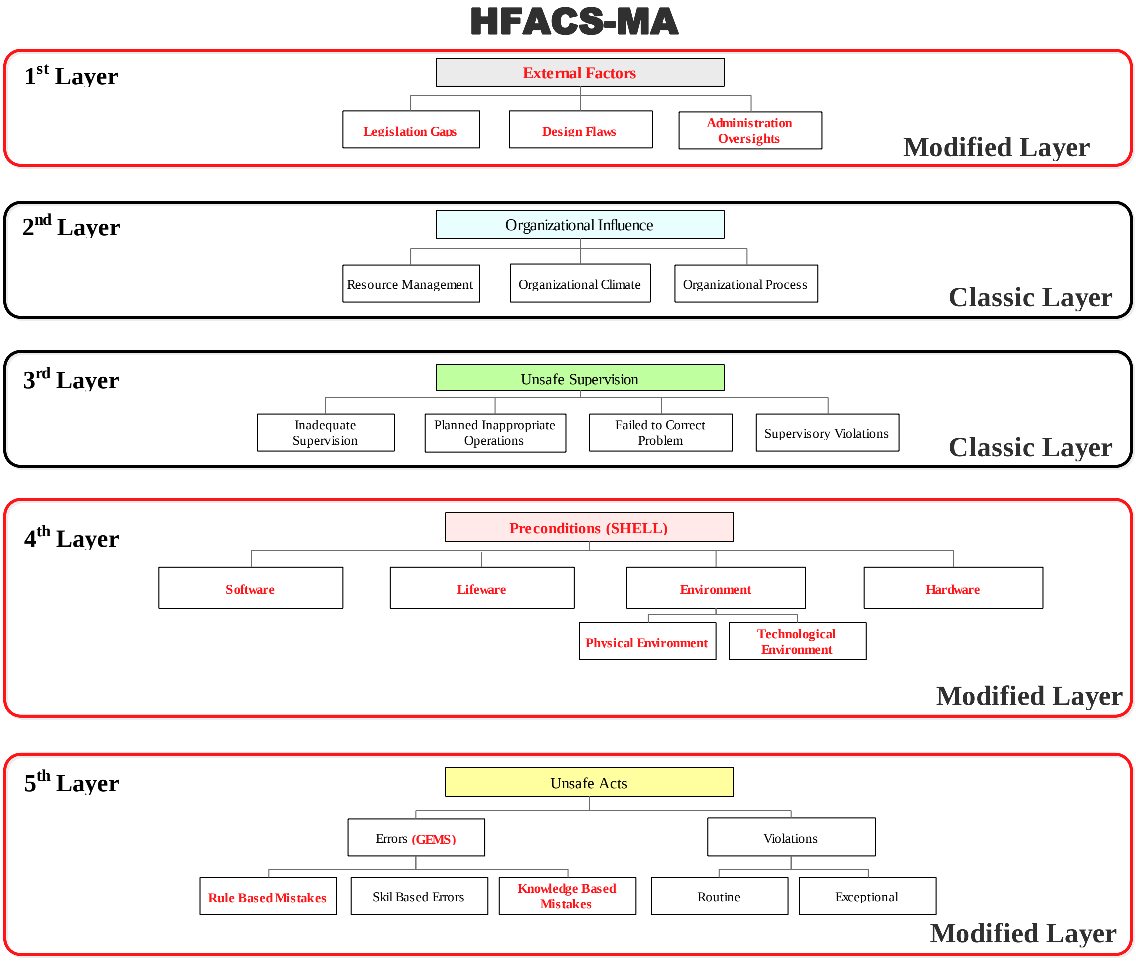

Figure 3. The overview of the HFACS-MA framework

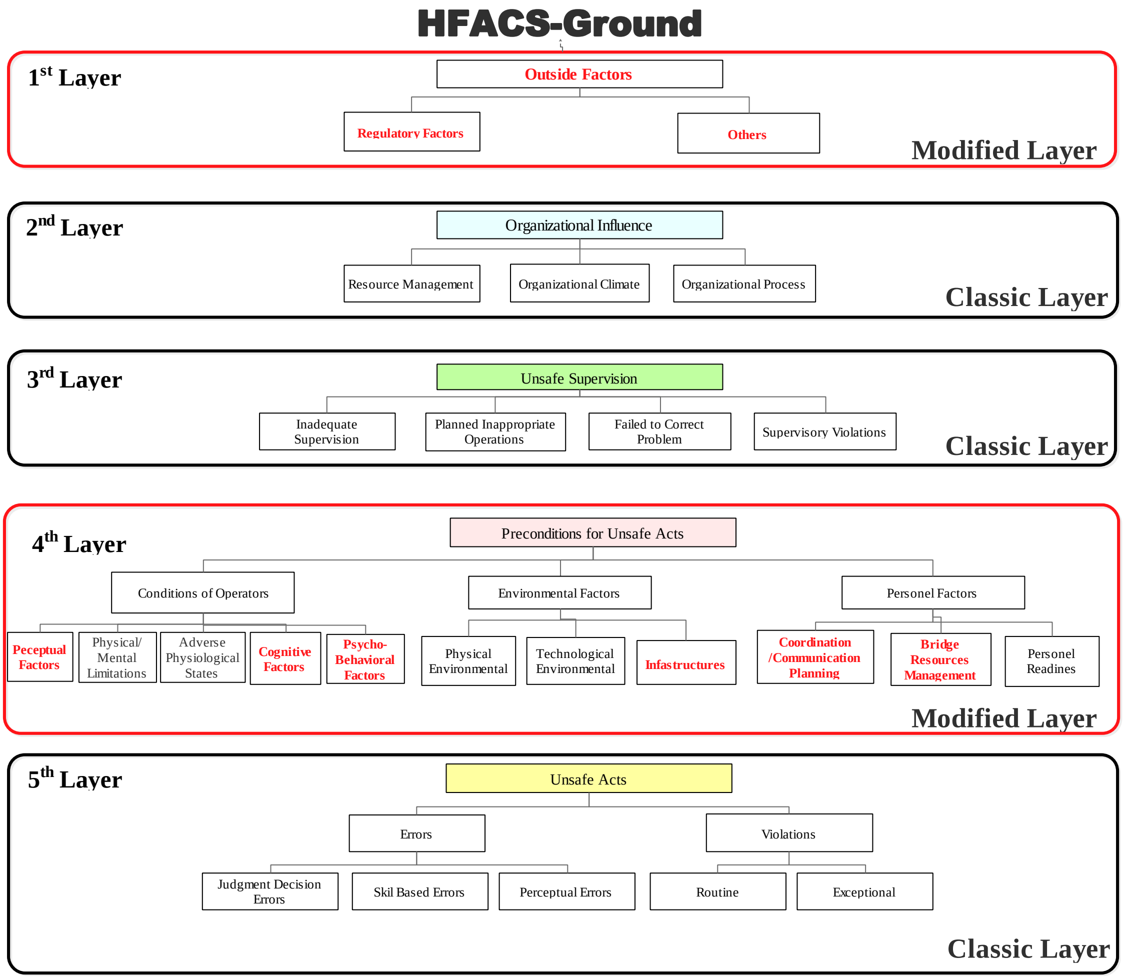

Figure 4. The overview of the HFACS-Ground framework

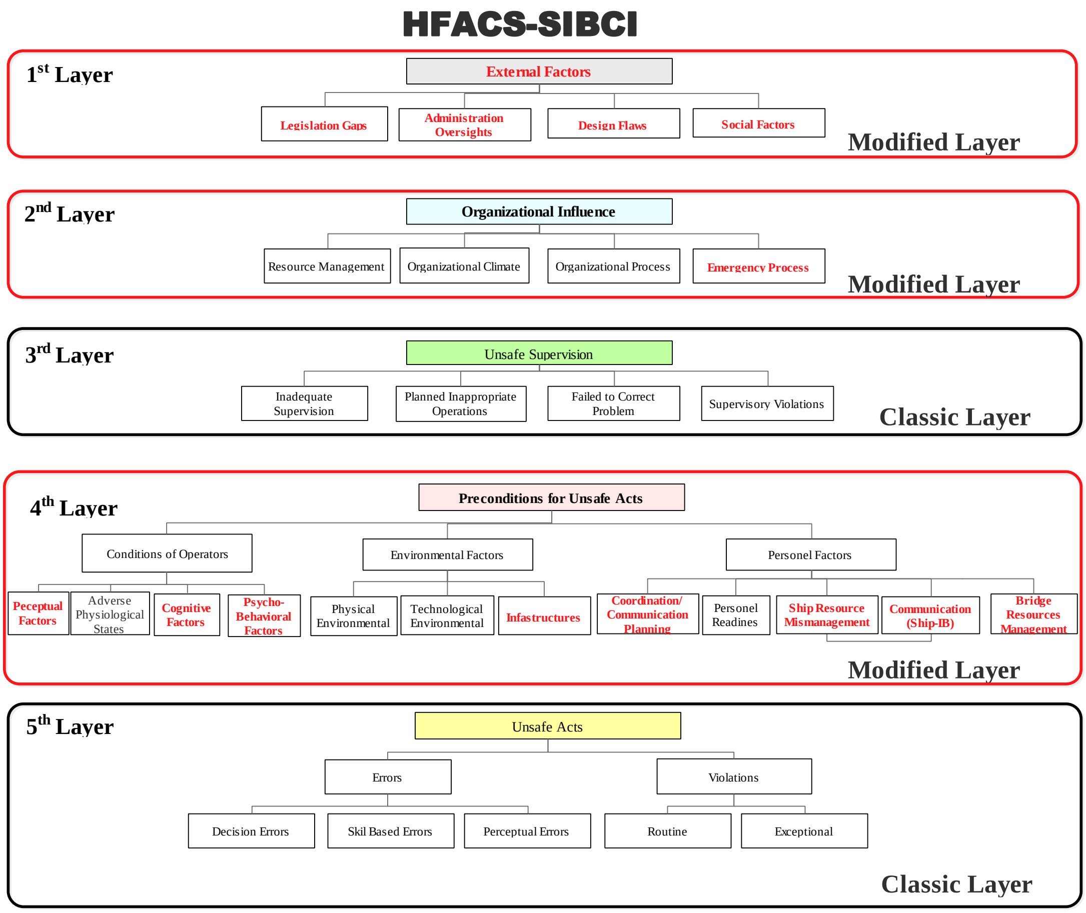

Figure 5. The overview of the HFACS-SIBCI framework

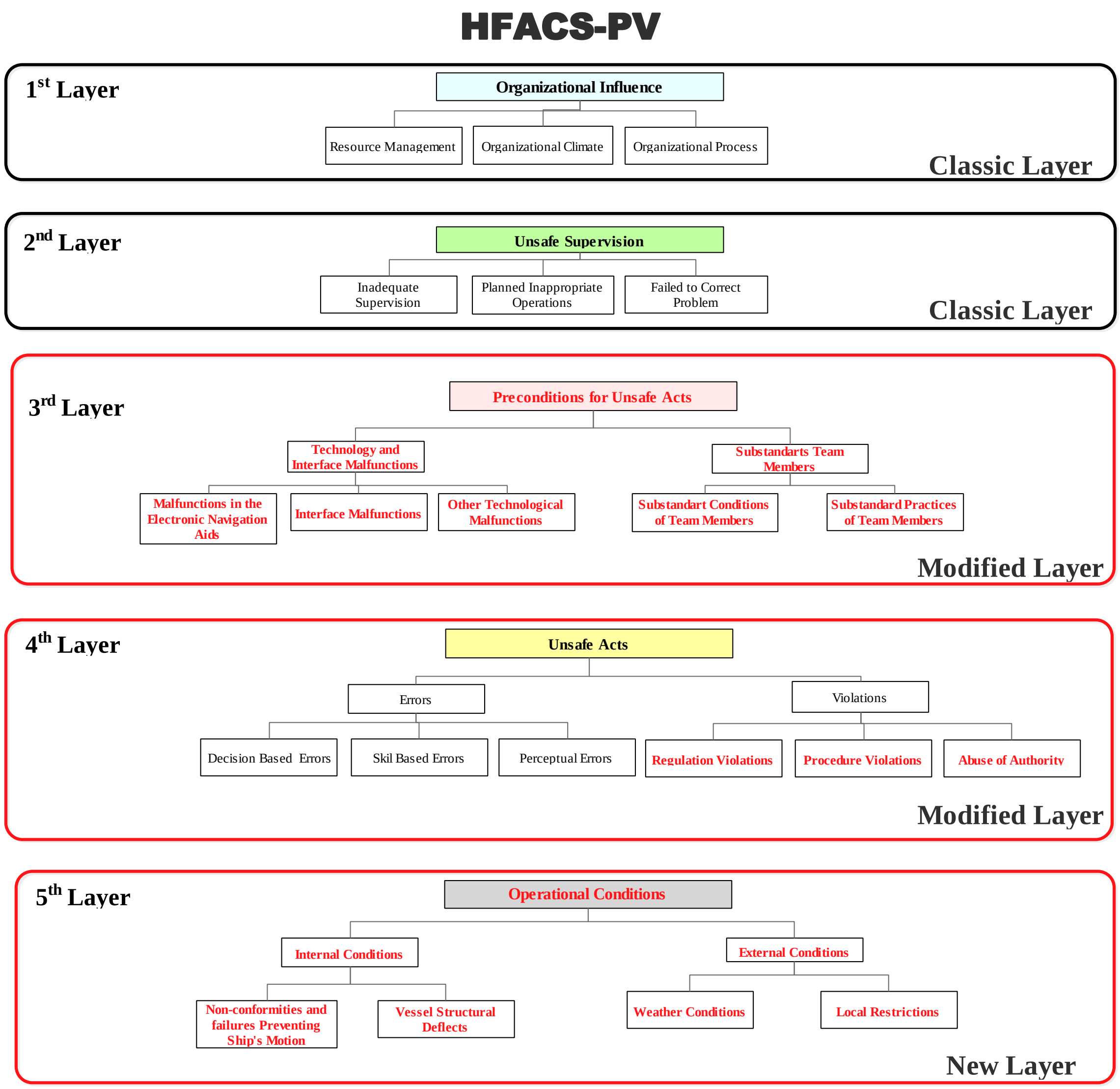

Figure 6. The overview of the HFACS-PV framework

Table 1. Human factor analysis methods

Methodology	Developed by	Domains	Definition of Method	Positive Attributes	Negative Attributes	References
SHELL (Software, Hardware, Environment, Liveware, Liveware/Human)	Edwards, E., 1972	AV, MD, MT, CI, FI	This method identifies human-machine interactions by covering all human factors in the system. This model sees the human being as an integral part of the productive system.	- It is a simple and understandable method. - It helps reduce system errors and prevent accidents. - It creates an awareness about the effect of the factors in the system on the decision-making process.	- This method does not cover interactions other than human factors (hardware-environment, hardware-hardware, software-hardware).	Wong and Tong, 2012 Akiyama et al., 2019
FRAM (Functional Resonance Accident Model)	Hollnagel E. and Goteman O., 2004	AV, RW, MT, MD SF, OA, FS, NI	It is a method based on the complex systemic accident theory. This method makes performance variability and function evaluation by systematic description. It argues that an undesirable event can arise from a large number of indistinguishable interactions.	- It clearly states the effect of the differences in the system on the accidents. - Structurally simple to implement. - All of the investigated accidents can be explained with a single diagram.	- FRAM analysis takes a long time. - Requires a learning process in the beginning. - Due to its theoretical basis, it needs extensive knowledge of human factors	Belmonte et al., 2011 Underwood and Waterson, 2013 Smith et al., 2017 Smith et al., 2018 Qiao et al., 2019 Patriarca et al., 2020
Accimap	Rasmussen, J., 1997	AV, RW, MD, MT CI, EI, ES, ML, OA, OC, RT, SF	Accimap analyses typically focus on failures across the following six organizational levels: government policy and budgeting; regulatory bodies and associations; local area government planning and budgeting (including company management) technical and operational management; physical processes and actor activities; and equipment and surroundings. The method graphically depicts actions,	- Accident occurrence can be explained with a single diagram. - Provides a clear and concise summary of the accident. - Analyzes the effect of dynamic behaviours in the system on accident occurrence.	- Explains events and actions rather than system components. - Provides little information about the structure and limits of the system. - Requires training to use the method	Woo and Vicente, 2003 Salmon et al., 2012 Underwood and Waterson, 2014 Waterson et al., 2017 Wang et al., 2018 Salmon, et al., 2020

			decisions and errors in accidents. It is focused on the causal flow of events.	- The propagation of events throughout the entire system can be visualized.		
STAMP (Systems Theoretic Accident Model and Process)	Leveson, N., 2004	RW, AV, MT, IN, ML, MD	It is a qualitative and comprehensive method based on cause and effect relationship. By providing a systemic view on causality, it examines indirect, non-linear feedback relationships between events. In this method, the boundaries of the systems are defined by security constraints.	- Provides a visual explanation of system hierarchy. - Explains how complexity within a system affects the occurrence of an accident.	- The model is only suitable for experienced users with extensive theoretical and domain knowledge. - Findings are mainly text-based. - There is no single graphic representation	Ouyang et al., 2010 Kontogiannis and Malakis, 2012 Altabbakh et al., 2014 Rong and Tian, 2015 Kim et al., 2016 Canham et al., 2018
THERP (Technique for Human Error Rate Prediction)	Swain, A. D. and Guttmann, H. E., 1983	AV, MD, MT, NI	This method is considered the first-generation method that remains valid today. It is one of the quantitative human reliability analysis techniques. The model includes failure definition and task analysis as well as evaluates human reliability by enabling quantification of human error probabilities.	- Compatible with Probabilistic Risk Assessment (PRA) models. - Allows transparent assessment of risks originating from human factors. - It makes it possible to analyze the dependency relationship between actions or errors quantitatively.	- Offers different results in the assessment of the risk associated with the same events by different analysts. - It requires intensive resource usage and time.	Yang et al., 2014 Castiglia et al., 2015 Shirley et al., 2015
HEART (Human Error Assessment and Reduction Technique)	Williams, J. C., 1988	NI, CI, AV, MD, RW, MT, SF, OA, FS, ES	The method is used to measure the probability of an error occurring during the completion of a particular task by applying weighting factors. It is a versatile, fast and straightforward human reliability calculation method that advises the user on error reduction.	- Provides the user with suggestions for reducing the occurrence of errors. - It is quick to apply. - It is possible to make an evaluation with limited resources.	- Different evaluators have the potential to calculate very different Human Error Probabilities (HEPs) for the same task. - Lack of information about the extent to	Kirwan, 1996 Deacon et al., 2013 Akyuz and Celik, 2015 Wang et al., 2018

					which tasks should be decomposed for analysis.	
Swiss Cheese Model	Reason, J., 1990	AV, MT	It is a theoretical method. Defines the relationship of human error between active defects and latent conditions. Accidents are a combination of active failures and latent factors and, result from errors or omissions in the system.	- Accident occurrence can be explained with a single diagram. - Provides a general framework to assist in data collection.	- Descriptions of events and actions are made instead of system components. - Provides little information about system structure and limits.	Reason et al., 2006 Uğurlu et al., 2018 Yıldız et al. 2021
ATHEANA (A Technique for Human Error Analysis)	Cooper, S. F., 1996	IN, NI, MT, OA, EI, ES, CI, RW, SF	ATHEANA is considered a second-generation technique and provides a detailed search process to identify human actions. The method allows for an evaluation of the probability of human error while performing a particular task.	- Systematically explains how action errors can occur.	- The guidance provided by the method is complex. - Using the method requires expertise. - The quantification method is weak, and the quantitative results are unsubstantiated.	Forester et al., 2007 Pinto et al., 2015

AV: Aviation; CI: Chemical Industry; EC: Ecology; EI: Electrical Industry / Electricity; EN: Energy; ES: Emergency Services; FI: Food Industry; FS: Financial Services; IN: Industry; MD: Medical; ML: Military; MT: Maritime; NI: Nuclear Industry; OA: Outdoor Activities; OC: Occupational; RW: Railway; RT: Road Traffic, SF: Space Flight

Table 2. An overview of HFACS methods related to maritime safety

	Name of modified HFACS structures				
	HFACS-Coll	HFACS-MA	HFACS- Ground	HFACS- SIBCI	HFACS-PV
Developed by	Chauvin et al., 2013	Chen et al., 2013	Mazaheri et al., 2015	Zhang et al., 2018	Ugurlu et al., 2018
Levels	1- Outside Factors 2- Organizational Influence 3- Unsafe Supervision 4- Precondition for Unsafe Acts 5-Unsafe Acts	1- External Factors 2- Organizational Influence 3- Unsafe Supervision 4- Preconditions (SHELL) 5- Unsafe Acts	1- Outside Factors 2- Organizational Influence 3- Unsafe Supervision 4- Precondition for Unsafe Acts 5-Unsafe Acts	1- External Factors 2- Organizational Influence 3- Unsafe Supervision 4- Precondition for Unsafe Acts 5-Unsafe Acts	1- Organizational Influence 2- Unsafe Supervision 3- Precondition for Unsafe Acts 4-Unsafe Acts 5- Operational Conditions
Number of subcategories	14	16	14	17	12
Number of accidents	27	1	115	17	70
The type of accident it is based on	Collision accidents	Sinking accidents	Grounding accidents	Collision accidents	Collision accidents
The type of ship it is based on	General	Ro-Ro	General	Buz kıran	Passenger
Number of nonconformities	230	27	147	28	517

Table 3. Comparison of the modified methods developed with the original HFACS framework

		HFACS	HFACS-Coll	HFACS-MA	HFACS-SIBCI	HFACS-Ground	HFACS-PV
100	**Organizational Influences**						
110	Resource Management	✓	✓	✓	✓	✓	✓
120	Organizational Climate	✓	✓	✓	✓	✓	✓
130	Organizational Process	✓	✓	✓	✓	✓	✓
140	Emergency Process				✓		
200	**Unsafe Supervision**						
210	Inadequate/ Insufficient Supervision	✓	✓	✓	✓	✓	✓
220	Planned Inappropriate Operations	✓	✓	✓	✓	✓	✓
230	Failure to Correct Known Problems	✓	✓	✓	✓	✓	✓
240	Supervisory Violations	✓	✓	✓	✓	✓	
300	**Preconditions for Unsafe Acts**						
310	*Environmental Factors*						
311	Physical Environment	✓	✓		✓	✓	
312	Technological Environment	✓	✓		✓	✓	
313	Infrastructure				✓	✓	
320	*Condition of Operators*	✓			✓	✓	
321	Substandard Condition of Team Members		✓				✓
322	Adverse Mental States	✓	✓				✓
323	Adverse Physiological States	✓	✓		✓	✓	✓
324	Physical and/or Mental Limitations	✓	✓			✓	✓
325	Cognitive Factors				✓	✓	
326	Psycho-Behavioural Factors				✓	✓	
327	Perceptual Factors				✓	✓	
330	*Substandard Practices of Team Members*						✓
331	Readiness for Operation						✓
332	Bridge Team Management						✓
340	*Personnel Factors*						
341	Crew Resource Management	✓					
342	Personal Readiness	✓	✓		✓	✓	

343	SRM		✓		✓		
344	Communication- Ship-IB				✓		
345	BRM		✓		✓	✓	
346	Coordination-Communication Planning		✓		✓	✓	
350	*Technology And Interface Malfunctions*						✓
351	Malfunction In the Electronic Navigation Aids						✓
352	Interface Malfunctions						✓
353	Other Technological Malfunctions						✓
400	**Unsafe Act**						
410	*Errors*						
411	Decision/Judgment Errors	✓	✓		✓	✓	✓
412	Skill-Based Errors	✓	✓	✓	✓	✓	✓
413	Perceptual Errors	✓	✓		✓	✓	✓
414	Rule-Based Mistakes			✓			
415	Knowledge-Based Mistakes			✓			
420	*Violations*						
421	Routine	✓	✓	✓	✓	✓	
422	Exceptional	✓	✓	✓	✓	✓	
423	Regulation						✓
424	Procedure						✓
425	Abuse of Authority						✓
500	**External Factors**						
510	Legislation Gaps			✓	✓		
520	Administration Oversights			✓	✓		
530	Design Flaws			✓	✓		
540	Social Factors				✓		
600	**Outside Factors**						
610	Regulatory Factors		✓			✓	
620	Others		✓			✓	
700	**Pre-conditions (SHELL)**						
710	Condition of Operators			✓			

720	Software	✓	
730	Hardware	✓	
740	Environment	✓	
750	Technological Environment	✓	
760	Liveware	✓	
800	**Operational Conditions**		
810	Internal Conditions		✓
820	External Conditions		✓

Table 4. Distribution of distinct contributory factors according to HFACS' organizational influences level

Nonconformities	HFACS-MA (Code)	HFACS-Coll (Code)	HFACS-Ground (Code)	HFACS-SIBCI (Code)	HFACS-PV (Code)
Lack of Training and Familiarization Ship Equipment, Auxiliaries	110	110	110	110	110
Lack of Training and Familiarization Navigational Area	110	110	110	110	110
Minimum Safe Manning	220	110	110	110	110
Unqualified Crew	110	110	110	110	110
Insufficient Equipment and Facilities	750	110	110	530	110
Inappropriate Equipment and Facilities	750	110	110	530	110
Ergonomic Design Flaws	530	620	620	530	110
Drug and Alcohol Policies	120	120	120	120	120
Procedure Based Shortcoming	130	130	130	130	130
Emergency Procedure Based Shortcoming	130	130	130	140	130
Legislation Based Shortcoming	510	610	610	540	130
Risk Assessment Oversight	130	130	130	130	130
Safety Assessment Oversight	130	130	130	130	130

Table 5. Distribution of distinct contributory factors according to HFACS' unsafe supervision level

Nonconformities	HFACS-MA (Code)	HFACS-Coll (Code)	HFACS-Ground (Code)	HFACS-SIBCI (Code)	HFACS-PV (Code)
Testing and Control	210	210	210	210	210
Insufficient Maintenance	210	210	210	210	210
Lack of Internal Audit	210	210	210	210	210
Lack of External Audit	520	620	620	520	210
Planned Inappropriate Lookout	220	220	220	220	220
Planned Inappropriate Manoeuviring	220	220	220	220	220
Planned Inappropriate Planing (Voyage, rest hours, etc.)	220	220	220	220	220
Failure to Correct a Known Problem (Uncharted shoal, etc.)	230	230	230	230	230
Supervisory Violations	240	240	240	240	424

Table 6. Comparison of methods developed at the level of pre-conditions for unsafe acts

Nonconformities	HFACS-MA (Code)	HFACS-Coll (Code)	HFACS-Ground (Code)	HFACS-SIBCI (Code)	HFACS-PV (Code)
Lack of Situational Awareness	710	321	322	413	321
Overconfidence	710	321	322	322	321
Lack of Self-Confidence	710	321	322	322	321
Sleeplessness	710	321	322	322	321
Stress	710	321	322	322	321
Lack of Attention	710	321	322	322	321
Fatigue	710	321	322	322	322
Mental Conditions	710	321	324	324	323
Pyhsical Environmental	740	311	325	325	820
Malfunctions	312	312	312	312	350

Table 7. Distribution of Nonconformities according to HFACS' unsafe acts

Nonconformities	HFACS-MA (Code)	HFACS-Coll (Code)	HFACS-Ground (Code)	HFACS-SIBCI (Code)	HFACS-PV (Code)
Failure to Use of Bridge Navigation Equipment	412	412	412	412	412
Ineffective Usage of Engine Control Room	412	412	412	412	412
Maneuvering Failure	411	411	411	411	411
Incorrect Decision	415	411	411	411	411
Improper Route Selection	411	411	411	326	411
Ignored Warning of VTS, Marine Pilot	411	411	411	411	411
Interpretation Error	413	413	413	413	413
Failure to Detect the Presence of the Risk Marine Accident	413	413	413	413	413
Regulation Violations	414	421	421	421	423
Procedure Violations	421	421	421	421	424
Exceptional Violations	422	422	422	422	425