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Analytical HFACS for investigating human errors in shipping accidents

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ABSTRACT

Despite the innovative trends in marine technology and the implementation of safety-related regulations, shipping accidents are still a leading concern for global maritime interests. Ensuring the consistency of shipping accident investigation reports is recognized as a significant goal in order to clearly identify the root causes of these accidents. Hence, the goal of this paper is to generate an analytical Human Factors Analysis and Classification System (HFACS), based on a Fuzzy Analytical Hierarchy Process (FAHP), in order to identify the role of human errors in shipping accidents. Integration of FAHP improves the HFACS framework by providing an analytical foundation and group decision-making ability in order to ensure quantitative assessment of shipping accidents.

1. Motivation: shipping accidents

Exploring the root causes of merchant shipping accidents is one of the most focused upon themes within ongoing research aimed towards enhancing maritime safety. Recently, the statistical research of Rothblum (2000), O'Neil (2003), Darbra and Casal (2004), and Toffoli et al. (2005) has identified human error as the primary factor in the majority of marine accidents. The roles of the human element and human competency have been cited within previous research by Er and Celik (2005), Hetherington et al. (2006), Celik et al. (2009), and Celik and Er (2007). Although innovations in marine technology and automation systems (Grabowski and Sanborn, 2003) have made contributions to improved safety, the rates of shipping accidents have risen, raising safety and environmental concerns from maritime interests. Moreover, Skjong and Guedes Soares (2008) have discussed the urgent requirement for improvements in methodological approaches in order to enhance the safety of maritime transportation. Despite the invaluable contributions of existing studies on investigating shipping accidents (Antão et al., 2006; Antão and Guedes Soares, 2008), the urgent need to build an analytical framework for separately identifying human errors is clear. At this point, the feedback from maritime accident investigation reports shows enormous challenges to preventing shipping accidents. However, the lack of an effective response to lessons learned from marine accident reports has threatened precautions already taken towards system safety.

Hence, this paper proposes an analytical foundation for a Human Factors Analysis and Classification System (HFACS) quantitatively characterize the role of human errors. HFACS is a commonly utilized tool for investigating human contributions to aviation accidents under a widespread evaluation scheme. This study extends the HFACS on an analytical basis in a fuzzy environment to investigate shipping accidents in a consistent manner. As a means of quantification, the Fuzzy Analytic Hierarchy Process (FAHP) is integrated into an existing HFACS framework in order to quantify human contributions to shipping accidents. Using pairwise comparison matrices, active and latent failures that cause shipping accidents are identified. Moreover, the proposed methodology includes group decision-making ability to increase the consistency of model outcomes. Section 2 of this paper reviews the existing applications of HFACS to different accident cases. Section 3 proposes methodological improvements to enhance the HFACS framework on the basis of FAHP. The implementation of the proposed idea is illustrated with an accident scenario centering on a bulk carrier ship in Section 4. Finally, concluding remarks and further extensions in practicing analytical HFACS are given at the end of the paper.

2. Literature review of HFACS applications

The HFACS system was originally developed as an evaluation framework to analyze and classify operator errors in naval aviation accidents and mishaps. However, the advanced version of HFACS based upon Reason's model of latent and active failures (Reason,

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1990) has provided an applicable system for investigating human error in accidents. HFACS was cited by Dekker (2002) as one of the most powerful tools for reconstructing human contributions to various types of accidents. The generic framework of the HFACS model has been utilized intensively in investigating aviation accidents by Wiegmann and Shappell (2001), Gaur (2005), Li and Harris (2006), Dambier and Hinkelbein (2006), and Shappell et al. (2007). Furthermore, the Human Factors Investigation Tool (HFIT) (Gordon et al., 2005) and Curtailing Accidents by Managing Social Capital (CAM-SoC) (Rao, 2007) can be recognized as relatively new tools built based on the HFACS framework.

On the other hand, the application of the proposed HFACS framework is rarely seen in different disciplines. Krulak (2004) proposed the maintenance extension of the HFACS system which is called HFACS-ME in the literature. As a practical application, Boquet et al. (2004) designed an HFACS system to explain the latent and active failures which caused emergency medical transport accidents. For railway transportation, Reinach and Viale (2006) proposed HFACS-RR as a human error framework to conduct railroad accident investigations. Moreover, HFACS is such a generic model that it can be transposed to illustrate the origins of error in healthcare practice (Milligan, 2007) and surgery operations (El Bardissi et al., 2007) as well. For the maritime industry, the scope of the existing HFACS has recently been modified and extended by Celik and Er (2007) to identify the influence of system hardware on human errors in shipping accidents. Recently, HFACS was also proposed as a means to reduce occupational accidents in Turkish shipyards (Celik and Cebi, 2008a).

This literature review provides a framework to identify human error in shipping accidents. Additionally, the lack of quantitative analysis and group consensus within existing HFACS motivated this study to develop a quantified evaluation framework, which led to the involvement of multiple investigators in the investigation process. The analytical methodology proposed in this paper is expected to overcome the existing shortfalls of the HFACS model.

3. Quantification of HFACS implementation process

3.1. Brief introduction of HFACS framework

The fundamentals of HFACS lie in the theory of the *Swiss Cheese Model*, which was originally described by Reason (1990). Briefly, the HFACS mechanism investigates the active failures by the operators combined with latent conditions upstream in the organization. At the operational level, the active failures, which include operator actions and decisions, directly influence the occurrence of accidents. However, the theory of HFACS also motivates the accident investigators to seek out latent factors, such as fatigue, the physical atmosphere, technological environment, etc. The combined system has increased the consistency of the HFACS mechanism in accident surveying practices. The broad structure of HFACS includes four main levels of investigation schema, which are listed as follows: unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences. Wiegmann and Shappell (1997) and Shappell and Wiegmann (2001) extended the theory of the HFACS model in order to integrate sub-factors at the different levels as well.

3.2. Details of analytical HFACS

Despite the successful past applications of HFACS, its framework can be improved to ensure best practices in an accident investigation. Therefore, this paper aims to add an analytical capacity to the existing HFACS framework via the FAHP methodology, which is used to quantify the experts' judgments (i.e., marine accident surveyors' decisions) in order to define the leading causes of an accident. The necessities and motivation behind this idea are initiated by Celik and Cebi (2008b). The primary aim of using analytical HFACS instead of the traditional framework is to depict exact reasons for the accident. Although the HFACS methodology is based on the experts' judgments, the main deficiency of the HFACS methodology is that it does not quantify the factors contributing to an accident. In other words, these judgments do not define the degree of factors' influence on different accident cases.

Following this idea, the FAHP methodology enables quantification within the HFACS framework via pairwise comparisons among the factors at different levels. Based on an analytical HFACS algorithm, the probable factors that trigger the occurrence of an accident are assigned by the relevant experts in linguistic form. So, the system allows the involvement of several experts in the accident investigation process. This can be noted as one of the strengths of the analytical HFACS approach. Furthermore, the factors are quantified by transforming linguistic terms into fuzzy triangular numbers in a group consensus. Finally, the FAHP algorithm computes the priority weights of contributing factors by considering the aggregated judgments on pairwise comparisons based on a Buckley solution algorithm.

Fig. 1 illustrates the general framework of the analytical HFACS mechanism for the shipping accident investigation process. As seen in the figure, there are four main levels: (1) the Act level, which includes errors and violations; (2) the Precondition level, which includes environmental factors, condition of individuals, and personal factors; (3) the Supervision level, which includes inadequate supervision, inappropriate operation, failing to correct problems, and supervisory violations; and (4) the Organizational Influences level, which includes resource management, organizational climate, and organizational processes. Using the analytical HFACS methodology, the latent links between each segment are marked during the accident survey and investigation process. Therefore, the proposed idea is maintained and even supported by the nature of the *Swiss Cheese Theory* behind the existing HFACS framework.

3.3. Theory of FAHP and system integration

In Fig. 1, it is shown that there are four levels of error: *Acts*, *Preconditions*, *Supervision*, and *Organizational Influences*. In the evaluation procedure, an integrated methodology developed for this study is used to derive priority weights at each level of HFACS. Using this methodological basis, the relative importance of the effects which are the possible reasons for the accident are determined by FAHP and a Buckley solution algorithm. The FAHP is an extension of the traditional AHP methodology that incorporates fuzzy comparison ratios, a_{ij}. In Buckley's approach, a geometric mean method is used to derive fuzzy weights and performance scores. The FAHP is preferred, due to its simple nature, to extend the fuzzy case, and it guarantees a unique solution to the reciprocal comparison matrix. The procedure can be summarized as follows (Chen and Hwang, 1992; Hsieh et al., 2004):

$$\tilde{C} = \begin{matrix} 1 & \tilde{c}_{12} & \cdots & \tilde{c}_{1n} \\ \tilde{c}_{21} & 1 & \cdots & \tilde{c}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{c}_{m1} & \tilde{c}_{m2} & \cdots & 1 \end{matrix} \quad (1)$$

where $\tilde{C}$ is the pairwise comparison matrix.

The linguistic evaluation scale, given in Table 1 (Hsieh et al., 2004), can be used for triangular fuzzy numbers in Eq. (1).

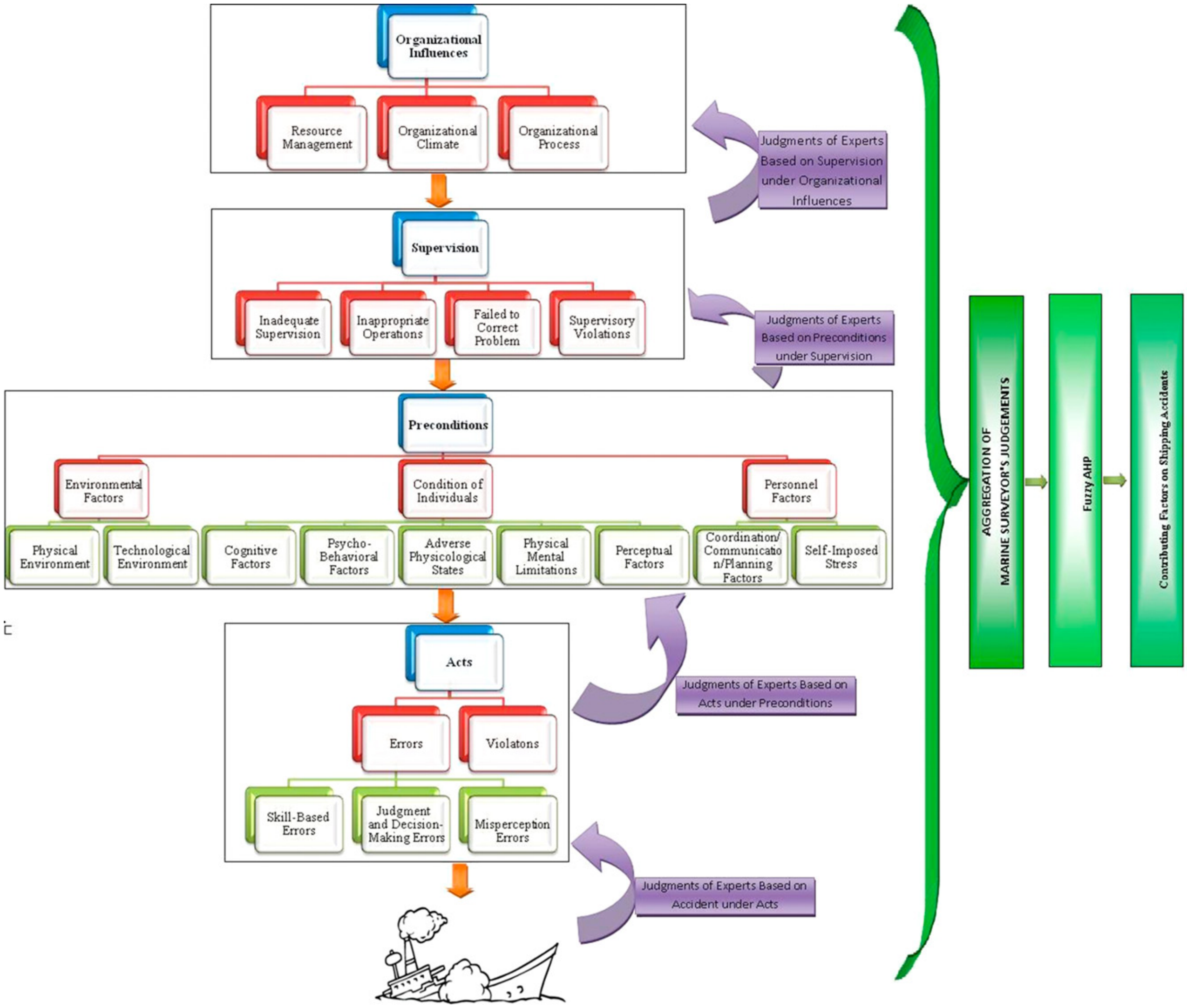

Fig. 1. Framework of analytical HFACS framework.

If there is more than one expert, the following equation can be used to aggregate the opinions of the experts.

$$\tilde{C}_{ij} = \frac{1}{K}(\tilde{C}_{ij}^1 + \tilde{C}_{ij}^2 + \cdots + \tilde{C}_{ij}^t + \cdots + \tilde{C}_{ij}^K), \quad \tilde{C}_{ij}^t = (a_{ij}, b_{ij}, c_{ij}), \tag{2}$$

where K is the number of experts, and $\tilde{C}_{ij}$ is the fuzzy comparison value of possible reason i to possible reason j. Then, the fuzzy weight matrix is calculated by Buckley's Method as follows:

$$\tilde{r}_i = (\tilde{c}_{i1} \otimes \tilde{c}_{i2} \otimes \cdots \otimes \tilde{c}_{in})^{1/n} \tag{3}$$

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 + \tilde{r}_2 + \cdots + \tilde{r}_n)^{-1}, \tag{4}$$

where $\tilde{r}_i$ is the geometric mean of fuzzy comparison values and $\tilde{w}_i$ is the fuzzy weight of possible reason i. The term $\tilde{w}_i$ denotes the relative importance of the possible cause. After the fuzzy relative weight matrix is obtained, a defuzzification process, which converts a fuzzy number into a crisp value, is utilized. Fuzzy numbers will be defuzzified into crisp values and then a normalization procedure will be applied. For the defuzzification process, a centroid method, which provides a crisp value based on the center of gravity, is selected since it is the most commonly used method (Opricovic and Tzeng, 2004).

$$w_i = \frac{(w_l + w_m + w_u)}{3} \tag{5}$$

Then, the importance of the effects is calculated as follows:

$$w_r = \frac{w_i}{\sum_{i=1}^{n} w_i}, \tag{6}$$

where w_r and w_j are the importance of the possible cause and the relative importance, respectively.

Table 1
Linguistic judgments and corresponding TFNs.

Judgments		TFNs
Equal	(Eq)	(1,1,1)
Weakly high	(Wk)	(1,3,5)
Essentially high	(Es)	(3,5,7)
Very strongly high	(Vs)	(5,7,9)
Absolutely high	(Ab)	(7,9,9)

4. Shipping accident case: boiler explosions on board bulk carrier

An illustrative application of the proposed analytical HFACS model is applied to a casualty investigation report from a bulk carrier ship (ATSB, 2007). On the 2nd of April 2007, at New South Wales, a boiler explosion took place in the machinery space on board ship. The details of the shipping accident are introduced in order to provide familiarity with the case.

4.1. Technical description of shipping accident scenario

Briefly, the boiler explosion occurred on board the bulk carrier after engine room personnel completed the task of replacing the auxiliary boiler burner with a clean spare unit. The boiler was a vertical composite type, which has a working pressure of 6.0 bar. In principle, the system is designed to be utilized by the main engine exhaust gases during sea voyages, or to be started by an oil firing unit to produce steam at ports and manoeuvring positions. The automatic oil burner with purge air fan and the fuel oil feed pump are the main components of the oil firing unit of the boiler. To keep system performance at desired levels, routine maintenance operations are required on the integrated pieces of the burners, such as the atomizer block, fuel nozzle, ignition electrodes, and flame stabilization ring. The maintenance cover at the top of the oil firing unit can be removed to facilitate repairs on the burner device.

Prior investigations of the shipping accident case underline that it occurred during maintenance activities on the burner device of the composite boiler. The chief engineer, the second engineer, the third engineer, and a fitter were burned and heavily injured due to flashback from the boiler furnace during inspection of the furnace and burner device. Moreover, the flashback also caused a small fire on the deck, which was quickly extinguished. The injured personnel had to be taken from the ship via medical evacuation for first aid treatment in a hospital. The *Australian Transport Safety Bureau* (ATSB, 2007) published an independent investigation report on this incident. As a result of the investigation, the ATSB has suggested that the boiler manufacturer and the shipping firm should take a number of actions in order to improve the safety environment of shipping operations in the future.

4.2. Analytical HFACS extension to shipping accident investigation

The well-documented investigation report ensures that feedback is available; however, it is also necessary to extend the discussion of initial findings from the report in order to outline clearly the role of human error in the shipping accident. At this point, the proposed methodology in this paper focuses on identifying the contributing factors behind the shipping accident at the managerial and operational levels. Briefly, the following points of the shipping accident case can be linked to these latent failures:

- The evidence in the shipping accident case has clearly outlined the shortage of technical information flow on updating boiler manuals for operators. Periodic information circulars from the manufacturing firms regarding similar previous flashbacks in the same types of boilers aboard different ships were not followed by the engine room personnel. This also indicates insufficient organizational supervision from the shipping firm to the relevant personnel on the ship.
- The other safety concern is related to the utilization of personal protective equipment by crew members during maintenance of the boiler burner. As a result of inadequate protection, injuries occurred. This failure can be linked with the technological environment of the ship machinery space and defects in safety procedures during maintenance aboard ships.
- Problems were also seen in the first aid plan of the shipboard organization as well. Subsequent to the accident, the injured crew members were not provided with the appropriate first aid treatment for their burn injuries. This failure addresses the shortfalls in plans and procedures for emergency drills on board ship.

Following the accident investigation reports, this study proposes to explore quantitatively the human errors that contributed to the occurrence of the shipping accident. At this point, the analytical HFACS mechanism provides a quantitative framework to analyze the contributing factors in detail. In this case, the judg-

Table 2
Judgments of marine accident surveyors under Act level.

Judgments of marine accident surveyors with respect to “Accident”

Accident	Errors			Violations		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Errors				Wk	Es	Wk
Violations						

Aggregated judgments of marine accident surveyors

Accident	Errors	Violations
Errors		(1.67,3.67,5.67)
Violations	(0.18,0.27,0.6)	

Judgments of marine accident surveyors with respect to “Errors”

Errors	Skill-based errors			Judgment and decision-making errors			Misperception Errors		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Skill-based errors				Vs	Vs	Ab	Ab	Ab	Vs
Judgment and decision-making errors							Wk	Es	Eq
Misperception errors									

Aggregated judgments of marine accident surveyors

Errors	Skill-based errors	Judgment and decision-making errors	Misperception errors
Skill-based errors		(5.67,7.67,9)	(6.33,8.33,9)
Judgment and decision-making errors	(0.11, 0.13,0.1)		(1.67,3,4.33)
Misperception errors	(0.11,0.12,0.16)	(0.23,0.33,0.6)	

Table 3
Judgments of marine accident surveyors under Precondition level.

Judgments of marine accident surveyors with respect to “skill-based errors”

Skill-based errors	Environmental factors			Condition of individuals			Personnel factors		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Environmental factors				1/Wk	Eq	Eq	1/Ab	1/Ab	1/Vs
Condition of individuals							1/Ab	1/Vs	1/Vs
Personnel factors									

Aggregated judgments of marine accident surveyors

Skill-based errors	Environmental factors	Condition of individuals	Personnel factors
Environmental factors		(0.733,0.778,1)	(0.11,0.12,0.16)
Condition of individuals	(1,1.27,1.36)		(0.11,0.13,0.18)
Personnel factors	(6.18,8.22,9)	(5.53,7.56,9)	

Judgments of marine accident surveyors with respect to “judgment and decision-making errors”

Judgment and decision-making errors	Environmental factors			Condition of individuals			Personnel factors		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Environmental factors				1/Es	1/Vs	1/Vs	1/Ab	1/Vs	1/Ab
Condition of individuals							1/Ab	1/Vs	1/Es
Personnel factors									

Aggregated judgments of marine accident surveyors

Judgment and decision-making errors	Environmental factors	Condition of individuals	Personnel factors
Environmental factors		(0.12,0.16,0.24)	(0.11,0.12,0.16)
Condition of individuals	(4.09,6.18,8.13)		(0.12,0.15,0.23)
Personnel factors	(6.18,8.22,9)	(4.44,6.61,8.28)	

Judgments of marine accident surveyors with respect to “misperception errors”

Misperception errors	Environmental factors			Condition of individuals			Personnel factors		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Environmental factors				Eq	Eq	Eq	Eq	1/Vs	1/Vs
Condition of individuals							Eq	1/Vs	1/Vs
Personnel factors									

Aggregated judgments of marine accident surveyors

Misperception errors	Environmental factors	Condition of individuals	Personnel factors
Environmental factors		(1,1,1)	(0.41,0.43,0.47)
Condition of individuals	(1,1,1)		(0.41,0.43,0.47)
Personnel factors	(2.14,2.33,2.45)	(2.14,2.33,2.45)	

Judgments of marine accident surveyors with respect to “environmental factors”

Environmental factors	Physical			Technological environment		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Physical environment				1/Ab	1/Ab	1/Vs
Technological environment						

Aggregated judgments of marine accident surveyors

Environmental factors	Physical environment	Technological environment
Physical environment		(0.11,0.12,0.16)
Technological environment	(6.18,8.22,9)	

Judgments of marine accident surveyors with respect to “personnel factors”

Personnel factors	Coordination/communication/planning factors			Self-imposed stress		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Coordination/communication/planning				Ab	Vs	Ab
Self-imposed stress						

Aggregated judgments of marine accident surveyors

Personnel factors	Coordination/communication/planning factors	Self-imposed stress
Coordination/communication/planning		(6.33,8.33,9)
Self-imposed stress	(0.11,0.12,0.16)	

Table 3 (*Continued*)

Judgments of marine accident surveyors with respect to "condition of individuals"

Condition of individuals	Cognitive factors			Psycho behavioural factors			Adverse physiological			Physical mental limitations			Perceptual factor		
	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$
Cognitive factors				Eq	Eq	Es	Eq	Eq	1/Es	Eq	Es	Eq	1/Ab	1/Vs	1/Vs
Psycho behavioural factors							Es	Eq	Eq	1/Es	Es	Eq	1/Ab	1/Vs	1/Ab
Adverse physiological states										1/Es	Eq	Eq	1/Es	1/Es	1/Es
Physical mental limitations													1/Ab	1/Vs	1/Vs
Perceptual factors															

Aggregated judgments of marine accident surveyors

Condition of individuals	Cognitive factors	Psycho behavioural factors	Adverse physiological states	Physical mental limitations	Perceptual factors
Cognitive factors		(1.67,2.33,3)	(0.71,0.73,0.78)	(1.67,2.33,3)	(0.13,0.17,0.27)
Psycho behavioural factors	(0.33,0.42,0.60)		(1,1,1)	(1.38,2.07,2.78)	(0.12,0.14,0.21)
Adverse physiological states	(1.29,1.36,1.40)	(1,1,1)		(0.71,0.73,0.78)	(0.14,0.20,0.33)
Physical mental limitations	(0.33,0.43,0.60)	(0.36,0.48,0.72)	(1.27,1.36,1.4)		(0.13,0.17,0.27)
Perceptual factors	(3.71,5.87,7.56)	(4.84,7.11,8.22)	(3,5,7)	(3.71,5.87)	

Table 4
Judgments of marine accident surveyors under Supervision level.

Judgments of marine accident surveyors with respect to "physical environment"

Physical environment	Inadequate supervision			Inappropriate operations			Failed to correct problem			Supervisory violation		
	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$
Inadequate supervision				1/Ab	1/Vs	1/Vs	1/Es	1/Vs	1/Es	Es	1/Es	Eq
Inappropriate operations							Ab	Vs	Vs	Ab	Vs	Ab
Failed to correct problem										Vs	Vs	Ab
Supervisory violation												

Aggregated judgments of marine accident surveyors

Physical environment	Inadequate supervision	Inappropriate operations	Failed to correct problem	Supervisory violation
Inadequate supervision		(0.11,0.13,0.18)	(0.13,0.18,0.29)	(1.38,2.07,2.78)
Inappropriate operations	(5.55,7.58,9.03)		(5.67,7.67,9)	(6.33,8.33,9)
Failed to correct problem	(3.46,5.52,7.56)	(0.11,0.13,0.18)		(5.67,7.67,9)
Supervisory violation	(0.36,0.48,0.72)	(0.11,0.12,0.16)	(0.11,0.13,0.17)	

Judgments of marine accident surveyors with respect to "technological environment"

Technological environment	Inadequate supervision			Inappropriate operations			Failed to correct problem			Supervisory violation		
	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$
Inadequate supervision				Eq	Eq	1/Es	1/Es	1/Es	1/Es	Ab	Vs	Vs
Inappropriate operations							Eq	Eq	Eq	Es	Es	Ab
Failed to correct problem										Ab	Ab	Ab
Supervisory violation												

Aggregated judgments of marine accident surveyors

Technological environment	Inadequate supervision	Inappropriate operations	Failed to correct problem	Supervisory violation
Inadequate supervision		(1,1,1)	(0.73,0.78,1)	(3,5,7)
Inappropriate operations	(1,1,1)		(1.38,2.07,2.78)	(2.33,3.67,5)
Failed to correct problem	(1,1.29,1.36)	(0.36,0.48,0.72)		(3,5,7)
Supervisory violation	(0.14,0.20,0.33)	(0.2,0.27,0.43)	(0.14,0.20,0.33)	

Judgments of marine accident surveyors with respect to "cognitive factors"

Cognitive factors	Inadequate supervision			Inappropriate operations			Failed to correct problem			Supervisory violation		
	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$	DM$_1$	DM$_2$	DM$_3$
Inadequate supervision				Eq	Eq	Eq	Eq	1/Wk	Eq	Es	Es	Es
Inappropriate operations							1/Es	Es	Eq	Es	Es	Eq
Failed to correct problem										Es	Es	Es
Supervisory violation												

Aggregated judgments of marine accident surveyors

Cognitive factors	Inadequate supervision	Inappropriate operations	Failed to correct problem	Supervisory violation
Inadequate supervision		(1,1,1)	(0.73,0.78,1)	(3,5,7)
Inappropriate operations	(1,1,1)		(1.38,2.07,2.78)	(2.33,3.67,5)
Failed to correct problem	(0.36,0.48,0.72)	(0.36,0.58,0.72)		(3,5,7)
Supervisory violation	(0.14,0.20,0.33)	(0.20,0.27,0.42)	(0.14,0.20,0.33)	

Table 4 (*Continued*)

Judgments of marine accident surveyors with respect to “psycho behavioural factors”

Psycho behavioural factors	Inadequate supervision			Inappropriate operations			Failed to correct problem			Supervisory violation		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Inadequate supervision				Eq	Es	Eq	Eq	1/Es	1/Es	1/Ab	1/Ab	1/Vs
Inappropriate operations							Eq	1/Es	Eq	Es	Es	Vs
Failed to correct problem										Vs	Es	Es
Supervisory violation												

Aggregated judgments of marine accident surveyors

Psycho behavioural factors	Inadequate supervision	Inappropriate operations	Failed to correct problem	Supervisory violation
Inadequate supervision		(1.67,2.33,3)	(0.43,0.47,0.56)	(0.11,0.12,0.16)
Inappropriate operations	(0.33,0.42,0.6)		(0.71,0.73,0.78)	(3.67,5.67,7.67)
Failed to correct problem	(1.8,2.14,2.33)			(3.67,5.67,7.67)
Supervisory violation	(.617,8.22,9)	(0.13,0.17,0.27)	(0.13,0.17,0.27)	

Judgments of marine accident surveyors with respect to “adverse physiological states”

Adverse physiological states	Inadequate supervision			Inappropriate operations			Failed to correct problem			Supervisory violation		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Inadequate supervision				Eq	Es	Es	1/Es	1/Vk	1/Vs	Es	Es	Vs
Inappropriate operations							Eq	Eq	Vk	Es	Es	Es
Failed to correct problem										Ab	Es	Es
Supervisory violation												

Aggregated judgments of marine accident surveyors

Adverse physiological states	Inadequate supervision	Inappropriate operations	Failed to correct problem	Supervisory violation
Inadequate supervision		(2.33,3.67,5)	(0.15,0.23,0.51)	(3.67,5.67,7.67)
Inappropriate operations	(0.2,0.27,0.42)		(1,1.67,2.33)	(3,5,7)
Failed to correct problem	(1.95,4.43,6.61)	(0.42,0.60,1)		(4.33,6.33,7.67)
Supervisory violation	(0.13,0.18,0.27)	(0.14,0.20,0.33)	(0.13,0.15,0.23)	

Judgments of marine accident surveyors with respect to “physical mental limitations”

Physical mental limitations	Inadequate supervision			Inappropriate operations			Failed to correct problem			Supervisory violation		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Inadequate supervision				Eq	Es	Eq	1/Vs	Vk	Eq	Ab	Es	Ab
Inappropriate operations							1/Vs	Vk	1/Vs	Es	Vs	Es
Failed to correct problem										Es	Ab	Es
Supervisory violation												

Aggregated judgments of marine accident surveyors

Physical mental limitations	Inadequate supervision	Inappropriate operations	Failed to correct problem	Supervisory violation
Inadequate supervision		(1.67,2.33,3)	(0.44,0.49,0.73)	(5.67,7.67,8.33)
Inappropriate operations	(0.33,0.43,0.60)		(0.14,0.21,0.47)	(3.67,5.67,7.67)
Failed to correct problem	(1.36,2.03,2.28)	(2.14,4.85,7.10)		(4.33,6.33,7.67)
Supervisory violation	(0.12,0.13,0.17)	(0.13,0.17,0.27)	(0.13,0.16,0.23)	

Judgments of marine accident surveyors with respect to “perceptual factors”

Perceptual factors	Inadequate supervision			Inappropriate operations			Failed to correct problem			Supervisory violation		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Inadequate supervision				Eq	1/Es	Eq	Eq	Vk	Eq	Es	Ab	Vs
Inappropriate operations							Eq	1/Vk	Eq	Es	Ab	Ab
Failed to correct problem										Vs	Ab	Ab
Supervisory violation												

Aggregated judgments of marine accident surveyors

Perceptual factors	Inadequate supervision	Inappropriate operations	Failed to correct problem	Supervisory violation
Inadequate supervision		(0.71,0.73,0.78)	(1,1.67,2.33)	(5,7,8.33)
Inappropriate operations	(1.29,1.36,1.4)		(0.73,0.78,1)	(5.67,7.67,8.33)
Failed to correct problem	(0.43,0.60,1)	(1,1.23,1.36)		(6.33,833,9)
Supervisory violation	(0.12,0.14,0.20)	(0.12,0.13,0.17)	(0.11,0.12,0.16)	

Table 4 (*Continued*)

Judgments of marine accident surveyors with respect to “coordination/communication/planning factors”

Coordination/communication/planning factors	Inadequate supervision			Inappropriate operations			Failed to correct problem			Supervisory violation		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Inadequate supervision				Eq	Vk	Eq	Eq	1/Vk	Eq	Es	Ab	Vs
Inappropriate operations							1/Vs	1/Es	1/Vs	Es	Es	Ab
Failed to correct problem										Es	Es	Vs
Supervisory violation												

Aggregated judgments of marine accident surveyors

Coordination/communication/planning factors	Inadequate supervision	Inappropriate operations	Failed to correct problem	Supervisory violation
Inadequate supervision		(1,167,2,33)	(0.73,0.78,1)	(5,7,8.33)
Inappropriate operations	(0.43,060,1)		(0.12,0.16,0.24)	(4.33,6.33,7.67)
Failed to correct problem	(1,1.28,1.36)	(4.09,6.18,8.22)		(3.67,5.67,7.67)
Supervisory violation	(0.12,0.14,0.20)	(0.13,0.15,0.23)	(0.13,0.18,0.27)	

Judgments of marine accident surveyors with respect to “self-imposed stress”

Self-imposed stress	Inadequate supervision			Inappropriate operations			Failed to correct problem			Supervisory violation		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Inadequate supervision				Eq	1/Vk	Eq	Eq	Eq	Eq	Eq	Eq	Vk
Inappropriate operations							Eq	Vk	Vk	Eq	Eq	Vk
Failed to correct problem										Eq	Vk	Eq
Supervisory violation												

Aggregated judgments of marine accident surveyors

Self-imposed stress	Inadequate supervision	Inappropriate operations	Failed to correct problem	Supervisory violation
Inadequate supervision		(0.73,0.78,1)	(1,1,1)	(1,1.67,2.33)
Inappropriate operations	(1,1.29,1.36)		(1,2.33,3.67)	(1,1.67,2.33)
Failed to correct problem	(1,1,1)	(0.27,0.42,1)		(1,1.67,2.33)
Supervisory violation	(0.43,0.60,1)	(0.42,0.60,1)	(0.43,0.6,1)	

Table 5

Judgments of marine accident surveyors under Organizational Influences.

Judgments of marine accident surveyors with respect to “inadequate supervision”

Inadequate supervision	Resource management			Organizational climate			Organizational process		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Resource management				1/Vs	1/Vk	1/Vs	1/Vs	1/Ab	1/Vs
Organizational climate							Eq	Eq	Vk
Organizational process									

Aggregated judgments of marine accident surveyors

Inadequate supervision	Resource management	Organizational climate	Organizational process
Resource management		(0.14,0.21,0.47)	(0.11,0.13,0.18)
Organizational climate	(2.14,4.84,7.11)		(0.73,0.78,1)
Organizational process	(5.53,7.56,9)	(1,1.29,1.36)	

Judgments of marine accident surveyors with respect to “planned inappropriate operations”

Inappropriate operations	Resource management			Organizational climate			Organizational process		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Resource management				1/Vs	1/Vs	1/Ab	1/Vs	1/Vk	1/Vs
Organizational climate							Eq	Eq	Eq
Organizational process									

Aggregated judgments of marine accident surveyors

Inappropriate operation	Resource management	Organizational climate	Organizational process
Resource management		(0.11,0.13,0.18)	(0.14,0.21,0.47)
Organizational climate	(5.53,7.56,9)		(1,1,1)
Organizational process	(2.14,4.85,7.11)	(1,1,1)	

Table 5 (*Continued*)

Judgments of marine accident surveyors with respect to “failure to correct known problem”

Failure to correct problem	Resource management			Organizational climate			Organizational process		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Resource management				1/Vs	1/Vk	Eq	Eq	1/Vk	1/Vk
Organizational climate							Eq	Eq	1/Vk
Organizational process									

Aggregated judgments of marine accident surveyors

Failed to correct problem	Resource management	Organizational climate	Organizational process
Resource management		(0.44,0.49,0.73)	(0.17,0.27,0.73)
Organizational climate	(1.36,2.03,2.29)		(0.73,0.78,1)
Organizational process	(1.36,3.71,5.87)	(1,1.29,1.36)	

Judgments of marine accident surveyors with respect to “supervisory violation”

Supervisory violation	Resource management			Organizational climate			Organizational process		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Resource management				1/Vs	1/Ab	1/Vs	Eq	1/Vk	Eq
Organizational climate							1/Ab	1/Vs	1/Ab
Organizational process									

Aggregated judgments of marine accident surveyors

Supervisory violation	Resource management	Organizational climate	Organizational process
Resource management		(0.11,0.13,0.18)	(0.73,0.78,1)
Organizational climate	(5.53,7.56,9)		(0.11,0.12,0.16)
Organizational process	(1,1.29,1.36)	(6.17,8.21,9)	

ments of marine accident surveyors for different levels of HFACS were involved in the investigation process to ensure group consensus. Then, Eq. (2) was used to obtain a group consensus in the decision-making process. Assigned judgments of experts and aggregated values that derive from the statements of three marine accident survivors are given in Tables 2–5 . A sample calculation for aggregation is given as follows:

$$\tilde{C}_{12} = \frac{1}{3}(\tilde{C}_{ij}^{1} + \tilde{C}_{ij}^{2} + \tilde{C}_{ij}^{3})$$

$$\tilde{C}_{12} = \frac{1}{3}((1, 3, 5) + (3, 5, 7) + (1, 3, 5))$$

$$\tilde{C}_{12} = (1.67, 3.67, 5.67)$$

The weights of contributing factors are calculated by Eqs. (3)–(6). The contributing factors are given in Table 6.

Following the priority weights on the factors within the analytical HFACS framework, the next step is to interpret them as meaningful information, and then to implement corrective/preventive actions. The following sections of this paper discuss how the quantitative results can be traced to point out the contributing factors.

4.3. Findings and discussion

According to the distribution of priority weights, clusters of highly contributing factors appeared in first impressions from the results. Considering the distances between the priority weights is an ideal philosophy to eliminate factors which do not deal with the occurrence of shipping accidents. As a strong point of analytical HFACS in practice, the relevant decision-makers (marine accident surveyors, shipping managers, legislative authorities) can follow the factors' weights in order to determine precautionary roadmaps for reducing the probability of similar accidents.

Recalling the computed priority weights on factors, a technical synthesis of the shipping accident case can be propounded as follows: First, skill-based errors (priority weight 0.60) are the primary cause at the first level of the HFACS framework for this accident case. The incompetence of some engine room personnel, especially the third engineer and other engine room crew on boiler maintenance, is clearly underlined. At the second level of analytical HFACS, the lack of preconditions, especially in personnel-related factors such as coordination, communication, and planning

Table 6
Weights of contributing factors to shipping accident.

Contributing factors on shipping accident		Priority weights
Acts		
Errors	Skill-based errors	0.60
	Judgment and decision-making errors	0.11
	Misperception errors	0.05
Violations		0.24
Preconditions		
Environmental	Physical environmental	0.01
	Technological environmental	0.11
Condition of individuals	Cognitive factors	0.02
	Psycho behavioural factors	0.02
	Adverse physiological states	0.02
	Physical mental limitations	0.01
	Perceptual factors	0.11
Personnel factors	Coordination/communication/planning factors	0.61
	Self-imposed stress	0.08
Supervision		
Inadequate supervision		0.32
Inappropriate operation		0.28
Failed to correct problem		0.31
Supervisory violations		0.09
Organizational influences		
Resource management		0.12
Organizational climate		0.38
Organizational process		0.50

(priority weight 0.61), is noted. Inadequate crew potential and disorganization in maintenance planning and management processes are significantly evidenced at both levels, and appear to have been triggered by the inadequate supervision (0.32) and failure to correct problems (priority weight 0.31) at the third level of analytical HFACS. At the fourth level, the root causes of this shipping accident appear to be significant shortfalls in the execution of organizational processes (priority weight 0.50), especially in shipboard maintenance and organizational climate (priority weight 0.38), which is related to the spreading of an occupational safety culture as well.

Consequently, the proposed analytical HFACS method ensures evaluation of active and latent human errors quantitatively. Future efforts can be focused on redesigning managerial and operational procedures and considering preventive/corrective actions based on the priority weights of contributing factors in this shipping accident case.

5. Conclusion

This paper proposed an analytical HFACS mechanism for identifying latent human errors in shipping accidents. In a broad sense, this research enables the following contributions to the accident analysis and prevention literature: (1) improving the structure of the existing HFACS model, (2) extending the application of HFACS to shipping accidents. It is especially novel to add quantification ability to the analytical HFACS to prioritize the contributing factors in accidents, which satisfies the need to redesign safety guidelines in different industries. Additionally, the practical application of analytical HFACS to a real case involving a shipping accident is recognized as an original application.

In detail, the findings of this illustrative case application indicate human errors as contributing factors at different levels of the organization. Statistical reports have also been concerned with human errors in shipping accidents (Rothblum, 2000; O'Neil, 2003; Darbra and Casal, 2004; Toffoli et al., 2005), and international maritime authorities are seeking solutions. Therefore, the outcomes of an analytical HFACS model meet a need that currently exists in the shipping industry. Besides providing satisfaction of industrial needs, the analytical HFACS mechanism is expected to increase the consistency of findings and to prevent the possible manipulation of data in the shipping accident investigation process, using the advantages of FAHP integration. The results can be either the improvement of safety precautions in shipping companies or the publication of new maritime regulations.

Furthermore, an extended database of human errors can easily be established based on the analytical HFACS mechanism, utilizing the reports of maritime accident investigation branches. The original contribution of adding a quantification process to the HFACS framework can also be recognized as an advance in ongoing research towards enhancement of the accident investigation process in different disciplines.

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