A comprehensive model for human factors evaluation in maritime accident: HFACS and FAHP

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Abstract: Human factors are widely regarded to be the most highly contributing factors to maritime accident prevention system failures. A comprehensive analysis model involving Human Factors Analysis and Classification System (HFACS) and Fuzzy Analytic Hierarchy Process (FAHP) is proposed in this study, which is applied to investigation human factors involved in maritime accidents. the accident scenarios stemmed from sand carrier accident database in China are developed to verified the proposed analysis model, and the top ten most highly contributing primary events associated with the human factors leading to sand carrier accidents are identified. Moreover, potential safety countermeasures for the most highly contributing human factors are proposed.

1. Introduction

Maritime transportation is characterized by highly complex and uncertain safety risks originating from various stakeholders associated with the shipping industry. Of all the causes of maritime accidents, human factors, including human error and organizational failure, are considered the primary contributors to maritime accidents. However, the assessment of human factors involved in maritime accidents is undoubtedly difficult due to the lack of data on human factors available from the maritime industry. Therefore, a variety of assessment techniques have been introduced by safety scholars and practitioners. These techniques can be divided into two branches, namely, empirical techniques and expert judgment. Empirical techniques emphasize the collection of data on human factors. The human factors involved in worldwide ship accidents occurring in 2000-2012 were analyzed by Eleftheria et al.[1]. Expert judgment is being given increased attention due to the complexity and uncertainty of the human factors associated with maritime accidents. Additional techniques have been broadly used to analyze human factors, such as the System-Theoretic Accident Model and Processes, Classification of Socio-Technical Systems[2], System Dynamics, AcciMap, the Human Factors Analysis and Classification System (HFACS) and STAMP. Among these models, Salmon et al.[3] Suggested that HFACS was the most reliable due to its taxonomic nature, especially for multiple case studies. Akyuz et al.[4] Defined ERROR-Producing Conditions (EPCs) in terms of ship operational management by combining multi-dimensional approaches, including HFACS, HEART and AHP, that help maritime safety professionals and practitioners predict human errors.

The present study mainly aims to pioneer the combined application of HFACS and FAHP to investigate the influence of human factors on maritime accident prevention. For this purpose, a comprehensive analysis model is first developed based on HFACS and FAHP. Then, a maritime accident scenario is defined based on the accident database of sand carriers operating in the domestic waters in the P. R. China in 2018, consisting of 58 accidents totally. Finally, the proposed methodology in this study is applied to analysis human factors associated in the defined scenario.

2. Methodology

2.1 HFACS framework

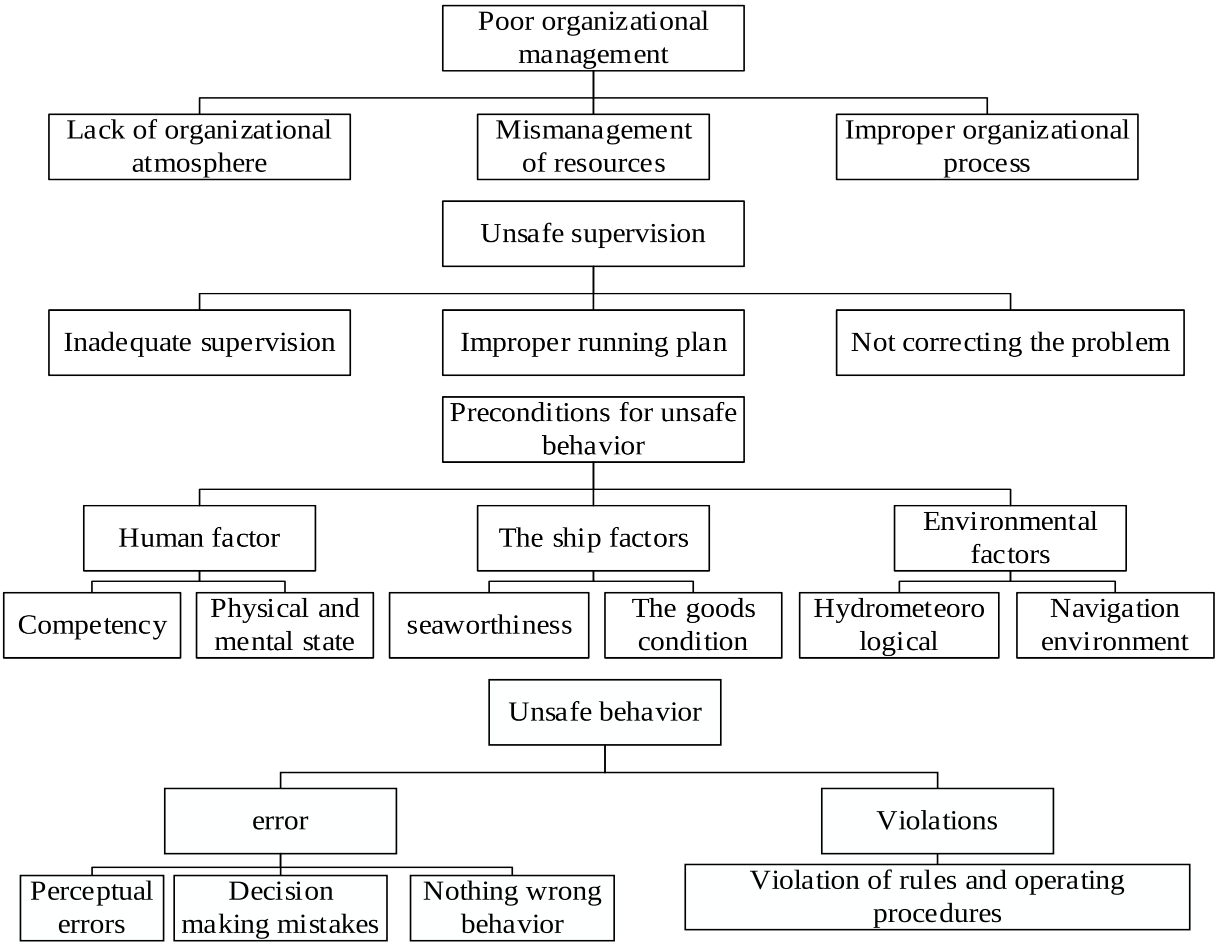

Figure 1. HFACS model diagram

2.2 Fuzzy AHP

There are three main approaches to addressing the probability of system failure, namely, statistical methods, extrapolation, and expert judgment. In this study, the expert judgment method is applied as a scientific consensus technique to weight the identified human factors involved in the marine accident scenario. However, as specialists tend to express their opinions on each event based on their individual vision, purpose and intellectual characteristics, various analysis models have been developed, such as fuzzy priority relations, game theory, the max-min Delphi method and the similarity aggregation method (SAM). It is very difficult to identify a technique that is superior to the others for aggregating expert opinions[5]; however, it is widely accepted that ambiguous expression from experts is extremely common. Thus, a combination of fuzzy set theory and the Analytic Hierarchy Process (AHP) is frequently used to deal with experts' ambiguity.

Fuzzy numbers have been frequently utilized in various case studies. The trapezoidal fuzzy numbers would be adopted in the study, the membership function can be found in Wojciech T. et al [6].The linguistic expression of experts is critically valuable to handle complex circumstances and obtain meaningful conclusions. Subsequently, the relationships between the qualitative expression of experts and the corresponding fuzzy numbers are extremely significant. Several attempts have been made to translate qualitative linguistic expressions into their corresponding fuzzy numbers.

2.3 The expert capability evaluation

The expert judgment method has been widely adopted in different fields, including risk analysis, accident investigation, decision examination, etc. Expert elicitation is applied in this studyto accumulated specialist opinions about human factors under physical circumstances with uncertainty; therein, expert competence is critically significant for scientific conclusions. To deal with any cognitive biases presented by individual expert viewpoints, it is vital to aggregate expert opinions. The information about expertscan be continuously processed according to the methodology associated by Buckley J. J.[7]. Until the weight of the individual expert is calculated.

2.4 Fuzzy aggregation data

These linguistic expressions of each expert can then be converted into their corresponding trapezoidal fuzzy numbers, which can be processed as follows, until defuzzification is achieved.

(1) Calculation of the degree of similarity. $S_{uv}(\widetilde{E}_u, \widetilde{E}_v)$ Is defined as the degree of agreement for different opinions between each pair of experts. Suppose $\widetilde{E}_u$ and $\widetilde{E}_v$ are represented as two triangular fuzzy numbers ($u \neq v$), then,

$$S_{uv}(\widetilde{E}_u, \widetilde{E}_v) = 1 - \frac{1}{J}\sum_{i=1}^{J}\left|a_i - b_i\right| \quad i = 1,2,3 \tag{1}$$

Where J is the number of fuzzy set members, $J = 4$ for standard trapezoidal fuzzy numbers.

(2) Calculation for the Average of Agreement (AA) degree for each expert viewpoint.

$$AA\left(E_u\right) = \frac{1}{U-1}\sum_{u \neq v, v=1}^{U} S_{uv}(\widetilde{E}_u, \widetilde{E}_v) \tag{2}$$

Where U is the total number of experts.

(3) Calculation for the Relative Agreement (RA) degree between two kinds of experts. The value of $RA(E_u)$ can be obtained by,

$$RA(E_u) = \frac{AA\left(E_u\right)}{\sum_{u=1}^{U} AA\left(E_u\right)} \tag{3}$$

(4) Estimation of the Consensus Coefficient (CC) for each expert. The value of $CC(E_u)$ for the u^{th} expert can be obtained by,

$$CC\left(E_u\right) = \beta * P(E_u) + (1-\beta) * RA(E_u) \tag{4}$$

Where the coefficient $\beta (0 \leq \beta \leq 1)$ is introduced to represent the importance of $P(E_u)$ over $RA(E_u)$.

(5) Calculation for the aggregated results of the experts' viewpoints. The aggregated results denoted by $\widetilde{R}_A$ can be computed by

$$\widetilde{R}_A = CC\left(E_1\right) \otimes \widetilde{E}_1 \oplus CC\left(E_2\right) \otimes \widetilde{E}_2 \oplus \cdots \oplus CC\left(E_U\right) \otimes \widetilde{E}_U \tag{5}$$

(6) Defuzzification of the aggregated results. The method of Center of Area (CoA) extended by Prasad N. R. et al[8]. Is widely used for the defuzzification operation, which is expressed as,

$$AV = \frac{\int \mu_M(x)xdx}{\int \mu_M(x)dx} \tag{6}$$

Where AV (Aggregated value) represents the defuzzification result, and $\mu_M(x)$ indicates the aggregated membership functions. Therefore, the fuzzy numbers of the aggregated results, denoted as $\widetilde{R}_A(c_1, c_2, c_3, c_4)$ for fuzzy trapezoidal numbers, can be defuzzificated by (4) and (5), respectively.

3. Application of the methodology

3.1 Scenario development

In this section, a marine case study is selected to illustrate the developed methodology. In this study, sand carrier accidents occurring in China in 2018 are used as a database (58 total accidents). As the first step of this case study, accident investigation reports were collected from maritime authorities. A large number of maritime accident investigators, as well as people associated with the accidents, were interviewed face-to-face to obtain detailed information. Based on the information obtained, it was preliminarily found that the human factors were distributed across the whole shipping process.

3.2 Human factors identification based on HFACS

Table 1. Identified human errors based on HFACS—Unsafe Acts

Item	Unsafe Acts
UA1	no inspection of emergency equipment, such as life boat, emergency steering gear, etc.
UA2	Inspection absence of communication between ship and ashore, deck and engine dep.
UA3	violations against safety regulations and law
UA4	unable to operate equipment or operate equipment incorrectly
UA5	decision errors, such as ignorance of weather ,inappropriate decisions in an emergency
UA6	lack of operational equipment on ship, especially emergency equipment
UA7	incorrect loading, including overloading and failing to follow loading procedures
UA8	ships intended for other purposes are used to carry sand
UA9	no navigation notice for rough seas
UA10	incorrect pilot operation
UA11	information missing during watching duty handover
UA12	fatigue watch keeping
UA13	attention deficit during watch keeping
UA14	lack of understanding of watch keeping responsibility

Table 2. Identified human errors based on HFACS-Unsafe Preconditions

Item	Unsafe Preconditions
UP1	no inspection of physical and mental limitations: including knowledge, aptitude, skill, etc.
UP2	lack of inspection of the safety related documentation on board the ship
UP3	poor organization and teamwork of seafarers on board the ship
UP4	insufficient number of crew employed
UP5	incompetent seafarers or lack of competency certificates
UP6	lack of understanding of safety regulations and laws
UP7	insufficient operational procedure instruction for equipment
UP8	ship resource mismanagement and/or bridge resource management deficiencies
UP9	failures in bridge design/instrumentation
UP10	sand carrier registered for inland waters sailing in coastal area illegally
UP11	ship structure changed without authorization
UP12	insufficient learning from accidents
UP13	improper natural environmental conditions: fog, poor visibility, etc.
UP14	seafarer readiness failure: excessive work duties, violations of rest regulations
UP15	being under the influence of alcohol
UP16	the Automatic Identification System (AIS) is shut off manually or lack of AIS

Table 3. Identified human errors based on HFACS-Unsafe Supervision

Item	Unsafe Supervision
US1	Little attention paid to drills before departure and lack of drill records
US2	Inadequate inspection for equipment certificates and maintenance records
US3	lack of cargo (sand) inspection before departing the port
US4	unqualified inspection for seafarer training and/or restricted time for training
US5	seafarer competency certificate mismanagement
US6	little responsiveness to maritime authorities for corrective measures of deficiencies
US7	no compliance with the Safety Management System
US8	failure to provide guidance, operational doctrine and navigating products, etc.
US9	failure to track performance and qualifications
US10	failure to identify illegal sand carriers sailing in coastal areas
US11	little attention paid to watch keeping records

Table. 4. Identified human errors based on HFACS-Organizational Influence

Item	Organizational Influence
OI1	commands, regulations, and policies not reaching the ship prior to departure
OI2	no implementation of risk assessment before departure
OI3	training planning and implementation is performed superficially
OI4	the cost of illegal behavior for seafarers due to lack of credit management
OI5	inappropriate safety management organization on board the ship
OI6	purchasing substandard equipment and/or spare parts for the ship
OI7	inadequate budget for ship safety
OI8	the influence of commercial pressure
OI9	deficiencies in the Safety Management System established by the company
OI10	lack of effective communication between port and maritime authorities
OI11	the cost of illegal behavior for the company due to lack of credit management
OI12	multiple parties are involved in the management of the sand carrier sailing inland waters
OI13	watch keeping regulation is missing or implemented superficially
OI14	watch keeping responsibility is confusing

3.3 Expert elicitation and aggregating data

In the present study, transformation scale six, including 5 verbal expressions, was selected to design an expert questionnaire to determine the impact of the human factors on the defined accident scenario. The fuzzy trapezoidal numbers can be found by Gupta S. et al[9].

Table 5. Evaluation results of expert capabilities

Expert	Position	Experience	Education	Age	Certificate	Weight
Expert 1	Engineer	30	Master	53	Senior Captain	0.29
Expert 2	Engineer	27	Master	50	Chief Officer	0.18
Expert 3	Senior academic	22	Ph.D	48	Senior Chief Engineer	0.33
Expert 4	Junior academic	18	Master	41	Captain	0.19
Expert 5	Engineer	8	Bachelor	32	2nd Engineer	0.08

Organizing opinions on the failure rate of language expression by experts and using the similarity aggregation method (SAM) to aggregate expert opinions. According to the study of Yazdi et al.[10], $\beta = 0.5$ was considered to be optimal value. Following the calculation principle presented in section 2, and the methodology proposed by Onisawa [11] for the transmission of the impact rate of the human factors into Failure Probability (FP), the results for the aggregation of the experts' opinions and defuzzification are represented in Table 6.

Table 6. Aggregation computation for each human factors

Item	AV	FP	Item	AV	FP	Item	AV	FP	Item	AV	FP
UA1	0.624	0.011	UP1	0.220	0.000	UP15	0.372	0.001	OI2	0.245	0.000
UA2	0.541	0.006	UP2	0.326	0.001	UP16	0.449	0.003	OI3	0.582	0.008
UA3	0.907	0.084	UP3	0.343	0.001	US1	0.680	0.016	OI4	0.696	0.018
UA4	0.828	0.043	UP4	0.566	0.007	US2	0.291	0.001	OI5	0.631	0.011
UA5	0.780	0.031	UP5	0.553	0.007	US3	0.555	0.007	OI6	0.659	0.014
UA6	0.805	0.037	UP6	0.566	0.007	US4	0.429	0.002	OI7	0.566	0.007
UA7	0.848	0.050	UP7	0.462	0.003	US5	0.215	0.000	OI8	0.683	0.016
UA8	0.790	0.033	UP8	0.489	0.004	US6	0.583	0.008	OI9	0.664	0.014
UA9	0.456	0.003	UP9	0.810	0.038	US7	0.720	0.020	OI10	0.512	0.005
UA10	0.354	0.001	UP10	0.900	0.078	US8	0.641	0.012	OI11	0.710	0.019
UA11	0.427	0.002	UP11	0.748	0.025	US9	0.489	0.004	OI12	0.597	0.009
UA12	0.711	0.019	UP12	0.445	0.003	US10	0.613	0.010	OI13	0.575	0.008
UA13	0.844	0.048	UP13	0.561	0.007	US11	0.597	0.009	OI14	0.508	0.005
UA14	0.363	0.001	UP14	0.569	0.008	OI1	0.630	0.011			

4. Conclusion

In the present study, a comprehensive model is proposed combining HFACSand FAHP. Focusing on human factors (human errors and organizational failures), the model first aims to identify, characterize and rank the human factors involved in maritime accidents from a causation perspective. Then, the proposed model is applied to a defined maritime accident scenario based on an accident database of sand carriers in China.

Additionally, the proposed model can effectively handle the uncertainty and intuitive opinions of experts regarding sand carrier accident analysis. The results show that unsafe supervision and unsafe preconditions are highly responsible for the defined accident scenario.

Furthermore, the probability updates point to human errors concerning routine violations against existing laws and regulations (associated with UP6, UP10, and IO11) and supervision failures concerning shipping company management (associated with US4, US7, SU9, and SU6) as the most critical areas of failure.

Based on the findings and conclusions above, specific safety countermeasures can be proposed to improve the safety level of sand carrier operation and prevent the re-occurrence of similar accidents. Such as: offering occupational safety training and certificate management for seafarers, developing a safety checklist for ship operators and companies, improving the effectiveness and implementation of laws and regulations.

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