A preliminary mapping network model for unsafe acts in maritime accidents

Shanshan Fu¹, Hui Zhuang¹, Changjiang Zhang¹ and Yongtao Xi²
¹ College of Transport and Communications, Shanghai Maritime University, Shanghai, 201306, China
² Merchant Marine College, Shanghai Maritime University, Shanghai, 201306, China

Email: ssfu@shmtu.edu.cn

Abstract. Unsafe acts are a critical issue causing maritime accidents. In order to explore the correlations between the crew’s unsafe acts and the induced maritime accidents, this paper proposes a preliminary mapping network model. Its first part is a hierarchical model, making crews’ unsafe acts as the top layer, skill-based failures, rule- and knowledge-based mistakes and violations acts as criteria, and basic unsafe acts (BUA) as the bottom layer. Therein, the BUAs are identified from 413 marine accident/incident investigation reports and 91 crews’ questionnaires. The second part is composed of several maritime accident types. The connection links between these two parts are aiming to reveal the correlations between each BUA and the specific maritime accident type. The proposed mapping network model can not only support unsafe acts analysis for one and multiple maritime accidents but also present the common BUAs for safety management.

1. Introduction
The maritime accident is a permanent issue of common concern in the safety management of maritime transportation systems (MTS). Among various influencing factors, the contribution of human factors to maritime accidents is approximately 80% [1], according to the records of marine accident/incident investigation.

In the last decades, unsafe acts and human factors in maritime accidents have been studied from various perspectives and with different techniques. For example, Akhtar and Bouwer Utne [2] studied human fatigue-related accidents using cognitive reliability and error analysis method (CREAM). Lema [3] studied the combined effects of human factors, equipment and environment by applying the K-means clustering method to analyze 355 accidents. Graziano et al. [4] applied the TRACER taxonomy for the classification of human errors in grounding and collision accidents. Mazaheri et al. [5] proposed an
evidence-based risk model for grounding accidents using human factors analysis and classification system (HFACS).

The literature focuses on analyzing one or two specific types of maritime accidents. However, it rarely explores the direct linkage between the crew’s unsafe acts and different types of maritime accidents. Also, the existing frameworks of human factors are academic and abstract [6], resulting in the difficulty of being applied in practice. Therefore, this study proposes preliminary mapping network model based on objective maritime accident investigation reports and on-the-job crews’ experience feedback in the questionnaire survey, in order to recognize typical unsafe acts on board, understand linkages between specific unsafe acts and maritime accidents, reveal the mechanism of unsafe acts in an individual level, and propose practical interventions.

The rest of the paper is organized as follows. Section 2 proposes a preliminary mapping network model for unsafe acts in maritime accidents. Sections 3 introduces the data sources used for the identification of critical BUAs. Section 4 shows the statistic results and the mapping relationship results. Section 5 discusses the resulting mapping network model and proposes some suggestions, and section 6 provides concluding remarks.

2. Methods

2.1. Hierarchical unsafe acts model

Recall the researches of human factors in the last half-century, some popular frameworks of human factors were proposed, such as skill-rule-knowledge (S-R-K) taxonomy [7], generic error modeling system (GEMS) [8], the Swiss cheese model (SCM) [9], cognitive reliability error analysis method (CREAM) [10], human factor analysis and classification system (HFACS) [11]. Among them, Rasmussen’s S-R-K taxonomy and the Reason’s GEMS are the most typical ones that classified unsafe acts at the individual level, while others may consider human factors at the organizational level or describe human factors in chains.

Rasmussen’s S-R-K taxonomy was proposed from the perspective of internal information processing, see figure 1. Moreover, Reason’s GEMS extended the concept of unsafe acts by adding the violation type, see figure 2.

In light of these two frameworks, a conceptional mapping network model is proposed, as shown in figure 3. The first part is a hierarchical model, including three layers. Unsafe acts as the top goal in this study is put in the top layer. The taxonomy of the crew’s unsafe acts, which could be unfolded as skill-based failure, rule- and knowledge-based mistakes and violation acts, is the second layer, regarding Rasmussen’s S-R-K taxonomy and the Reason’s GEMS. The third layer is composed of the BUAs that occurred in marine accident/incident investigations and perspectives of crews in the questionnaire survey.
**Figure 1.** Rasmussen’s S-R-K taxonomy.

**Figure 2.** Reason’s GEMS.

Therein, a taxonomy of the crew’s unsafe acts is developed as follows:

- **Skill-based failures**: performance controlled by stored patterns of behavior, and subconscious routines.
- **Rule- and knowledge-based mistakes**: actions performed after consideration but result in errors without intention.
- Rule-based mistakes: performance controlled by stored rules, usually happens in familiar situations, such as wrong applications of good rules.
- Knowledge-based mistakes: performance with no rules to apply, depending on situations and individual knowledge, usually happens in unfamiliar situations.
- Violations: deliberate deviations from standard practice.

The rule-based and knowledge-based mistakes in the model are combined, due to the rule- and knowledge-based mistakes are difficult to be clearly distinguished in the actual maritime accident investigation reports. Hence, the three main origins of unsafe acts: skilled-based failure, rule- and knowledge-based mistakes and violation acts, are set as the second layer. The third layer is composed of BUAs, including inevitable human failure, mistake, and violation. These human factors are extracted from accident investigation reports and perspectives of crews in the questionnaire survey. The identification and acquirement process of these BUAs will be described in the subsequent sections.

![Hierarchical unsafe acts model](image)

**Figure 3.** A conceptual mapping network model for unsafe acts in maritime accidents.

### 2.2. Connected network

The accident scenarios part includes typical accident types in the MTS, such as collision, grounding, and fire/explosion. The connection lines of the mapping network model for maritime accidents are from the BUAs to specific accident scenarios. The decision process will be described in the subsequent sections. Based on these, a conceptual framework for unsafe acts in maritime accidents are obtained, see figure 3. Moreover, the mapping network model can not only support unsafe acts analysis for one and multiple maritime accidents but also present the common BUAs for several maritime accidents.
3. Data

3.1. Maritime accident investigation reports

This study focuses on three major accident scenarios in MTS, including collision, grounding, and fire/explosion. Marine accident/incident investigation reports are collected from UK’s Maritime Accident Investigation Branch (MAIB), the Australian Transport Safety Bureau (ATSB), the Transportation Safety Board of Canada (TSB) and the New Zealand’s Transport Accident Investigation Commission (TAIC) from 1998 to 2017.

As shown in Table 1, 413 marine accident/incident investigation reports are collected from the above databases, including 128 collision, 162 grounding, and 123 fire/explosion accident reports. Among these, 151 reports originate from the MAIB, 104 reports originate from the ATSB, 108 reports originate from the TSB, and 50 reports originate from the TAIC.

| Accident scenarios     | MAIB | ATSB | TSB | TAIC | Total |
|------------------------|------|------|-----|------|-------|
| Collision              | 52   | 30   | 18  | 28   | 128   |
| Grounding              | 60   | 43   | 59  | 0    | 162   |
| Fire/Explosion         | 39   | 31   | 31  | 22   | 123   |

3.2. Questionnaire survey

A questionnaire survey is conducted for identifying the critical unsafe acts in maritime accidents. From February 2019 to May 2019, crew members from the shipping company in Shanghai, Zhejiang and Jiangsu participated in this survey, and 91 valid questionnaires were obtained. It should be clarified that all the 91 crew members work in the international shipping line. The basic information of crew members is shown in Figure 4.

Among the 91 crew members surveyed, 71 are working in shipping enterprises, 9 are from maritime college/university, 3 are from the government department, and 8 are fishermen or lack of information, see Figure 4 (a). It consists of 25 captains/chief engineers, 28 chief officers/first engineers, 19 second officers/second engineers, 9 seamen and 1 third officer/engineer, see Figure 4 (b). In terms of education, 78.02% of them belong to junior college or below, 17.58% have a bachelor's degree, and 3.3% of the crew have a master's degree or above, see Figure 4 (c). As for working experience, 61.54% of them had 10 years or more of sailing experience, 28.57% had 6 to 10 years of sailing experience, and 8.79% had 1 to 5 years of sailing experience, see Figure 4 (d).

4. Results

4.1. Coding unsafe acts

First of all, the existing unsafe acts that affect the happening of the maritime accidents in the collected 413 marine accident/incident investigation reports are listed in Table 2, after omitting those that only exist for one or two times. There are thirty-six unsafe acts obtained and coded, and the scenarios in which they appear are also shown respectively in Table 2.
4.2. Identification of critical unsafe acts

Based on the unsafe acts extracted, a questionnaire survey is conducted for identifying the critical unsafe acts in maritime accidents. Participants are asked to make multiple choice with no more than six selections for each scenario. And the results are shown in figure 5. The statistic results show that Fail to keep a lookout (HF4), Inexperienced crews (HF3), and Failure of communications between two vessels (HF11) are the top three unsafe acts leading to collision, see figure 5 (a); Fail to keep a lookout (HF4), Inexperienced crews (HF3), and Did not be on duty as required (HF14) are the top three unsafe acts of grounding accidents, see figure 5 (b); Did not carry out safety inspections strictly (HF28), Store flammable materials without permissions (HF35), and Wiring in the living area without permission (HF27) are the top three in fire/explosion, see figure 5 (c).

Besides, according to the times that unsafe acts being selected, the frequency and percentage are calculated and these unsafe acts are ranked, as shown in table 3.
Table 2. Coded unsafe acts in maritime accidents.

| No. | Unsafe acts                                      | Scenario                        |
|-----|-------------------------------------------------|---------------------------------|
| HF1 | Incorrect light signal                         | Collision                       |
| HF2 | **Unsafe speed**                               | **Collision, grounding**        |
| HF3 | **Inexperienced crews**                        | **Collision, grounding, fire/explosion** |
| HF4 | **Fail to keep a lookout**                     | **Collision, grounding**        |
| HF5 | **Misjudgment on danger**                      | **Collision, grounding**        |
| HF6 | Wrong recognition on liability of collision avoidance | Collision                       |
| HF7 | Did not take collision avoidance                | Collision                       |
| HF8 | Belated response of collision danger            | Collision                       |
| HF9 | Improper response of collision danger           | Collision                       |
| HF10| Insufficient avoidance                         | Collision                       |
| HF11| Failure of communications between two vessels  | Collision                       |
| HF12| Did not check the effectiveness of collision avoidance | Collision                       |
| HF13| Improper route design                          | Grounding                       |
| HF14| Did not be on duty as required                  | Grounding                       |
| HF15| Did not take emergency measures                 | Grounding                       |
| HF16| Improper emergency measures                     | Grounding                       |
| HF17| Improper handling of the vessel                | Grounding                       |
| HF18| Inadequate preparation                         | Grounding                       |
| HF19| Failure of intra-vessel communications          | Grounding                       |
| HF20| Improper usage of navigation aid facilities    | Grounding                       |
| HF21| Negligence of crews                            | Grounding                       |
| HF22| Fatigue of crews                               | Grounding                       |
| HF23| Overconfidence of crews                        | Grounding                       |
| HF24| Crews’ weak sense of responsibility             | Grounding                       |
| HF25| Did not conduct prior risk assessments          | Fire/explosion                  |
| HF26| Improper operations that have produced sparks  | Fire/explosion                  |
| HF27| Did not carry out safety inspections strictly   | Fire/explosion                  |
| HF28| Store flammable materials without permissions  | Fire/explosion                  |
| HF29| Failure of intra-vessel communications          | Fire/explosion                  |
| HF30| Did not record hazardous materials              | Fire/explosion                  |
| HF31| Smoking in unauthorized areas                   | Fire/explosion                  |
| HF32| Did not be on duty as required                  | Fire/explosion                  |
| HF33| Did not dispose oily rags timely and properly   | Fire/explosion                  |
| HF34| Performing welding or painting in unsafe areas  | Fire/explosion                  |
| HF35| Wiring in the living area without permission    | Fire/explosion                  |
| HF36| Improper usage of fire in the galley           | Fire/explosion                  |
Figure 5. Frequency of the selected human factors for the three accident scenarios in the questionnaire survey.

Table 3. Results of the questionnaire survey for unsafe acts in maritime accidents.

| Ranking | Human factor | Frequency | Percentage | Ranking | Human factor | Frequency | Percentage |
|---------|--------------|-----------|------------|---------|--------------|-----------|------------|
| 1       | HF4          | 123       | 11.23%     | 19      | HF17         | 24        | 2.19%      |
| 2       | HF3          | 114       | 10.41%     | 20      | HF7          | 23        | 2.19%      |
| 3       | HF5          | 73        | 6.67%      | 21      | HF36         | 22        | 2.01%      |
| 4       | HF2          | 48        | 4.38%      | 22      | HF21         | 21        | 1.92%      |
| 5       | HF14         | 43        | 3.93%      | 23      | HF29         | 21        | 1.92%      |
| 6       | HF11         | 42        | 3.84%      | 24      | HF10         | 20        | 1.83%      |
| 7       | HF18         | 37        | 3.38%      | 25      | HF12         | 16        | 1.46%      |
| 8       | HF1          | 36        | 3.29%      | 26      | HF24         | 16        | 1.46%      |
| 9       | HF25         | 35        | 3.20%      | 27      | HF6          | 16        | 1.46%      |
| 10      | HF28         | 34        | 3.11%      | 28      | HF15         | 15        | 1.37%      |
| 11      | HF23         | 32        | 2.92%      | 29      | HF37         | 13        | 1.19%      |
| 12      | HF8          | 32        | 2.92%      | 30      | HF16         | 11        | 1.00%      |
| 13      | HF35         | 31        | 2.83%      | 31      | HF33         | 11        | 1.00%      |
| 14      | HF22         | 30        | 2.74%      | 32      | HF19         | 10        | 0.91%      |
| 15      | HF27         | 29        | 2.65%      | 33      | HF30         | 10        | 0.91%      |
| 16      | HF26         | 28        | 2.56%      | 34      | HF20         | 9         | 0.82%      |
| 17      | HF9          | 27        | 2.47%      | 35      | HF34         | 9         | 0.82%      |
| 18      | HF32         | 26        | 2.37%      | 36      | HF31         | 8         | 0.73%      |
4.3. Hierarchical network model

Finally, the unsafe acts whose frequency is no less than 30 are identified as critical unsafe acts of maritime accidents. Moreover, put them into the conceptual framework proposed in section 2, and the mapping network model for maritime accidents is fully presented, see figure 6.

In the proposed mapping network model, skill-based failure consists of Incorrect light signal (HF1), Fail to keep a lookout (HF4), Inadequate preparation (HF18), Fatigue of crews (HF22), and Overconfidence of crews (HF23); rule- and knowledge-based mistakes includes Unsafe speed (HF2), Inexperienced crews (HF3), Misjudgment on danger (HF5), Failure of communications between two vessels (HF11), and Belated response of collision danger (HF8); and violation acts covers Did not be on duty as required (HF14), Did not conduct prior risk assessments (HF25), Store flammable materials without permission (HF28), and Wiring in the living area without permission (HF35).

As for different types of maritime accident, the mapping network model shows that collision is always led by HF1, HF4, HF2, HF3, HF5, and HF11; grounding could be caused by HF4, HF18, HF22, HF23, HF2, HF3, HF5, HF8, and HF14; and fire/explosion would be brought by HF3, HF25, HF28, and HF35.

![Figure 6. A mapping network model for unsafe acts in maritime accidents.](image-url)

5. Discussion

In addition to the intuitive conclusions above, the mapping network model for maritime accidents also reveals something more in-depth.

First, there are some unsafe acts that connected to more than one accident scenario, namely Fail to
keep a lookout (HF4), Unsafe speed (HF2), Inexperienced crews (HF3), and Misjudgment on danger (HF5). Among them, HF4, HF2 and HF5 point to both collision and grounding. It suggests that there is a certain similarity between the occurrence of collision and grounding; and these three unsafe acts should be paid more attention as collision and grounding are most common maritime accidents. Moreover, HF2 is connected to all the scenarios discussed. It implies that the level of experience could influence crews’ performance in all aspects; thus, sufficient and regular training and educating the crew before boarding is a must.

Second, the characteristics of specific unsafe acts that point to the three accident scenarios are different. For collision, skill-based failures and rule- and knowledge-based mistakes both could result in accidents, but the rule- and knowledge-based mistakes is more closely connected. It reveals that collision always happens if the crew is not familiar with collision regulations (COLREGs), which is in line with the study of Mohovic et al. [12]. For grounding, it seems all three kinds of unsafe acts may influence the occurrence of accidents, but among them, skill-based failures and rule- and knowledge-based mistakes are more obvious. It implies that manning qualified crews, arranging regular skill training, and organizing courses of rules, regulations, and requirements could be useful for avoiding grounding. As for fire/explosion, violation acts is the main cause of the accident. It indicates that strict supervision and crew’s responsible attitudes should be obtained to reduce the happening of fire/explosion.

From all above, the mapping network model for maritime accidents presents the common BUAs for diverse maritime accidents, reveals the association between unsafe acts and maritime accidents, and shows good applicability in unsafe acts analysis of one and multiple maritime accidents.

6. Conclusion
This study mainly finished the following works: (1) extracting basic unsafe acts of maritime accident from 413 investigation reports; (2) recognizing critical unsafe acts by a comprehensive consideration of investigation reports and 91 crews’ questionnaires; (3) proposing a hierarchical network model for unsafe acts in maritime accidents; (4) revealing the main causes of collision, grounding, and fire/explosion in the level of individual unsafe acts; (5) and raising some interventions according to the characteristics of unsafe acts that result in specific types of maritime accidents.

The research shows that collision is always led by skill-based failure consists of Incorrect light signal (HF1), fail to keep a lookout (HF4), unsafe speed (HF2), inexperienced crews (HF3), misjudgment on danger (HF5), and failure of communications between two vessels (HF11); grounding could be caused by fail to keep a lookout (HF4), inadequate preparation (HF18), fatigue of crews (HF22), and overconfidence of crews (HF23), unsafe speed (HF2), inexperienced crews (HF3), misjudgment on danger (HF5) and belated response of collision danger (HF8), and did not be on duty as required (HF14); and fire/explosion would be brought by inexperienced crews (HF3), did not conduct prior risk assessments (HF25), store flammable materials without permissions (HF28), and wiring in the living area without permission (HF35).
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