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ACCIDENTS IN THE CHEMICAL INDUSTRY: AN ANALYSIS OF THE HFACS-PEFE MODEL TO EXAMINE THE ROLE OF HUMAN FACTORS

Amal S. George[a*], Nyzal Moideen[b], Sivi Varghese[a], Anoop Warrier[a], M. S. Khan[a]

[a]*International college of Engineering and Management, Muscat - 111, Oman.*

[b]*Cochin University of Science and Technology, Kochi - 682022 India.*

**amal.g@icem.edu.om*

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ABSTRACT

One of the most common causes of accidents in chemical industry is human error. In order to minimize the accident frequency and associated damage, a better understanding of the role played by human factor in such accident is prerequisite. The Human Factors Analysis and Classification System-Petrochemical Enterprise Fire and Explosion (HFACS-PEFE) model is established to examine the mechanism of human failure. According to the model, violations, intellectual limitations, inadequate supervision, and insufficient safety culture are the most essential elements in the occurrence of accidents. Both direct causes and latent human failures involved in chemical industry accidents are identified and are then analyzed. An accident database is constructed which includes accident date, location, death and injuries. Relationships between different human factors, which are involved in the HFACS-PEFE framework, are identified by conducting chi-square test and odds ratio (OR) analysis. Different accident development paths and corresponding probabilities are achieved with the help of these relationships.

Keywords: *Human Factors, HFACS-PEFE, Chemical Industry.*

1. INTRODUCTION

Human factors are responsible for numerous chemical accidents, including fire safety problems in storage tank farms [Varghese and Renjith, 2022], (Renjith et al., 2007), such that the research on human causes has received a lot of attention in the last decade. [Zhang, 2012], (George and Renjith, 2022). An integrated process safety management system (IPSMS) model was established by Theophilus through incorporating Human Factors Analysis and Classification System (HFACS) framework into the process safety management (PSM) system [Theophilus, 2018]. In the IPSMS model, human factors were underlined. The HFACS framework [Shappell, 2001 & 2000] provides an effective tool for conducting human factor analysis in various fields. The framework was initially proposed by Wiegmann and Shappell based on James Reason's Swiss Chesses model [Reason, 1997 & 1990]. The HFACS framework identifies the causal factors of accidents and classifies them into separated categories.

Figure 1 depicts the original HFACS framework, which was modified from Reason's Swiss cheese model. The human errors are classified into four levels, including unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences. In the framework, all associated personnel factors are categorized into 19 types [Wiegmann, 2015, 2003 & 2001]. The unsafe act is further divided into errors and violations. The former is mainly composed of decision errors, skill-based errors and perceptual errors while the latter composed of routine violations and exceptional violations. The preconditions for unsafe acts include environmental factors, conditions of the operators, and personnel factors. Both physical and technological environments are taken as environmental factors. In respect to the conditions of the operators, adverse mental states, adverse physiological states, and physical/mental limitations are taken into account. Crew resource management and personal readiness are categorized into personnel factors. Main components of the unsafe supervision are classified into inadequate supervision, planned inappropriate operations, failure to correct problems and supervisory violations. The last organizational influence is separated into three main sections, which are resource management, organizational climate, and organizational process.

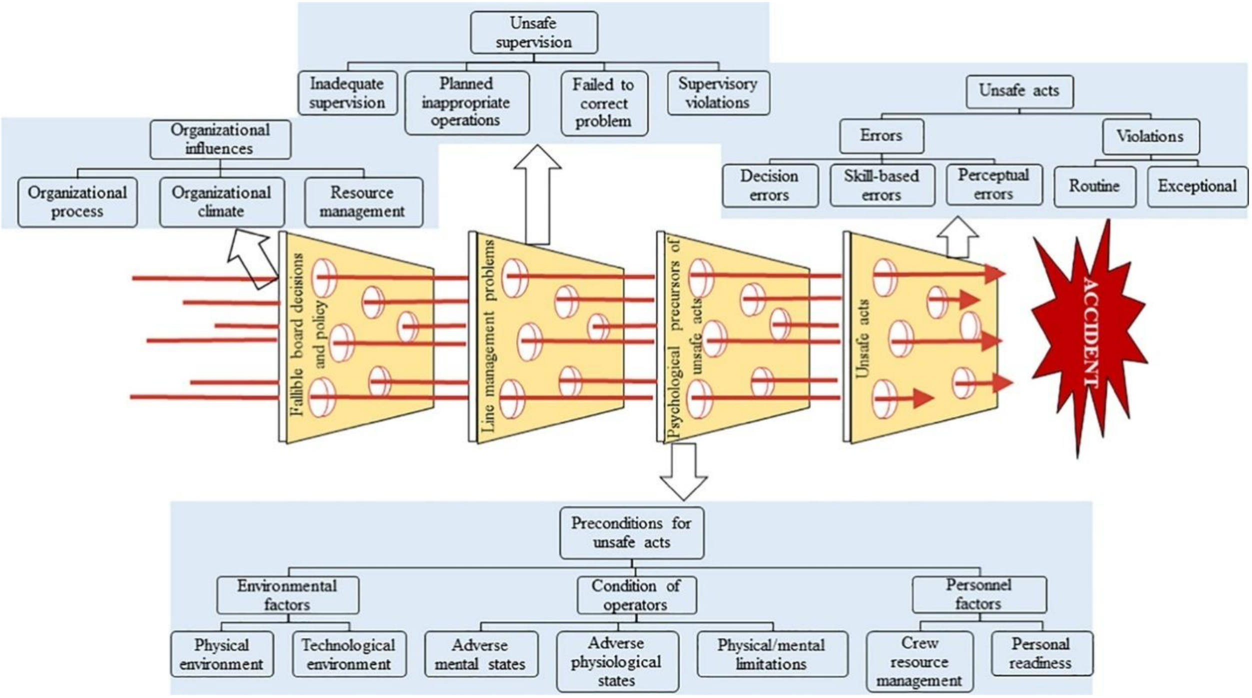

Fig. 1: The original framework of HFACS corresponding to Reason's Swiss cheese model (Mengmeng Chen, 2018).

In this paper, a modified HFACS framework related to the Human Factors Analysis and Classification System-Petrochemical Enterprise Fire and Explosion (HFACS-PEFE) is applied. The framework is then utilized to analyse the main causes of over one hundred selected accident scenarios in the chemical industries with an emphasis on investigating the influence of human factors and also, determining their accident causational routes. Based on the results obtained from the modified framework, safety measures can be proposed to improve the human factors of chemical enterprises.

2. METHODOLOGY AND DATA ANALYSIS

The methodology involves collection of accident data from the chemical industry, followed by classification of the collected data based on human factors and analysis done using the model. Then the relationship between the human factors of different levels is determined using chi-square test and odds ratio test using the SPSS Software. Finally, the accident causational routes and their corresponding probabilities are identified. A total of 123 accidents of the selected chemical enterprise are collected and analyzed in this study during the period from January 2011 to July 2019 (Varghese et al., n.d.), (Varghese et al., n.d.). No deaths were reported during this period.

2.1 Classification Method

The accident classification is realized through four stages in this study. In the first stage, the investigation reports or other accessed information of the accidents are carefully reviewed. Both direct causes and latent human failures involved in the collected accidents are identified. Then, with the help of expert elicitation, contribute to analyzing the human errors which the accident should be attributed to. Thus, the proper factors are identified for each accident. After that, the classification is reviewed again by the first and corresponding experts to make sure it is reasonable. At last, an accident database is constructed by using the Microsoft Excel. The database records the analysis results of the accidents, which include accident date, location, deaths, injuries, direct causes and latent human failures.

2.2 HFACS-PEFE Analysis

Based on the accident classification result, a human factor is marked as "1" if it led to an accident and marked as "0" if it does not. The frequencies of different human factors within the modified framework are counted through summation. The calculated frequencies are listed in Table 2. The statistical data analysis can then be conducted for the classified results. According to the data listed in Table 2, the importance of the human factors included in the HFACS-PEFE framework can be revealed.

Table 2: Frequencies and percentage of accidents causes of HFACS-PEFE framework

Levels	Sub-Levels	Frequency	Percentage
Level 4: Organizational influences	Inappropriate resource management	75	32.19
	Insufficient safety culture	92	39.49
	Organizational process vulnerability	66	28.32
Level 3: Unsafe supervision	Inadequate supervision	90	43.48
	Planned inappropriate operations	40	19.32
	Failure to correct problems	30	14.50
	Illegal commands	47	22.70
Level 2: Preconditions for unsafe acts	Poor physical environment	60	20
	Poor technological environment	35	11.67
	Adverse mental states	17	5.67
	Intellectual limitations	92	30.67
	Adverse physiological states	14	4.67
	Insufficient communication and coordination	30	10
	Inadequate personal readiness	52	17.33
Level 1: Unsafe acts	Skill-based errors	47	27.97
	Decision errors	39	23.21
	Perceptual errors	23	13.69
	Violations	59	37.11

Skill-based errors, decision errors, perceptual errors and violations account for 27.97, 23.21, 13.69, and 37.11%, respectively. The number of accidents caused by violations stands at the first place followed by that resulted from skill-based errors. The number of accidents resulted from above two unsafe acts are larger than that attributed to decision errors and perceptual errors. That means violations and skill-based errors are the most common unsafe acts involved in the operations of chemical enterprises.

Ninety-two fire and explosion accidents are resulted from intellectual limitations, accounting for 30.67% of the accidents attributed to this level. This number is followed by the accidents caused by poor physical environment. Sixty such accidents occupy a percentage of 20%. The number of accidents attributed to inadequate personal readiness stands at the third place, whose number and percentage are 52 and 17.33%, respectively. Poor technological environment results in 35 accidents according to the collected data accounting for 11.67%. The number of accidents resulted from adverse physiological states and adverse mental states are small.

According to the classified results in Table 2.1, there are 90 accidents related to inadequate supervision. This number accounts for 43.48% of the accidents attributed to unsafe supervision. The number is followed by the accidents induced by illegal command, which accounts for 22.70%. The accidents numbers related to planned inappropriate operations and failure to correct problems stand at the third and fourth places, with the percentage of 19.32% and 14.50%, respectively.

There are 92 accidents related to insufficient safety culture in the chemical enterprise. About 39.49% of accidents attributed to the organizational influences level is occupied by safety culture. Inappropriate resource management results in 75 fire and explosion accidents, the number stands at the second place and accounts a percentage of 32.19%. Meanwhile, there are 66 accidents resulting from the vulnerabilities in the organizational process, with a percentage of 28.32%. Herein, the enterprise should pay more attention to the construction of safety culture.

2.3 Relationship Between Human Factors

Relationships between different levels of human factors can be identified by Chi-square test and Odds ratio test using SPSS software.

Chi-square ($\chi 2$) test is a type of hypothesis test approach based on the chi-square distribution. The method was proposed by Karl Pearson in the earlier 1900s [Pearson, 1900]. In this study, it is used to analyze the associations between two adjacent levels of the HFACS-PEFE framework. Chi-square test is commonly performed based on the following assumptions. H0: there are no significant associations between the factors of the upper and lower levels and H1: there are significant associations between the factors of the adjacent levels composed of the HFACS-PEFE model. According to $\chi 2$ distribution, $\chi 2$ statistic and freedom degree, the probability P can be determined when H0 is right. If the value of P is smaller than 0.05, H0 should be rejected, and H1 is accepted. That means the relationship between the upper and lower levels is significant. If the value of P is larger than 0.05, the hypothesis H0 should be accepted while H1 is rejected. That means the relationship between the upper and lower levels is not significant.

The odds ratio (OR) is commonly used to estimate how likely an event will occur compare to another event. In this study the OR test is used to estimate whether the failure of the factors at the upper level of HFACSPEFE increases that at the lower level. If the OR is greater than 1, the failure of factors at the upper level would increase that at the next level [Lenne and Trotter, 2012 & Fu, Fan and Tong, 2016].

3. RESULTS AND DISCUSSIONS

The results obtained from SPSS software are summarized in Table 3. Only the results with $P < 0.05$ and $OR > 1$ are listed in the table.

3.1 Relationships Between the Level 1 Unsafe Acts and Level 2 Preconditions for Unsafe Acts

According to Table 3, there are five groups of significant relationships existing between the Level 1 unsafe acts and Level 2 preconditions for unsafe acts. Intellectual limitations may lead to decision errors, skill-based errors and violations. In addition, decision errors and violations may be attributed to poor technological environment and inadequate personal readiness. Intellectual limitations account for 30.67% of the collected accidents. It is considered as the main cause of accidents at the Level 2 preconditions for unsafe acts. Intellectual limitations mainly include insufficient operation skills, inadequate work experience, and poor safety knowledge. It can be deduced from the OR value 7.441 that the intellectual limitations may cause the occurrence probability of violations to increase by 7.4 times.

3.2 Relationships Between the Level 2 Preconditions for Unsafe Acts and Level 3 Unsafe Supervision

There are three groups of significant relationships existing between the Level 2 preconditions for unsafe acts and Level 3 unsafe supervision. Inadequate supervision may result in intellectual limitations and inadequate personal readiness, while planned inappropriate operations may lead to poor technological environment. Within the accidents attributed to the Level 3 unsafe supervision, inadequate supervision accounts for a percentage of 43.48%. The operators in specific working environment may ignore the production procedures due to insufficient supervision, education or training. According to the OR values (3.087 and 2.761), the occurrence possibilities of intellectual limitations and inadequate personal readiness are increased by 3.1 times and 2.7 times respectively by inadequate supervision.

3.3 Relationships Between the Level 3 Unsafe Supervision and Level 4 Organizational Influences

Six groups of significant relationships are found between the Level 3 unsafe supervision and Level 4 organizational influences. Insufficient safety culture may cause the failure in correcting problems and inadequate supervision, while inappropriate resource management may result in the planned inappropriate operations and failure in correcting the involved problems. In addition, vulnerabilities in the organizational process may also lead to the failure in addressing problems and illegal command. Insufficient safety culture may increase the possibilities of failure in correcting problems and inadequate supervision by approximately 3.1 times and 2.4 times, respectively. Such increase is mainly attributed to the lack of safety culture concept and safety carriers in the organization. The poor safety knowledge and safety consciousness of workers lead to inadequate supervision. Inappropriate resource management may increase the occurrence probability of planned inappropriate operations and failure in correcting problems by approximately 2.1 times and 3.4 times, respectively. The vulnerabilities in the organizational process mainly include the procedures, emergency plans, safety management system, supervision system, and other imperfects. It may increase the occurrence probability of failure in addressing problems and illegal command by approximately 11.4 times and 2.3 times, respectively.

Table 3: Chi-square test and OR values between different HFACS-PEFE levels.

HFACS-PEFE Framework	**$\chi 2$**	**P**	**OR**
Relationship between level 3 unsafe supervision and Level 4 organizational influence			
Inappropriate resource management x Planned inappropriate operations	3.308	0.042	2.121
Inappropriate resource management x Failure to correct problems	5.632	0.011	3.430
Insufficient safety culture x Inadequate supervision	8.192	0.009	2.381
Insufficient safety culture x Failure to correct problems	4.868	0.031	3.113
Organizational process vulnerability x Failure to correct problems	10.418	0.005	11.430
Organizational process vulnerability x Illegal commands	4.879	0.034	2.287

Relationship between Level 2 preconditions for unsafe acts level 3 unsafe supervision			
Inadequate supervision x Intellectual limitations	12.539	0.002	3.087
Inadequate supervision x inadequate personal readiness	5.124	0.036	2.761
Planned inappropriate operations x Poor physical environment	8.247	0.007	3.358
Relationship between Level 1 unsafe acts and Level 2 preconditions for unsafe acts			
Poor physical environment x decision errors	4.932	0.021	2.857
Intellectual limitations x skill-based errors	16.296	0.000	3.366
Intellectual limitations x decision errors	9.431	0.006	4.228
Intellectual limitations x violations	21.863	0.000	7.441
Inadequate personal readiness x violations	8.274	0.008	2.961

3.4 Relationships Between all the Levels

According to the results of Chi-square test and OR analysis, close relationships between the human factors involved in the HFACS-PEFE framework are identified and illustrated in Figure 3 (a). Insufficient safety culture increases the possibilities of inadequate supervision and failure in correcting problems by approximately 2.4 times and 3.0 times, respectively. The possibilities of intellectual limitations and inadequate personal readiness are increased by nearly 3 times and 2.8 times, respectively by inadequate supervision. Then, the intellectual limitations may cause the occurrence of violations, decision errors and skill-based errors. Meanwhile, inadequate personal readiness may increase the possibility of violations by nearly 3.0 times. In addition, there is a direct relationship between inappropriate resource management and decision errors, which are connected by the planned inappropriate operations and poor technological environment.

Five paths across four levels of the HFACS-PEFE framework are revealed in Figure 3 (a). The weight (accident percent) accounted by the human factor within corresponding level is signed in the bracket. Obviously, insufficient safety culture, inadequate supervision, intellectual limitations, and violations are the most important accident causing human factors in corresponding levels. The accident would happen if the operation failure passes through all layers involved in the James Reason's Swiss Chesses model. The HFACS framework was initially proposed based on the James Reason's Swiss Chesses model. Therefore, fire and explosion accident would occur if human failures involved in the four levels are connected. That implies the five paths across four levels of the HFACS-PEFE framework are potential routes for accidents in the selected petrochemical enterprise.

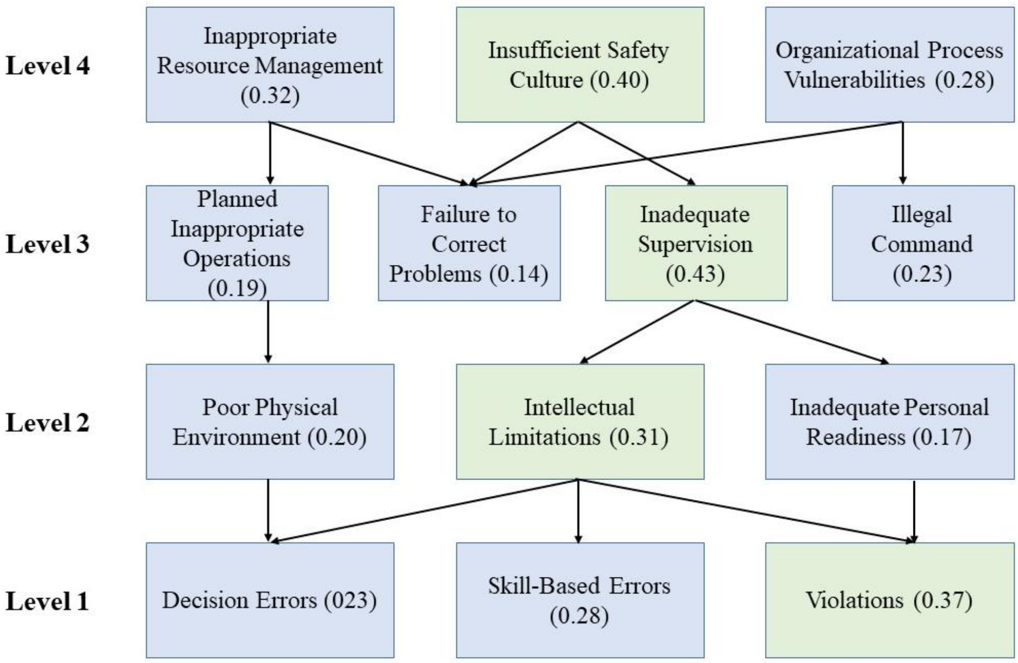

Figure 3 (a): Relationship between the human factors

3.5 The Main Accident Causational Routes

Five routes for the accidents are identified in Figure 3 (b). Considering the accident percentage related to the human factors (presented in the bracket), the easiest path for accident development can be distinguished. The relative probability for the accident development through each route can be deduced from the product of the percentage occupied by the factors involved in the route.

Based on the case histories of the accidents collected and analyzed in the present study, the probability corresponding paths 1–5 is equal to 0.28%, 1.22%, 1.50%, 1.97%, and 1.08%, respectively. Note that the relative probability calculated here is not the real probability for fire and explosion accidents. The result is utilized to identify relative magnitude of the probability that the accident evolves along different routes. Obviously, the accident is easier to be induced through Route, followed by the accidents arising from Route 3. The probabilities associated with Routes 5 and Route 2 stand at the third and fourth places, respectively. The probability for Route 1 is so small that the accident is difficult to be induced in this route. It is worth outlining that Route 4 is composed of insufficient safety culture, inadequate supervision, intellectual limitations, and violations. They are the most important human factors in corresponding level. So the relative probability along this route is largest, which means safety barriers should be carefully designed regarding to Route 4 in petrochemical enterprises.

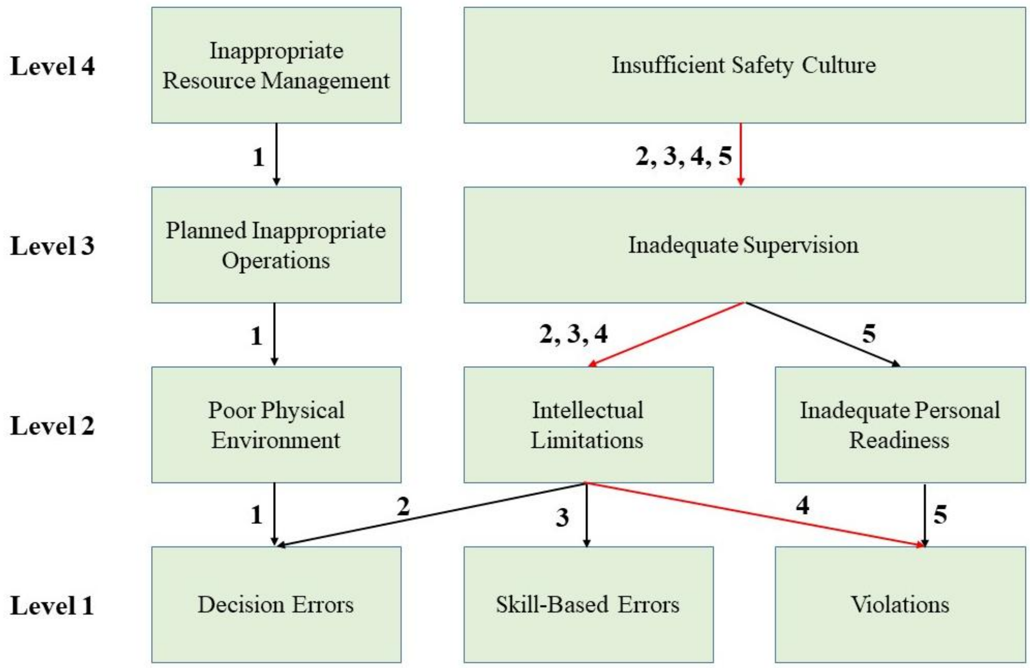

Figure 3 (b): Accident causation routes.

4. SUMMARY

The Human Factors Analysis and Classification System-Petrochemical Enterprise Fire and Explosion (HFACS-PEFE) model is established to examine the mechanism of human failure. The model indicates violations, intellectual limitations, inadequate supervision, and insufficient safety culture are the most important factors in causing the accidents. Both direct causes and latent human failures involved in collected accidents are identified and are then analyzed by experts. An accident database is constructed at last by using the Microsoft Excel. The database includes accident date, location, death and injuries. Relationships between different human factors, which are involved in the HFACS-PEFE framework, are identified by conducting chi-square test and odds ratio (OR) analysis. With the help of these relationships different accident development routes and corresponding probabilities are achieved. To avoid the occurrence of such accidents, direct and indirect measures are proposed to improve human performance.

5. CONCLUSION

Statistical analysis, chi-square test and OR analysis of 123 accidents in the selected petrochemical enterprise are carried out in this study. The accidents had happened in the firm within the period from January 2011 to July 2019. The HFACS-PEFE framework is established for analyzing the accidents in petrochemical enterprises. Relationships between human factors composed of the framework are obtained from Chi-square test and OR analysis. Insufficient safety culture increases the possibility of inadequate supervision by approximately 2.4 times, causing failure in correcting problems of the production. The possibilities of intellectual limitations and inadequate personal readiness are greatly increased by inadequate supervision. Such intellectual limitations lead to occurrence of violations, decision errors, and skill-based errors. Five development routes for accidents and corresponding probabilities are obtained. The fourth path is the easiest way for accident development, which is followed by Paths 3, 5, 2, and 1 in sequence.

The HFACS-PEFE framework would be further elaborated by covering more general and fire and explosion accidents. The factors out of the enterprises, such as government supervision, social economy and national policies, etc. would be taken into consideration. Besides, this study mainly conducted statistical analysis on the accidents to obtain the relationships among human factors involved in the HFACS-PEFE framework. Considering that unsafe acts are closely related to changes in various influence factors, dynamic analysis would be performed in the future work to reduce the probability of unsafe acts.

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