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Safety System Study of Gas Stations Based on Preliminary Hazard Analysis and Fault Tree Analysis

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Abstract: This study evaluates the safety management system at Xuefu Gas Station in Xiangtan City of China through a combination of Preliminary Hazard Analysis (PHA) and Fault Tree Analysis (FTA). Initially, PHA was employed to identify potential hazards and assess the probability of associated accidents. This analysis led to the formulation of preventive measures aimed at mitigating identified risks. Subsequently, FTA was utilized to construct a logical framework for analyzing the various causes of system failures and their interdependencies. The analysis revealed deficiencies in the management system, equipment, ignition sources, and human factors. An approximate calculation method was applied to rank the structural importance of these factors, thereby highlighting key areas of impact. Based on these findings, targeted recommendations were proposed to enhance the safety management practices at the gas station, thereby reducing accident likelihood and safeguarding personnel and property. The results underscore the necessity of improving management practices, upgrading equipment, controlling ignition sources, and bolstering human factors to achieve a comprehensive safety management system.

Keywords: Explosion risk; Gas station; Safety evaluation

1 Introduction

With the development of the economy, the number of vehicles is increasing, and the number of gas stations is also continuously rising. This growth trend has exacerbated the demand for petroleum. Given the flammable and explosive nature of oil products, accidents can result in severe economic losses and casualties. Therefore, it is necessary to conduct more in-depth research on the safety evaluation of gas station construction projects. Bedewy and Abdulameer [1] utilized a multi-criteria analysis method based on geographic information systems to analyze the spatial distribution of oil stations in Al-Mahaweel, Nile River City, and optimized station location and planning standards to reduce potential risks and enhance security. In the research direction of safety atmosphere evaluation, Lestari et al. [2] focused on analyzing the impact of the safety atmosphere on safety performance, while Aryo et al. [3] focused on examining the dimensions of the safety atmosphere that require significant improvement. Domínguez et al. [4] used PRA technology in the automotive industry to identify and assess hazards. Du et al. [5] modeled and analyzed fire and explosion accidents in oil and gas hydrogenation stations based on FTA, resulting in risk levels for fire and explosion accidents in oil-hydrogen gas stations and proposing a series of recommendations. Shao et al. [6] proposed a comprehensive evacuation model considering the dynamic evolution of crowd transfer inside and outside the plant using Anylogic software based on the social force model. Rathnasekara and Gunasekera [7] proposed a risk-based fire and explosion inherent environmental risk index to assist in selecting chemical process routes with minimal environmental risks. Wang et al. [8] conducted a case study using on-site investigation and computational fluid dynamics (CFD) technology to achieve accurate assessment and reproduction of multi-physical field loads. In terms of risk assessment and risk analysis research results, Yu et al. [9] focused on qualitative analysis, while Ahmet et al. [10] focused on quantitative evaluation. Kamil et al. [11] developed a framework for extracting database data by integrating three technologies: natural language processing, interpretive structural modeling, and probabilistic methods. Luo et al. constructed a gas station safety status mutation model from the perspective of human and material factors and proposed a gas station fire and explosion accident safety evaluation method based on mutation theory. Li and An [12] summarized the weak links in management during the operation and production process of gas stations by combining the Bowtie model and FTA with fire and explosion accidents at gas stations, starting from human, material, environmental, and management factors. Wu [13] used FTA to analyze and evaluate gas station fire and explosion accidents and proposed countermeasures to prevent gas station fire and explosion accidents. Huang [14] proposed a gas station construction safety risk evaluation method based on the fuzzy analytic hierarchy process for safety risks during gas station construction. Chang et al. [15] proposed a gas station unsafe behavior detection model based on the YOLO-V3 algorithm by combining accident statistics and FTA methods to control the risk of fire and explosion at gas stations. Zhao et al. [16] studied the safety range of explosions in the refueling area from both theoretical calculations and numerical simulations, further analyzing and verifying the correctness of the conclusions through model establishment of data results and error analysis. Wu [17] summarized and integrated some understandings and practical applications of the changes in new and old standards according to their safety evaluation practice after the implementation of the new national standards and their work experience. Wang [18] analyzed the fire risks of gas stations from the aspects of material fire risks and ignition sources and proposed a series of targeted fire prevention measures.

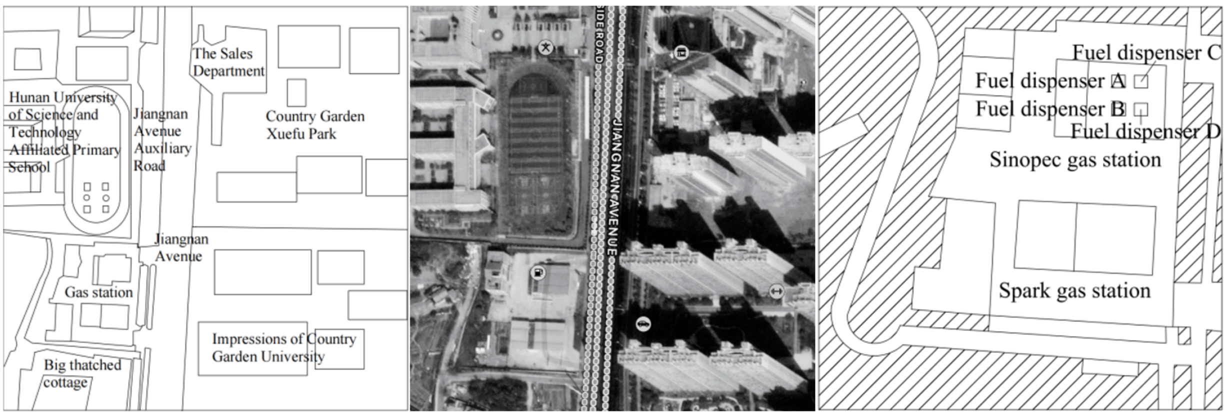
In summary, the research of foreign scholars on gas station safety issues focuses on the application of risk analysis methods, while domestic scholars' research concentrates on the improvement of evaluation methods and the proposal of evaluation measures. It can be seen that further analysis is needed for research on using diversified evaluation methods to assess system safety. Therefore, this study is based on the basic theory of safety system engineering and conducts diversified safety evaluation research on the fire and explosion hazards of the Xuefu Gas Station in Xiangtan City. It is expected that significant improvements in the comprehensive application of evaluation methods, refinement and standardization of the evaluation process, and the practicality and operability of evaluation results can be achieved, thereby providing more comprehensive, accurate, and effective support for the safety management of gas stations.

2 Overview of the Gas Station

2.1 Traffic Location

The Xuefu Gas Station in Xiangtan City is located on the east side of Hunan University of Science and Technology, adjacent to Jiangnan Avenue in the Jiuhua Economic Development Zone. The gas station is mainly divided into two parts: the upper part is the Sinopec gas station, and the lower part is the Xinghuo LNG-CNG gas station (now closed). Jiangnan Avenue is the main transportation hub for the gas station, as shown in subgraph (a) of Figure 1.

As shown in subgraph (b) of Figure 1, Jiangnan Avenue is a major traffic road for the gas station. Because its left side is Hunan University of Science and Technology Affiliated Primary School, and its right side is the Country Garden Xuefu Park and residential areas, there is a large flow of people, and students and vehicles frequently enter and exit, making it the main and most complex traffic road for the gas station.



(a) (b) (c)

Figure 1. (a) CAD drawing of Xuefu Gas Station traffic (b) Satellite image of Xuefu Gas Station traffic (c) Overall layout CAD drawing of Xuefu Gas Station

2.2 Layout of Gas Station Facilities

2.2.1 Layout of working facilities

As shown in subgraph (c) of Figure 1, Xuefu Gas Station is equipped with four fuel dispensers and several underground storage tanks. The spacing between the fuel dispensers meets the standard requirements, and the storage tanks are designed as underground tanks containing diesel, 92-octane gasoline, and 95-octane gasoline. Each fuel dispenser is equipped with metering devices to ensure the accuracy of fuel measurement. Additionally, the gas station has a convenience store, allowing customers to purchase daily necessities while refueling; the office is located in a safe area of the station to facilitate daily work and monitoring by the management personnel; restrooms are also provided to meet the basic sanitary needs of customers and employees. Furthermore, a strip of greenery is arranged around the gas station to reduce noise and exhaust emissions' impact on the surrounding environment(the shaded area in subgraph (c) of Figure 1 represents the green belt area).

2.2.2 Layout of safety facilities

After on-site inspections, it was found that the gas station is equipped with a comprehensive surveillance system, capable of providing full coverage with no blind spots; firefighting equipment is placed around the unloading area; the gas station is equipped with an automatic fire alarm system, fire hydrant system, portable firefighting equipment such as extinguishers and fire blankets, ensuring timely alarms and efficient firefighting operations in case of a fire. At the same time, the gas station has planned emergency evacuation routes to ensure that personnel can quickly evacuate in an emergency. In daily operations, reasonable directional signs and safety symbols are used to ensure public safety, raise safety awareness, and maintain the normal operation of the gas station.

2.3 Statistics and Analysis of Gas Station Failure Factors

2.3.1 Sampling statistics of failure factors

Table 1. Investigation of fuel dispenser observation

Fuel Dispenser								
Time Period	Model	Usage Times	**Fault Factors**					
			Failure to Start	No Fuel Dispensing	Oil Leakage	Insufficient Fuel	Excessive Fuel	Normal
2023 / 12 / 18 16:40-18:00	Dispenser A	8	0	1	0	0	0	7
	Dispenser B	4	0	2	1	0	0	1
	Dispenser C	7	1	0	1	0	0	5
	Dispenser D	12	0	1	1	0	1	9

Table 2. Investigation of storage tank testing

Storage Tank								
Time Period	Model	Inspection Times	**Fault Factors**					
			Leakage	Accessory Failure	Equipment Corrosion	Cracks	Deformation	Normal
2023 / 12 / 19 10:40-11:00	Diesel	10	0	0	1	1	0	8
	92-Octane Gasoline	10	0	0	0	1	1	8
	95-Octane Gasoline	10	0	0	2	0	1	7

Table 3. Investigation of unloading point testing

Unloading Point								
Time Period	Area	Inspection Times	**Fault Factors**					
			Oil Leakage	Hose Damage	Foreign Sparks	Vapor Accumulation	Overfilled Tank	Normal
2023/12/19 11:40-12:00	Unloading Point	10	1	0	0	0	0	9

During the preliminary field investigation, the fuel dispensers, storage tanks, and unloading points of this gas station were selected for sampling statistics of system failures and related data. During the specified period, investigations and observations of each test point were conducted to obtain the initial data on failure factors. To ensure the accuracy and reliability of the failure factor analysis, further data preprocessing was conducted on the initial data, including data cleaning, transformation, aggregation and grouping, and verification. In the data cleaning stage, missing and abnormal data were identified and handled to maintain the integrity and accuracy of the dataset. The textual data was then converted into numerical data for quantitative analysis and normalized to eliminate the impact of different dimensions and magnitudes. The data was then aggregated and grouped according to time periods and machine models/types to analyze the failure conditions under different conditions. In the data validation stage, consistency and completeness checks were completed to ensure the reliability and integrity of the data. Based on the data preprocessing process, the following detailed data records were summarized and compiled as shown in Table 1, Table 2, and Table 3.

2.3.2 Overall analysis of fault factors

Further analysis of the fault factors in the tables above was conducted for the fuel dispenser system. From the data in the Table 1, it can be seen that fuel dispensers are used frequently, and the failure rate of the fuel dispensers accounts for about 30% of the overall situation. Although the failure rate is not high, the gas station cannot afford to have major failures, as they can easily lead to fire and explosion hazards. In addition to the data mentioned above, there are other risk factors at this gas station. First, the gas station is located next to a busy intersection, where complex road conditions and frequent vehicle entry and exit increase the risk of traffic accidents. The narrow passageways often lead to traffic congestion. Second, gasoline, as a harmful substance, poses a serious threat to human health, whether through inhalation, ingestion, or skin contact, and can lead to symptoms of poisoning or even long-term health damage. Additionally, improper storage and use of flammable and explosive materials can lead to fires or explosions, while nearby open flames and electrical sparks also increase this risk. Moreover, due to insufficient technical skills, lack of safety knowledge, and low safety awareness among the personnel, fire and even explosion accidents often occur during fuel unloading operations. Therefore, strengthening gas station safety management and improving the safety awareness and skill levels of the personnel are crucial for ensuring the safe operation of the gas station. Figure 2 shows the failure conditions of fuel dispensers.

The above is the overall analysis of fault factors based on the preprocessed dataset. To further enhance the reliability of the data, a data enhancement method has been proposed. On the one hand, resampling was conducted for data with a low failure occurrence frequency to enhance the existing data. On the other hand, external data such as weather and traffic flow has been introduced to enrich the dataset, achieving the purpose of external data fusion.

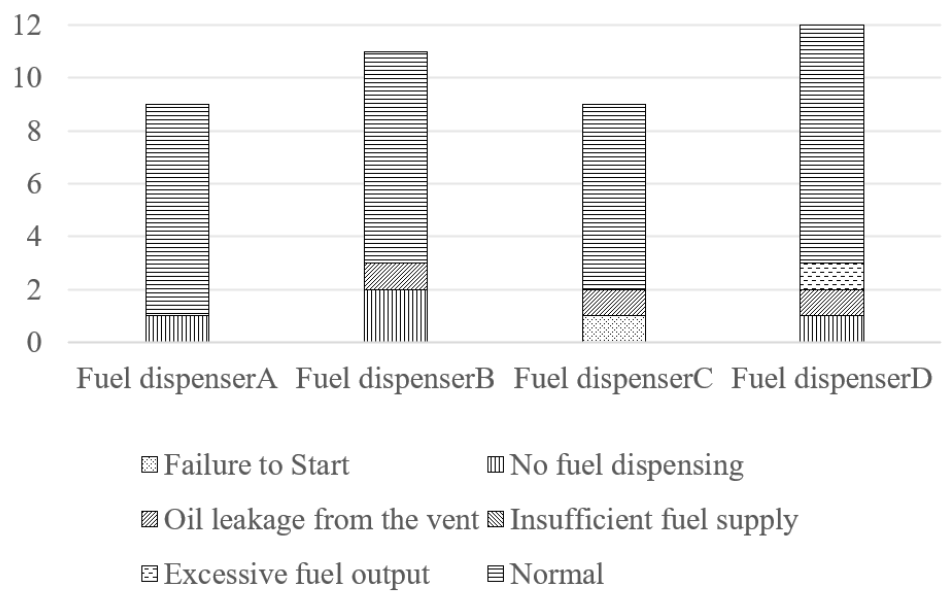


Figure 2. Statistics of fuel dispenser fault conditions

3 Safety System Evaluation Procedure and Selection of Evaluation Methods

3.1 Safety Evaluation Procedure

The safety evaluation procedure mainly includes: the preparation stage, identification and analysis of hazardous and harmful factors, qualitative and quantitative evaluation, proposing safety countermeasures, forming safety evaluation conclusions and recommendations, and compiling the safety evaluation report [19], as shown in Figure 3.

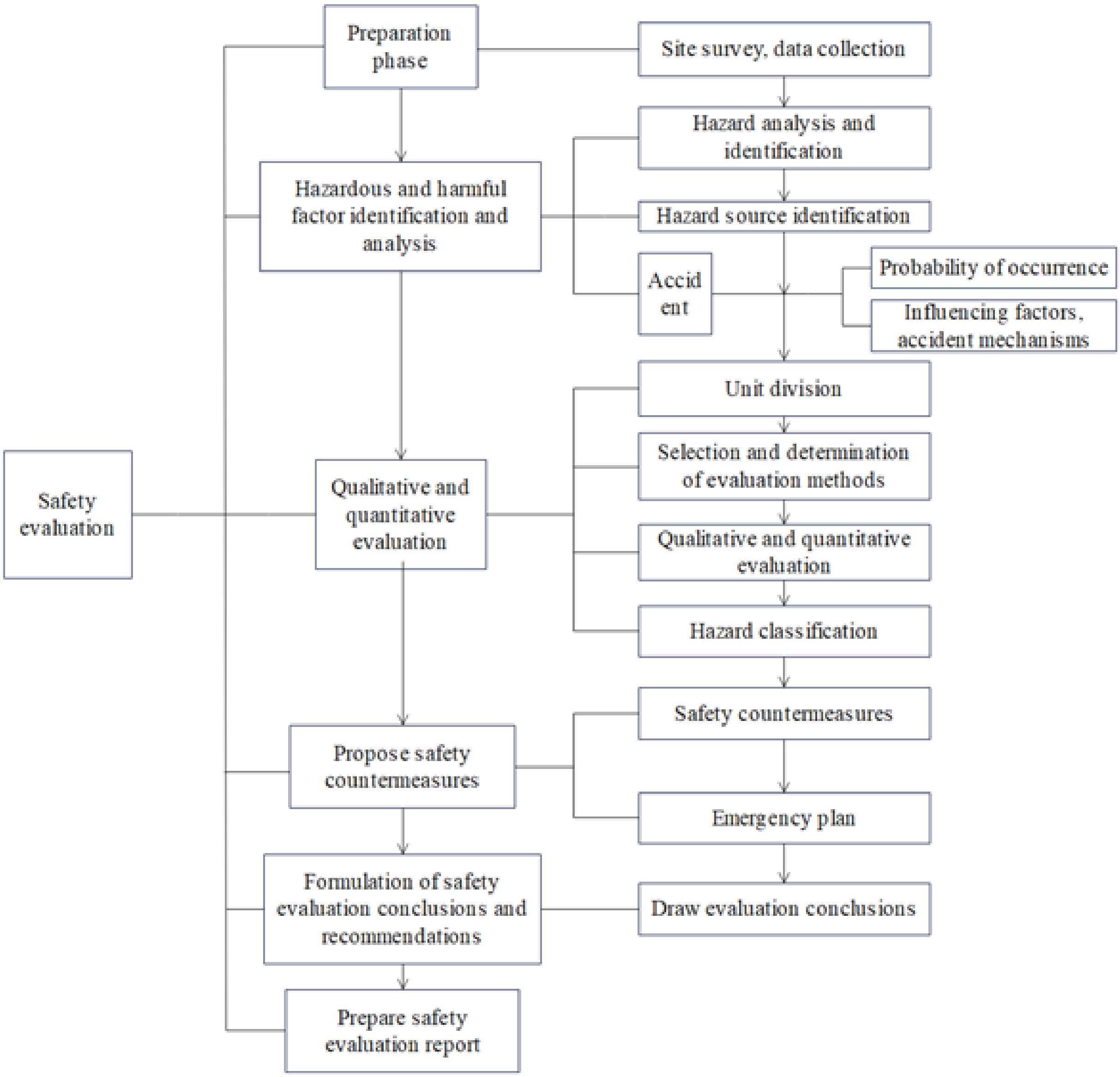


Figure 3. Safety evaluation flowchart

3.2 Selection of Safety Evaluation Methods

Based on the principles and considerations for selecting safety evaluation methods, the evaluated system, i.e., Xiangtan Xuefu Gas Station, was analyzed, and the goal of achieving safe operation through safety evaluation was clarified. Secondly, safety evaluation methods were collected and categorized as shown in Table 4 [19]. Additionally, the basic data and information that the evaluated system can provide were clarified. According to the basic data, processes, and other information required for safety evaluation, the applicable safety evaluation methods for the evaluated system were selected, namely the PHA method and the FTA method. By combining the qualitative analysis method of PHA with the quantitative analysis method of FTA, the basic evaluation of the gas station safety system can be achieved. The PHA method provides basic data and direction for FTA, while the FTA method further deeply analyzes the mechanism and probability of accidents. The combined use of both methods not only improves the accuracy and effectiveness of gas station safety risk assessment but also provides more comprehensive and scientific support for safety management decision-making.

(1) PHA

PHA is a qualitative method for analyzing hazards and the degree of danger within a system. PHA is conducted before any engineering activity, such as design, construction, or production, or after technical modifications, such as the formulation of operating procedures and the adoption of new technologies. This analysis provides a general overview of the types of hazards present in the system, their sources, the conditions under which they appear, the consequences that may lead to accidents, and the relevant measures to be taken. The purpose is to identify potential

Table 4. Comparison of selected evaluation methods

Evaluation Method	Evaluation Target	Method Characteristics	Scope of Use	Application Conditions	Advantages and Disadvantages
Safety Checklist (SCL)	Hazardous and harmful factors analysis, safety level	Step-by-step inspection using pre-prepared checklists with standard requirements,assigning scores according to regulations, and evaluating safety level	Design, acceptance, operation, management, accident investigation of various systems	Availability of pre-prepared checklists and scoring and rating standards	Simple, easy to master; difficulty and workload in preparing checklists are high
PHA	Hazardous and harmful factors analysis, hazard level	Discuss and analyze existing hazards, harmful factors, triggering conditions, accident types, and assess hazard levels	Preliminary analysis and evaluation before the design, construction, production, and maintenance of various systems	Analysts and evaluators are familiar with the system, have extensive knowledge and practical experience	Simple and easy to use, influenced by the subjective factors of the analysts and evaluators
Hazard and Operability Study (HAZOP)	Deviation, its causes, and consequences on the system	The study results can be used for design evaluation, operational evaluation, the preparation and improvement of safety procedures, and as operable safety education materials	Operability study applicable to both design stages and existing production facilities	No need for professional knowledge of reliability engineering, easy to master	Complex and detailed, influenced by the subjective factors of the analysts and evaluators
Event Tree Analysis (ETA)	Accident causes, triggering conditions, accident probability	Inductive method, determining the causes of accidents and the probability of events within the system based on the initial event, and calculating the accident probability	Event tree analysis is very suitable for analyzing situations where an initial event may lead to multiple outcomes	Familiarity with the system, causal relationships between elements, and availability of event probability data	Simple and easy to use, influenced by the subjective factors of the analysts and evaluators
FTA	Accident causes, accident probability	Deductive method, logically inferring the causes of accidents from the accident and basic events, and calculating the accident probability from the probability of basic events	Accident analysis of complex systems such as aerospace, nuclear power, processes, and equipment	Proficiency in the method and understanding of the relationships between accidents and basic events, availability of basic event probability data	Complex, high workload, accurate, but errors in fault tree construction can lead to distortion
Fishbone Diagram Method	Accident causes	Qualitative evaluation using the checklist method, quantitative evaluation using the baseline method, taking measures, re-evaluation using analogous data, re-evaluation of level 1 hazardous devices using methods such as ETA and FTA	Chemical plants and related facilities	Familiarity with the system, mastery of relevant methods, possession of related knowledge and experience, availability of analogous data	Comprehensive application of several methods for repeated evaluation, high accuracy, high workload
Job Hazard Analysis	Hazard level	Through discussion, analyze possible deviations and their causes, deviation consequences, and their impact on the entire system	Safety analysis of chemical systems, thermal systems, hydraulic systems	Analysts and evaluators are familiar with the system, have extensive knowledge and practical experience	Simple and easy to use, influenced by the subjective factors of the analysts and evaluators

hazards in the system, determine their hazard levels, and prevent these hazards from developing into accidents [19].

(2) FTA

A fault tree is a directed logical tree that describes the occurrence of an event from the result back to its causes.

The process of conducting a deductive analysis on such a tree to find countermeasures to prevent the result from occurring is known as FTA. FTA is a deductive logical analysis method that breaks down a result into the multiple causes that constitute it and then constructs these causes according to logical relationships, seeking measures to prevent the result from occurring. FTA can identify and evaluate the hazards of various systems, not only analyzing the direct causes of accidents but also deeply revealing the underlying causes. It describes the cause-and-effect relationship of accidents in a direct and clear manner, with clear thinking and strong logic, enabling both qualitative and quantitative analysis [19].

4 System Safety Analysis

4.1 PHA

4.1.1 PHA procedure

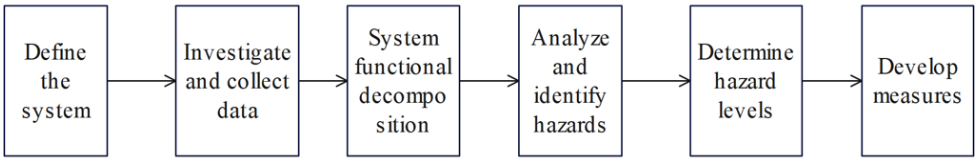


Figure 4. PHA procedure

4.1.2 PHA of the gas station safety system

Through qualitative hazard analysis of the gas station safety system, the potential hazards can be deeply explored, providing scientific basis and reference for formulating effective preventive measures.

(1) PHA process: According to Figure 4, first, the research object is identified as the Xiangtan Shifu Gas Station system, and its functional areas are defined as oil unloading operations, refueling operations, oil storage, and maintenance operations areas. Then, through comprehensive surveys and on-site inspections, the four evaluation units of the gas station system are divided into three sub-units, namely the oil tank truck, the fuel dispenser, and the oil storage tank. Based on the results of the system functional decomposition, potential hazardous accidents such as poisoning, fire explosions, electric shocks, mechanical injuries, and traffic accidents are summarized. On this basis, from multiple dimensions such as unsafe human behaviors, unsafe conditions of objects, environmental factors, and management deficiencies, the sources of hazards, initial injuries, and their associated risks are identified, and the hazard levels are classified according to Table 5. Finally, corresponding measures are formulated to prevent the identified potential hazards from occurring.

Table 5. Distribution of hazard levels

Level	Degree of Hazard	Potential Consequences
1	Safe	Will not cause harm or illness; no loss to the system; can be ignored
2	Critical	In a borderline state of an accident; temporarily will not cause casualties or system damage, but should be eliminated or controlled
3	Dangerous	Will cause casualties and system damage; measures must be taken immediately to control it
4	Destructive	Will cause death or system scrapping; must be eliminated

(2) Prepare the PHA table. See Table 6.

(3) Conclusion: Through the PHA of the entire gas station system, potential hazardous accidents, the hazardous factors leading to these potential accidents, and their dangers can be identified, and corresponding preventive measures can be taken to avoid or reduce the occurrence of accidents or disasters. To ensure the safety of the gas station, the management of the static grounding system of oil unloading vehicles should be strengthened, and equipment such as firefighting, leakage protection, and leakage detection should be installed. Ventilation and protection should be enhanced, and regular inspections of work equipment should be conducted. Protective gear should be worn during operations, prominent safety signs and vehicle entry/exit signs should be set up, closed refueling technology should be adopted, and maintenance operations should be standardized. It should be noted that this PHA is based on normal weather conditions. Gasoline is flammable and volatile, and it often disperses when refueling. The newly added gasoline also evaporates, greatly increasing the concentration of oil mist in the air around the refueling vehicle [20]. Therefore, it is prone to danger during thunderstorms. The influence of the external environment on the occurrence of disasters at the gas station should also be considered in the PHA.

Table 6. PHA of the gas station system

Evaluation Unit	Sub-Unit	Potential Accident	Triggering Cause	Hazard Level	Preventive Measures
Oil Unloading Operations	Oil Tank Truck	Fire/Explosion	Illegal operations; static or grounding failure of unloading vehicle; presence of ignition source; oil unloading operations	4	Ensure proper static grounding of unloading vehicles; sufficient resting time for oil tank truck before unloading; equip with firefighting equipment
		Poisoning	Gasoline evaporation; employees not taking protective measures	2	Wear protective equipment; improve ventilation
Refueling Operations	Fuel Dispenser	Fire/Explosion	Fuel dispenser not statically grounded; improper use of open flame devices; fuel dispenser leaking; fuel dispenser refueling too quickly	4	Equip with firefighting equipment; strengthen safety management; assign dedicated refueling staff; conduct regular inspections of fuel dispensers
		Electrical Injury	Electrical equipment leakage; static grounding system failure	2	Install leakage protection devices; conduct regular inspections of static grounding devices; strictly follow operating procedures
	Refueling Vehicle	Fire/Explosion	Refueling vehicle not turned off; driver illegally using open flame	2	Post safety signs; strengthen driver education
		Traffic Accident	Driver ignoring vehicle entry/exit signs; vehicles parked chaotically	2	Improve vehicle management system; set up more prominent entry/exit signs
		Poisoning	Oil evaporation; inhalation of excessive oil vapor	2	Use closed refueling technology
Oil Storage	Storage Tank	Fire/Explosion	Oil leakage or vapor accumulation; improper use of open flame devices; underground storage tank corrosion	4	Equip with firefighting equipment; install leakage detection equipment
		Poisoning	No replacement during maintenance; residual oil during tank cleaning; not wearing protective gear; oil leakage	3	Properly wear protective gear; install leakage detection equipment; conduct thorough replacement before maintenance
Maintenance Operations		Fire/Explosion	Illegal operations; use of non-explosion-proof equipment; presence of open flames	4	Conduct maintenance according to procedures; equip with explosion-proof equipment
		Mechanical Injury	Collisions during handling operations	2	Operate according to procedures

4.2 FTA

4.2.1 General procedure for FTA

4.2.2 FTA of gas station safety system

According to Figure 5, conducting a qualitative and quantitative FTA of fire and explosion accidents at gas stations can determine the occurrence patterns, causes, and impact levels of fire and explosion incidents. It can also calculate the probability of accidents occurring, providing alternative measures for improving system safety.

(1) Familiarize with the system: Understand the general overview of the Xuefu Gas Station, including its traffic

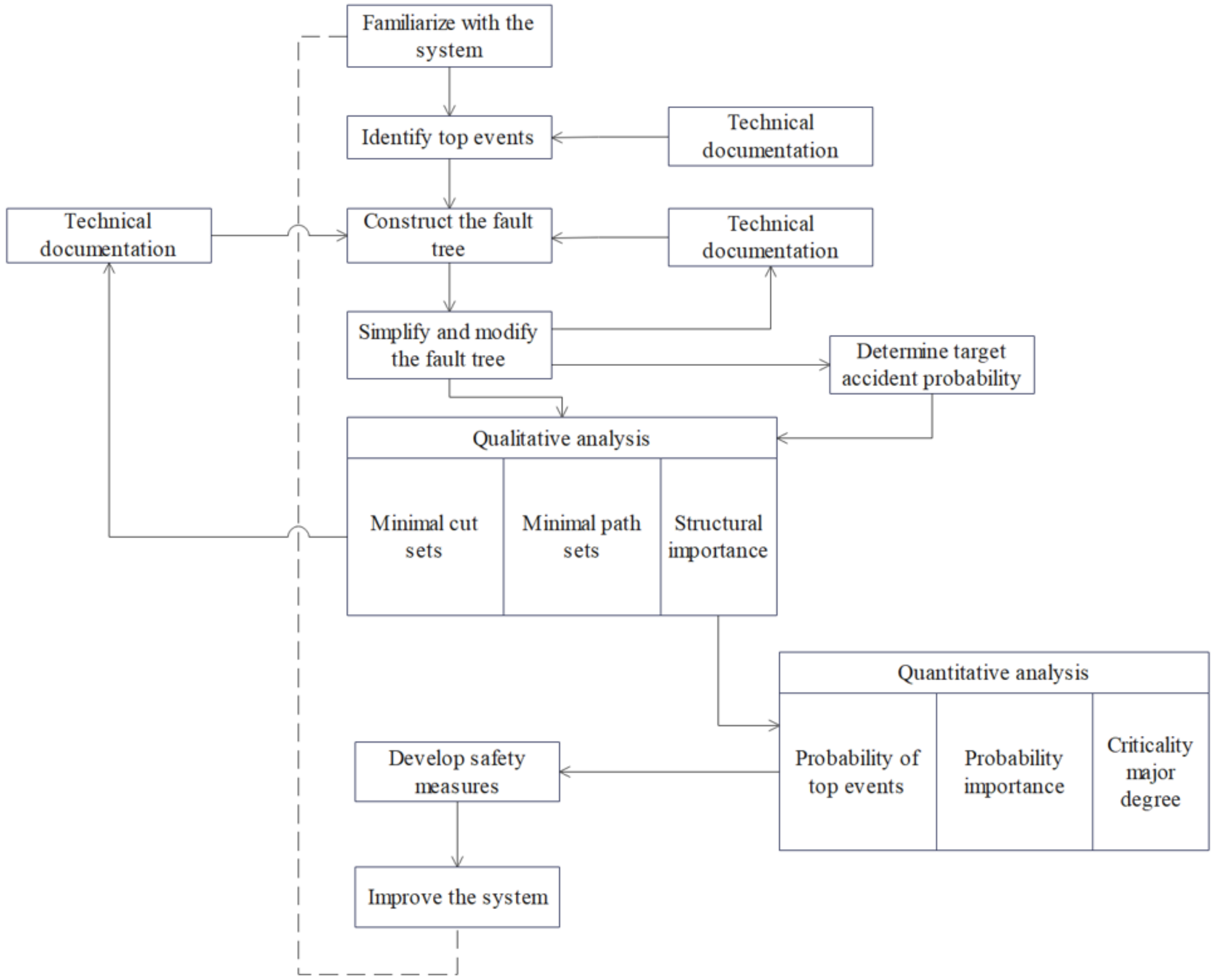


Figure 5. General procedure for FTA

location and facility layout.

(2) Investigate accidents: Preliminary potential hazardous accidents in the system, identified through the PHA method, include poisoning, fire and explosion, electrical injury, mechanical injury, and traffic accidents.

(3) Determine the top event: Among these, fire and explosion pose the highest hazard level; therefore, in the FTA, the fire and explosion accident at the gas station is set as the top event.

(4) Determine the target accident probability: Referring to accident data from similar systems, it is found that the risk of explosion accidents at gas stations is relatively high [12]. Therefore, the goal is to reduce the probability of fire and explosion accidents as close to zero as possible to ensure the safe operation of the gas station.

(5) Investigate cause events: Investigating the hazardous factors leading to fire and explosion accidents can be approached from multiple dimensions, including human unsafe factors, unsafe conditions of objects, environmental factors, and management deficiencies. Specifically, these can be categorized into human factors, equipment factors, management factors, and ignition source factors. Human factors can be divided into psychological factors and unsafe behavior; equipment factors can be divided into gasoline leakage and vapor accumulation; management factors refer to personnel management; ignition source factors can be divided into open flames and sparks.

(6) Draw the fault tree: As shown in Figure 6.

T: Fire and explosion accident at the gas station; M_1: Human factors; M_2: Equipment factors; M_3: Management factors; M_4: Ignition source factors; K_1: Psychological factors; K_2: Unsafe behavior; K_3: Gasoline leakage; K_4: Vapor accumulation; K_5: Personnel management; K_6: Open flames; K_7: Sparks; X_1: Risk-taking mentality; X_2: Energy-saving mentality; X_3 : Seeking excitement mentality; X_4: Rebellious mentality; X_5: Smoking at will; X_6: Not turning off the engine while refueling; X_7: Tank rupture; X_8: Equipment and pipeline corrosion and aging; X_9: Tank leakage; X_{10}: Illegal operations; X_{11}: Incomplete regulations; X_{12}: Lighter; X_{13}: Matches; X_{14}: Electrical sparks; X_{15}: Lightning discharge; X_{16}: Car engine.

(7) Qualitative analysis

(a). Calculation of minimal cut sets

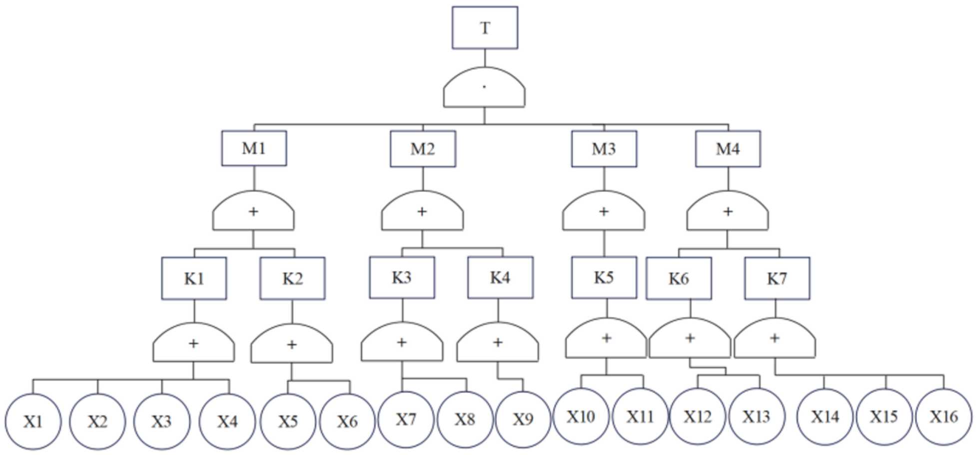


Figure 6. Fault tree for fire and explosion accident at Xuefu Gas Station

Minimal cut sets represent hazardousness. The occurrence of any combination within a minimal cut set will lead to the occurrence of the top event. The more minimal cut sets, the more dangerous the system.

The calculation of the fault tree structure function, simplified through Boolean algebra, yields:

$$T = M_1M_2M_3M_4 = (K_1 + K_2)(K_3 + K_4)K_5(K_6 + K_7) = (X_1 + X_2 + X_3 + X_4 + X_5 + X_6)(X_7 + X_8 + X_9)(X_{10} + X_{11})(X_{12} + X_{13} + X_{14} + X_{15} + X_{16}) = X_1X_7X_{10}X_{12} + X_1X_8X_{10}X_{12} + X_1X_9X_{10}X_{12} + X_1X_7X_{11}X_{12} + X_1X_8X_{11}X_{12} + X_1X_9X_{11}X_{12} + X_1X_7X_{10}X_{13} + X_1X_8X_{10}X_{13} + X_1X_9X_{10}X_{13} + X_1X_7X_{11}X_{13} + X_1X_8X_{11}X_{13} + X_1X_9X_{11}X_{13} + X_1X_7X_{10}X_{14} + X_1X_8X_{10}X_{14} + X_1X_9X_{10}X_{14} + X_1X_7X_{11}X_{14} + X_1X_8X_{11}X_{14} + X_1X_9X_{11}X_{14} + X_1X_7X_{10}X_{15} + X_1X_8X_{10}X_{15} + X_1X_9X_{10}X_{15} + X_1X_7X_{11}X_{15} + X_1X_8X_{11}X_{15} + X_1X_9X_{11}X_{15} + X_1X_7X_{10}X_{16} + X_1X_8X_{10}X_{16} + X_1X_9X_{10}X_{16} + X_1X_7X_{11}X_{16} + X_1X_8X_{11}X_{16} + X_1X_8X_{11}X_{16} + X_2X_7X_{10}X_{12} + X_2X_8X_{10}X_{12} + X_2X_9X_{10}X_{12} + X_2X_7X_{11}X_{12} + X_2X_8X_{11}X_{12} + X_2X_9X_{11}X_{12} + X_2X_7X_{10}X_{13} + X_2X_8X_{10}X_{13} + X_2X_9X_{10}X_{13} + X_2X_7X_{11}X_{13} + X_2X_8X_{11}X_{13} + X_2X_9X_{11}X_{13} + X_2X_7X_{10}X_{14} + X_2X_8X_{10}X_{14} + X_2X_9X_{10}X_{14} + X_2X_7X_{11}X_{14} + X_2X_8X_{11}X_{14} + X_2X_9X_{11}X_{14} + X_2X_7X_{10}X_{15} + X_2X_8X_{10}X_{15} + X_2X_9X_{10}X_{15} + X_2X_7X_{11}X_{15} + X_2X_8X_{11}X_{15} + X_2X_9X_{11}X_{15} + X_2X_7X_{10}X_{16} + X_2X_8X_{10}X_{16} + X_2X_9X_{10}X_{16} + X_2X_7X_{11}X_{16} + X_2X_8X_{11}X_{16} + X_2X_8X_{11}X_{16} + X_3X_7X_{10}X_{12} + X_3X_8X_{10}X_{12} + X_3X_9X_{10}X_{12} + X_3X_7X_{11}X_{12} + X_3X_8X_{11}X_{12} + X_3X_9X_{11}X_{12} + X_3X_7X_{10}X_{13} + X_3X_8X_{10}X_{13} + X_3X_9X_{10}X_{13} + X_3X_7X_{11}X_{13} + X_3X_8X_{11}X_{13} + X_3X_9X_{11}X_{13} + X_3X_7X_{10}X_{14} + X_3X_8X_{10}X_{14} + X_3X_9X_{10}X_{14} + X_3X_7X_{11}X_{14} + X_3X_8X_{11}X_{14} + X_3X_9X_{11}X_{14} + X_3X_7X_{10}X_{15} + X_3X_8X_{10}X_{15} + X_3X_9X_{10}X_{15} + X_3X_7X_{11}X_{15} + X_3X_8X_{11}X_{15} + X_3X_9X_{11}X_{15} + X_3X_7X_{10}X_{16} + X_3X_8X_{10}X_{16} + X_3X_9X_{10}X_{16} + X_3X_7X_{11}X_{16} + X_3X_8X_{11}X_{16} + X_3X_8X_{11}X_{16} + X_4X_7X_{10}X_{12} + X_4X_8X_{10}X_{12} + X_4X_9X_{10}X_{12} + X_4X_7X_{11}X_{12} + X_4X_8X_{11}X_{12} + X_4X_9X_{11}X_{12} + X_4X_7X_{10}X_{13} + X_4X_8X_{10}X_{13} + X_4X_9X_{10}X_{13} + X_4X_7X_{11}X_{13} + X_4X_8X_{11}X_{13} + X_4X_9X_{11}X_{13} + X_4X_7X_{10}X_{14} + X_4X_8X_{10}X_{14} + X_4X_9X_{10}X_{14} + X_4X_7X_{11}X_{14} + X_4X_8X_{11}X_{14} + X_4X_9X_{11}X_{14} + X_4X_7X_{10}X_{15} + X_4X_8X_{10}X_{15} + X_4X_9X_{10}X_{15} + X_4X_7X_{11}X_{15} + X_4X_8X_{11}X_{15} + X_4X_9X_{11}X_{15} + X_4X_7X_{10}X_{16} + X_4X_8X_{10}X_{16} + X_4X_9X_{10}X_{16} + X_4X_7X_{11}X_{16} + X_4X_8X_{11}X_{16} + X_4X_8X_{11}X_{16} + X_5X_7X_{10}X_{12} + X_5X_8X_{10}X_{12} + X_5X_9X_{10}X_{12} + X_5X_7X_{11}X_{12} + X_5X_8X_{11}X_{12} + X_5X_9X_{11}X_{12} + X_5X_7X_{10}X_{13} + X_5X_8X_{10}X_{13} + X_5X_9X_{10}X_{13} + X_5X_7X_{11}X_{13} + X_5X_8X_{11}X_{13} + X_5X_9X_{11}X_{13} + X_5X_7X_{10}X_{14} + X_5X_8X_{10}X_{14} + X_5X_9X_{10}X_{14} + X_5X_7X_{11}X_{14} + X_5X_8X_{11}X_{14} + X_5X_9X_{11}X_{14} + X_5X_7X_{10}X_{15} + X_5X_8X_{10}X_{15} + X_5X_9X_{10}X_{15} + X_5X_7X_{11}X_{15} + X_5X_8X_{11}X_{15} + X_5X_9X_{11}X_{15} + X_5X_7X_{10}X_{16} + X_5X_8X_{10}X_{16} + X_5X_9X_{10}X_{16} + X_5X_7X_{11}X_{16} + X_5X_8X_{11}X_{16} + X_5X_8X_{11}X_{16} + X_6X_7X_{10}X_{12} + X_6X_8X_{10}X_{12} + X_6X_9X_{10}X_{12} + X_6X_7X_{11}X_{12} + X_6X_8X_{11}X_{12} + X_6X_9X_{11}X_{12} + X_6X_7X_{10}X_{13} + X_6X_8X_{10}X_{13} + X_6X_9X_{10}X_{13} + X_6X_7X_{11}X_{13} + X_6X_8X_{11}X_{13} + X_6X_9X_{11}X_{13} + X_6X_7X_{10}X_{14} + X_6X_8X_{10}X_{14} + X_6X_9X_{10}X_{14} + X_6X_7X_{11}X_{14} + X_6X_8X_{11}X_{14} + X_6X_9X_{11}X_{14} + X_6X_7X_{10}X_{15} + X_6X_8X_{10}X_{15} + X_6X_9X_{10}X_{15} + X_6X_7X_{11}X_{15} + X_6X_8X_{11}X_{15} + X_6X_9X_{11}X_{15} + X_6X_7X_{10}X_{16} + X_6X_8X_{10}X_{16} + X_6X_9X_{10}X_{16} + X_6X_7X_{11}X_{16} + X_6X_8X_{11}X_{16} + X_6X_8X_{11}X_{16} + X_6X_9X_{11}X_{16}$$

Due to the large number of basic events in the fault tree, the number of minimal cut sets obtained by solving the above equation is too large, making qualitative analysis of the fault tree inconvenient. Therefore, the expansion of the minimal cut sets is omitted, and the calculation of the minimal path sets for the fault tree is performed next.

(b). Calculation of minimal path sets

Utilizing the duality between minimal path sets and minimal cut sets, the “AND gate" in the original fault tree is replaced with an “OR gate," the “OR gate" is replaced with an “AND gate," and the condition of occurrence is replaced with non-occurrence to create a success tree that is dual to the fault tree [19]. Minimal path sets represent the safety of the system; if any combination within a minimal path set does not occur, the top event will not occur. The more minimal path sets in the fault tree, the safer the system, as shown in Figure 7.

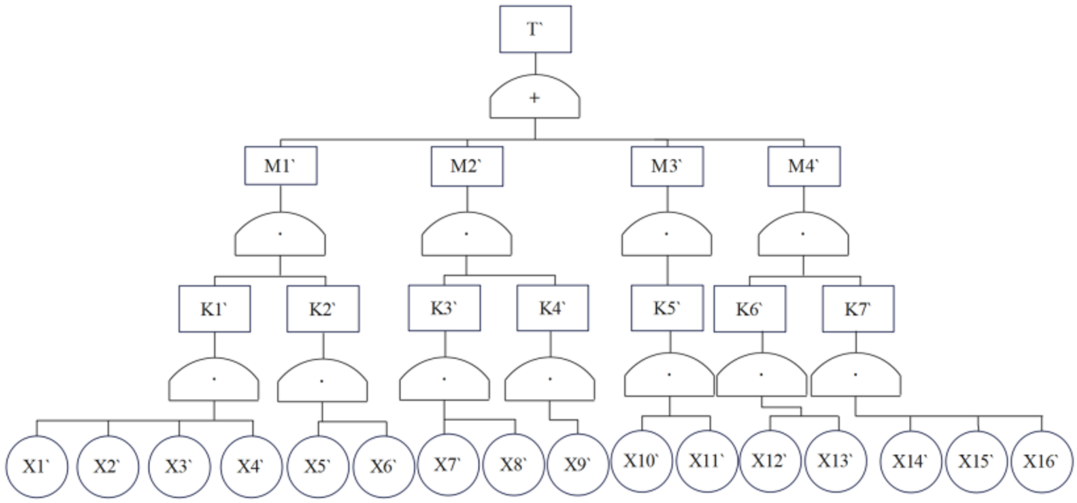


Figure 7. Success tree for non-occurrence of fire and explosion at Xuefu Gas Station

The structure function of this success tree is simplified using Boolean functions to obtain:

$$\mathrm{T}' = \mathrm{M_1}' + \mathrm{M_2}' + \mathrm{M_3}' + \mathrm{M_4}'$$
$$= \mathrm{K_1}'\mathrm{K_2}' + \mathrm{K_3}'\mathrm{K_4}' + \mathrm{K_5}' + \mathrm{K_6}'\mathrm{K_7}'$$
$$= \mathrm{X_1}'\mathrm{X_2}'\mathrm{X_3}'\mathrm{X_4}'\mathrm{X_5}'\mathrm{X_6}' + \mathrm{X_7}'\mathrm{X_8}'\mathrm{X_9}' + \mathrm{X_{10}}'\mathrm{X_{11}}' + \mathrm{X_{12}}'\mathrm{X_{13}}'\mathrm{X_{14}}'\mathrm{X_{15}}'\mathrm{X_{16}}'$$
$$\mathrm{T} = (\mathrm{X_1} + \mathrm{X_2} + \mathrm{X_3} + \mathrm{X_4} + \mathrm{X_5} + \mathrm{X_6})(\mathrm{X_7} + \mathrm{X_8} + \mathrm{X_9})(\mathrm{X_{10}} + \mathrm{X_{11}})(\mathrm{X_{12}} + \mathrm{X_{13}} + \mathrm{X_{14}} + \mathrm{X_{15}} + \mathrm{X_{16}})$$

The minimal cut sets of the success tree are the minimal path sets $\mathrm{P_i}\,(\mathrm{i} = 1, 2, 3, 4)$ of the original fault tree, which are respectively: $P_1 = \{X_1, X_2, X_3, X_4, X_5, X_6\}$; $P_2 = \{X_7, X_8, X_9\}$; $P_3 = \{X_{10}, X_{11}\}$; $P_4 = \{X_{12,}, X_{13}, X_{14}, X_{15}, X_{16}\}$. Therefore, to prevent the accident from occurring, smoking at will while refueling with the engine running must be avoided, and risk-taking, energy-saving, seeking excitement, and rebellious mentalities should not be harbored. Additionally, regular inspections of tanks, equipment, and pipelines should be conducted to prevent tank rupture, leakage, and equipment and pipeline corrosion and aging. Furthermore, regulations should be improved, and illegal operations strictly monitored. Lastly, attention should be paid to ignition sources such as lighters, matches, electrical sparks, lightning discharge, and car engines. Particularly, due to limitations on subjective factors, some hazardous factors have not been considered, such as insufficient standing time and incorrect measurement [13], which should be supplemented and improved in the future.

(c) Calculation of structural importance

Structural importance analysis evaluates the importance of each basic event from the structure function and is part of the qualitative analysis of the fault tree. It can identify key nodes and weak links in the system, providing decision-making support for effective safety management and risk control measures. The approximate calculation formula is as follows:

$$I_{\varphi(i)} = 1 - \prod_{x_i \epsilon k_j} \left(1 - \frac{1}{2^{n_j - 1}}\right)$$

$I_{\varphi(i)}$: Structural importance coefficient of the i-th basic event;

n_j: Total number of basic events in k_j where the i-th basic event is located;

$n_j - 1$: Exponent of 2.

where,

$$\mathrm{I}\varphi(1) = \mathrm{I}\varphi(2) = \mathrm{I}\varphi(3) = \mathrm{I}\varphi(4) = \mathrm{I}\varphi(5) = \mathrm{I}\varphi(6) = 1 - \left(1 - \frac{1}{2^{6-1}}\right) = \frac{1}{32}$$

$$\mathrm{I}\varphi(7) = \mathrm{I}\varphi(8) = \mathrm{I}\varphi(9) = 1 - \left(1 - \frac{1}{2^{2-1}}\right) = \frac{1}{4}$$

$$\mathrm{I}\varphi(10) = \mathrm{I}\varphi(11) = 1 - \left(1 - \frac{1}{2^{2-1}}\right) = \frac{1}{2}$$

$$\mathrm{I}\varphi(12) = \mathrm{I}\varphi(13) = \mathrm{I}\varphi(14) = \mathrm{I}\varphi(15) = \mathrm{I}\varphi(16) = 1 - \left(1 - \frac{1}{2^{5-1}}\right) = \frac{1}{16}$$

So, the structural importance ranks as follows:

$$I\varphi(10) = I\varphi(11) > I\varphi(7) = I\varphi(8) = I\varphi(9) > I\varphi(12) = I\varphi(13)$$
$$= I\varphi(14) = I\varphi(15) = I\varphi(16) > I\varphi(1) = I\varphi(2) = I\varphi(3) = I\varphi(4) = I\varphi(5) = I\varphi(6)$$

This indicates that management factors have the highest impact on the occurrence of the top event, equipment factors have a higher impact, ignition source factors have a lower impact, and human factors have the lowest impact. Therefore, priority should be given to strengthening the management of regulations, followed by regular equipment maintenance, then preventing ignition sources, and finally overcoming psychological and behavioral influences of humans. However, when calculating the structural importance ranking using the approximate formula, even with high precision, errors may still occur . Therefore, the structural importance ranking should only be used as a basic reference for the importance of each basic event.

(8) Quantitative analysis: Calculation of top event occurrence probability

Referring to the study on the prediction of accident occurrence probability in a traffic system based on the Bayesian network model [21], the probabilities of the basic events are obtained as shown in Table 7.

Table 7. Probabilities of basic events

Time Number	Event Name	Event Probability
X_1	Risk-taking mentality	0.02
X_2	Energy-saving mentality	0.02
X_3	Seeking excitement mentality	0.01
X_4	Rebellious mentality	0.01
X_5	Smoking at will	0.02
X_6	Not turning off the engine while refueling	0.01
X_7	Tank rupture	0.01
X_8	Equipment and pipeline corrosion, aging	0.02
X_9	Tank leakage	0.01
X_{10}	Illegal operations	0.01
X_{11}	Incomplete regulations	0.01
X_{12}	Lighter	0.02
X_{13}	Matches	0.01
X_{14}	Electrical sparks	0.01
X_{15}	Lightning discharge	0.01
X_{16}	Car engine	0.01

From equation below, the equivalent diagram of the minimal path set is shown in Figure 8.

$$T' = M_1' + M_2' + M_3' + M_4'$$
$$= K_1'K_2' + K_3'K_4' + K_5' + K_6'K_7'$$
$$= X_1'X_2'X_3'X_4'X_5'X_6' + X_7'X_8'X_9' + X_{10}'X_{11}' + X_{12}'X_{13}'X_{14}'X_{15}'X_{16}'$$
$$T = (X_1 + X_2 + X_3 + X_4 + X_5 + X_6)(X_7 + X_8 + X_9)(X_{10} + X_{11})(X_{12} + X_{13} + X_{14} + X_{15} + X_{16})$$

According to Table 7, we have: q1=0.02, q2=0.02, q3=0.01, q4=0.01, q5=0.02, q6=0.01, q7=0.01, q8=0.02, q9=0.01, q10=0.01, q11=0.01, q12=0.02, q13=0.01, q14=0.01, q15=0.01, q16=0.01.

Thus, the probability of the top event is calculated as follows:

g=[1-(1-q1)(1-q2)(1-q3)(1-q4)(1-q5)(1-q6)][1-(1-q7)(1-q8)(1-q9)][1-(1-q10)(1-q11)][1-(1-q12)(1-q13)(1-q14)(1-q15)(1-q16)] =[1-0.98^{3}0.99^3][1-0.99^{2}0.98][1-0.99^2][1-0.9940.98] =0.00000399778

Therefore, the probability of a fire and explosion accident at Xuefu Gas Station in Xiangtan City is 0.00000399778. Although the probability of such an accident occurring at the gas station is very small, it has not reached the target accident probability. The gas station still faces some risk. Thus, further research is needed to explore methods to reduce the accident probability.

(9) Formulating safety measures

Based on the structural importance ranking and in accordance with the principles of system safety, practical safety countermeasures are proposed to address potential hazards leading to fire and explosion at the gas station.

(a) Management: A comprehensive and practical safety management system must be established. This includes clarifying management responsibilities at all levels, developing detailed safety operation procedures, and regularly reviewing and updating these procedures to adapt to the changing safety environment. Additionally, an effective supervision mechanism should be established to ensure strict adherence to safety management systems, ensuring the safe operation of production activities.

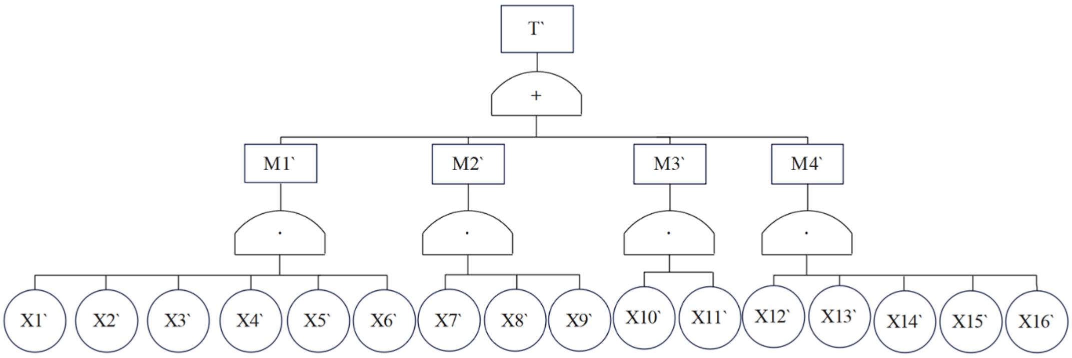


Figure 8. Equivalent diagram of minimal path set

(b) Equipment: Safety standards must be strictly followed, and equipment that complies with national safety regulations and industry standards should be selected. Furthermore, equipment monitoring and maintenance should be strengthened, with regular inspections, repairs, and upkeep to ensure equipment is in good working condition.

(c) Ignition sources: Fire safety regulations must be strictly followed, with rigorous control over fire sources and static sparks. This includes setting clear no-smoking signs in flammable and explosive areas, implementing strict fire permit systems, and closely supervising open flame operations. Effective measures should also be taken to prevent static electricity generation and accumulation, such as installing static elimination devices and wearing anti-static clothing, to reduce the risk of fire caused by static sparks.

(d) Human factors: Emphasis should be placed on improving employees' safety awareness and operational skills. Through regular safety education and training, employees should become proficient in safety operating procedures. Additionally, driver behavior management should be strengthened with strict driving regulations and supervision to ensure drivers adhere to safety norms and reduce safety accidents caused by human factors.

5 Evaluation Conclusions and Recommendations

The Conclusions section should clarify the main conclusions of the research, highlighting its significance and relevance. The limitations of the work and the directions of future research may also be mentioned. Please contain nothing not substantiated in the main text. Do not make this section a mere repetition of the Abstract.

Based on this study, the following conclusions are drawn:

(1) This study conducted a qualitative analysis of Xuefu Gas Station using a PHA method, identifying potential hazards in the gas station system, including poisoning, fire and explosion, electrical injuries, mechanical injuries, and traffic accidents. Corresponding preventive measures were proposed to reduce the occurrence of accidents. Emphasis should be placed on improving the grounding system of refueling vehicles, installing fire protection, leakage detection, and other equipment, strengthening ventilation and protection, regularly inspecting work equipment, wearing protective gear during operations, setting prominent safety signs and vehicle entry and exit signs, and adopting closed refueling technology with standardized maintenance operations.

(2) This study performed qualitative and quantitative analysis of Xuefu Gas Station using the FTA method. It was found that issues exist in the management, equipment, ignition sources, and human factors of the gas station system, and targeted recommendations were made. According to the recommendations, the gas station system should comprehensively optimize management, ensure strict implementation of safety regulations, select equipment that meets safety standards, enhance monitoring and maintenance, strictly control fire sources and static sparks, and improve employees' and drivers' safety awareness and operational skills to reinforce safety measures.

(3) This study employed an approximate calculation method in FTA to rank the structural importance of each influencing factor, identifying key influencing factors as management factors, equipment factors, ignition source factors, and human factors.

(4) Although this study has achieved certain results in gas station safety management, there is still room for improvement. Future research should focus on improving the adaptability of the analysis framework, optimizing data collection and analysis methods, and developing new computational models to provide more comprehensive and in-depth support for gas station safety management.

In summary, the application of safety evaluation technology to Xuefu Gas Station in Xiangtan City has been comprehensive, with logical and rigorous evaluation methods, appropriate selection of measures, and practical recommendations. This can positively address real safety issues at gas stations and has value for promotion and application in the gas station industry.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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