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Comparative Study of the Hazardous Chemical Transportation Accident Analyses Using the CREAM Model and the 24Model

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Abstract: Compared with other types of transportation, hazardous chemical transportation is more dangerous and more likely to cause accidents, such as combustion and explosion. To better study the advantages of different accident analysis models and realize the sustainable development of the accident analysis, this paper compares the 24Model and the cognitive reliability and error analysis method in their analyses of causes of hazardous chemical transportation accidents. Regarding their analyses of the causes of hazardous chemical transportation accidents, the causal factors of hazardous chemical transportation accidents are obtained. Then the analysis results of the two models are compared on three aspects: the object of accident influence, the module of accident analysis, and the number of accident causes. Gray correlation analysis and regression analysis are used to quantitatively compare and verify the focus of the two models on the cause of the accident. The results show that the 24Model emphasizes the safety culture of the enterprise, the cognitive reliability and error analysis method emphasizes the technology of the enterprise, and the two accident analysis models provide different emphases on preventing accidents to better achieve the goal of sustainable development.

Keywords: hazardous chemicals; transportation accidents; accident analysis model; 24Model; cognitive reliability and error analysis method

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1. Introduction

Hazardous chemical transportation accidents are different from other types of transportation accidents because they usually cause serious consequences, such as burning, explosion, and leakage, resulting in social problems, such as economic losses, environmental pollution, ecological damage, and injury [1].

There are models for accident cause analysis, such as the Swiss cheese model [2,3], human factor analysis and classification system (HFACS) [4], 24Model [5], functional resonance analysis method (FRAM) [6], accident map (Accimap) model [7], cognitive reliability and error analysis method (CREAM) [8], job demands resources (JD-R) model proposed [9], and systems-theoretic accident model and process (STAMP) model [10].

Both the 24Model and CREAM are systematic accident causation and modular models. The 24Model regards the organization where the accident occurs as a system, the safety culture and safety management system as contact media. Additionally, it reflects their interactions in a simple linear relationship that reflects the actual situation of complex systems [11,12]. In addition, the 24Model distinguishes organizational behavior from personal behavior. The former is the radical cause and root cause of the accident, while the latter is the immediate or indirect cause of the accident. The 24Model provides a systematic framework for accident analysis. The CREAM model focuses on the mechanism of human behavior. By describing the accident path through the system network structure, the qualitative analysis of human factors and the quantitative prediction of human error probability can be carried out. In some cases, it also includes studies of the possibility of human error in human observation, diagnosis, decision making, and other cognitive activities. Its unique cognitive model and framework provide a two-way analysis of tracking performance predictions, the "consequence–antecedent list" enables researchers to track the root cause of human error events, and each cause category has specific details.

The 24Model does provide a clear but not detailed classification of accident causes, although it provides a framework for cause analysis. Analysts may be limited by their own level and subjective consciousness to influence the analysis results in this framework. The CREAM provides a specific cause classification; however, when analyzing specific industries, analysts need expertise to choose the appropriate antecedent–consequence classification. The 24Model and CREAM represent two different accident analysis model characteristics; therefore, this paper tries to discover whether the accident results obtained by these two models have different emphases.

Gray correlation analysis and regression analysis were chosen to further investigate the accident analysis results of the two models. Gray correlation analysis is a common analysis method used to determine the degree of correlation among variables, and is used in fault diagnosis, optimal solution selection, and stability evaluation of projects [13–15]. Regression analysis is a statistical method used to determine the relationship among variables, and trend prediction analysis to determine the distribution type of variables and clarify the correlation among influencing factors [16,17].

Based on this, the paper studied the characteristics and differences between the 24Model and CREAM in the hazardous chemical transportation accident analysis, and gave quantitative results using gray correlation analysis and regression analysis.

2. Material and Methods

The 24Model was first proposed in 2005 [5], and the fifth edition was published in 2019, shown in Figure 1. The 24Model classifies accidents as having organizational causes, arguing that any accident occurs at least within an organization, and further divides accident causes into internal and external levels. Internal level includes organizational behaviors and individual behaviors. Organizational behaviors can be further divided into two stages, safety culture (root cause) and safety management system (radical cause). Individual behaviors include habitual behaviors (indirect cause), one-time behaviors, and conditions (immediate cause). Root cause, radical cause, indirect cause, and immediate cause were linked together to form the 24Model. By applying the 24Model, the immediate causes, indirect causes, radical causes, and root causes can be gradually deduced from the occurrence of an accident. The immediate causes of the accident are unsafe acts and unsafe conditions; the indirect causes are knowledge, psychology, consciousness, habits, and physiology; the radical causes are the safety management system; and the root causes are the safety culture.

The 24Model describes the accident path as a system network structure, covering a clear classification and comprehensive accident causes. Its analysis process is simple and easy to analyze accident causal factors and enables effective analysis of individual and organizational behaviors in accident causal factors divided. However, the analysis results are relatively broad and weakly targeted, and the model description in the probabilistic analysis of accident causes needs to be further enhanced [18,19].

The cognitive reliability and error analysis method (CREAM) is developed based on the systematic criticism of traditional HRA (human reliability analysis, referring to the quantitative or qualitative assessment of human errors that affect the availability or operational reliability of engineered safety features and components) principles and methods [8]. Its core ideas include general performance conditions, observable and unobservable errors, cyclic behavior models, human cognition, control modes, and bidirectional functions [20]. The CREAM model's contents are shown in Figure 2.

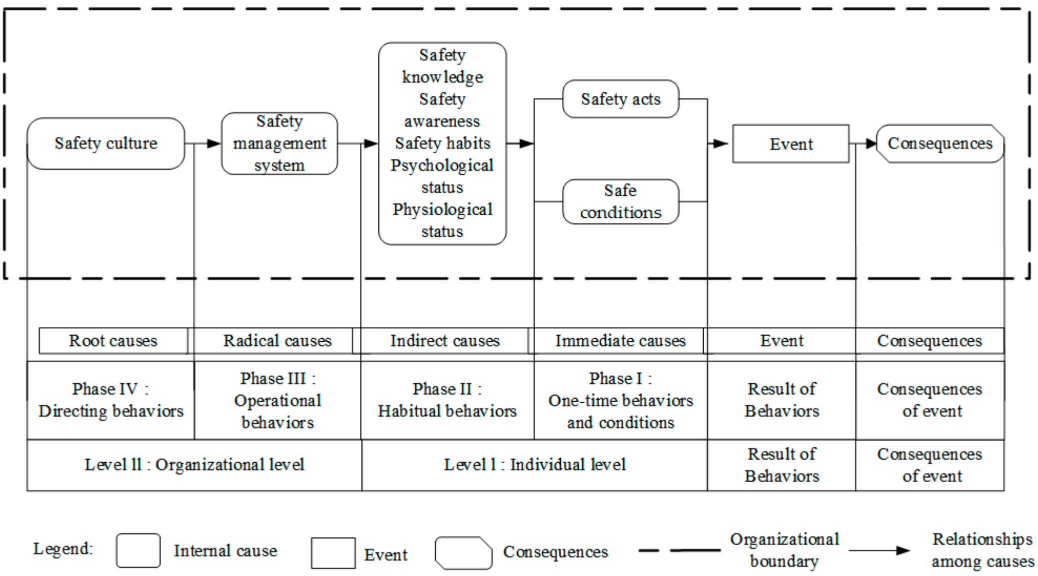

Figure 1. Fifth edition of the 24Model.

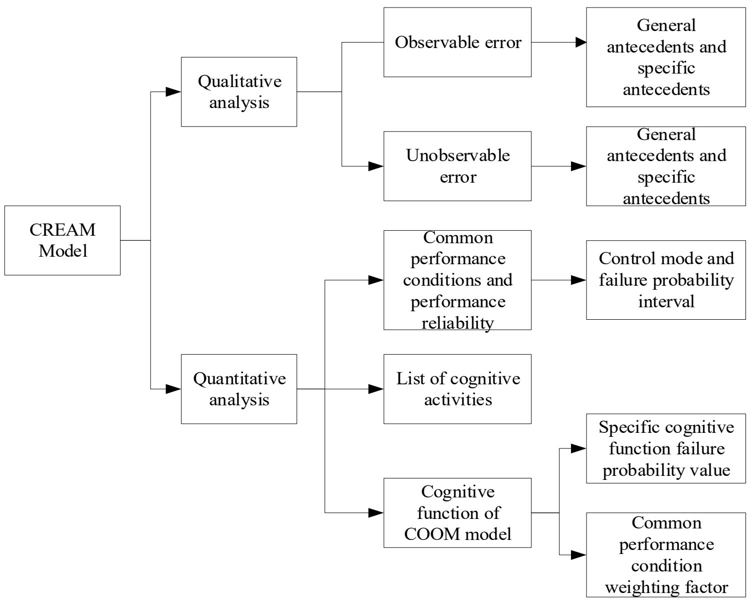

Figure 2. The content of the CREAM model.

The CREAM is a critical tool for the reliability of human factor analysis, performing qualitative analysis of human factors, and quantitative prediction of human error probability. In the field of human factor reliability analysis, the CREAM model has important significance [21,22]. However, the analysis takes human-caused errors as the starting point, having a higher demand for analysts in the quantitative prediction part of the process, which may be less efficient when applied in practice. In addition, when tracing the CREAM accident cause, a new antecedent–consequence classification table needs to be recreated for different areas, and the original cause classification is not detailed enough to obtain a more comprehensive cause [23].

To make the accident analysis more comprehensive, 30 cases were collected from the Ministry of Emergency Management of the People's Republic of China, Provincial Emergency Department (Bureau), China Chemical Safety Association, Registration Center for Chemicals of the Ministry of Emergency Management, other websites, and related papers and books to establish a sample database. The case contains four levels, including general, serious, major, and particularly serious hazardous chemical transportation accidents from

2000 to 2018. The criteria for the four levels are based on the Chinese law: Report on production safety accident and regulations of investigation and treatment [24]. The specific accident classification criteria are shown in Table 1. Any aspect that meets the criteria for a more serious accident level will result in the accident being classified as more serious. For example, an accident with fewer than 30 fatalities but with direct economic losses greater than RMB 100 million would be classified as a particularly serious accident. Therefore, some particularly serious accidents do not have as many fatalities as major accidents, but are classified as particularly serious accidents because of the economic losses or serious injuries, meeting the criteria for a special major accident.

Table 1. Accident classification criteria.

Accident Levels	Number of Deaths	Number of Serious Injuries	Direct Economic Losses (Million in RMB)
General accident	Deaths < 3	Seriously injured < 10 (including acute industrial poisoning, the same below)	Losses < 10
Serious accident	3 ≤ deaths < 10	10 ≤ seriously injured < 50	10 ≤ losses < 50
Major accident	10 ≤ deaths < 30	50 ≤ seriously injured < 100	50 ≤ losses < 100
Particularly serious accident	Deaths ≥ 30	Seriously injured ≥ 100	Losses ≥ 100

According to the China Chemical Accident Information Network, there were 2475 hazardous chemical transportation accidents in China during 2000–2018, of which 2421 were below general accident (did not result in fatalities or caused minimal economic losses), 29 were general accidents, 14 were serious accidents, 5 were major accidents, and 6 were particularly serious accidents. Among them, 2421 below general accidents did not have an accident investigation report and could not be studied in further depth. For the remaining accidents, due to the fact that some accidents occurred long ago and information is missing or less influential, this paper finally selected 30 hazardous chemical transportation accidents with complete information of accident investigation reports and more influential or serious losses. All the valuable cases that could be collected were gathered as much as possible.

In 30 accidents, 297 people died in total. Among them, there were 6 particularly serious accidents with 96 deaths, 5 major accidents with 171 deaths, 4 serious accidents with 18 deaths, and 15 general accidents with 12 deaths. Figure 3 shows the number of accidents and fatalities, and Figure 4 shows the proportion of deaths caused by accidents at various links in transportation. In Figure 3, GA, SA, MA, and PSA mean four accident levels. GA means general accident, SA means serious accident, MA means major accident, and PSA means particularly serious accident. In Figure 4, "handling" represents the loading and unloading process of hazardous chemicals, "before setting out" represents the process of preparing for departure after loading and unloading of hazardous chemicals, and "transportation" represents the transportation process of hazardous chemicals; and they all belong to hazardous chemical transportation accidents. And in particular, "unloading" represents unloading goods in the following text.

It should be noted that there is only one type of accident analyzed in this paper: hazardous chemical transportation accidents. Additionally, the accident is divided into three segments according to the different transportation processes: handling, before setting out, and transportation, as shown in Figure 4.

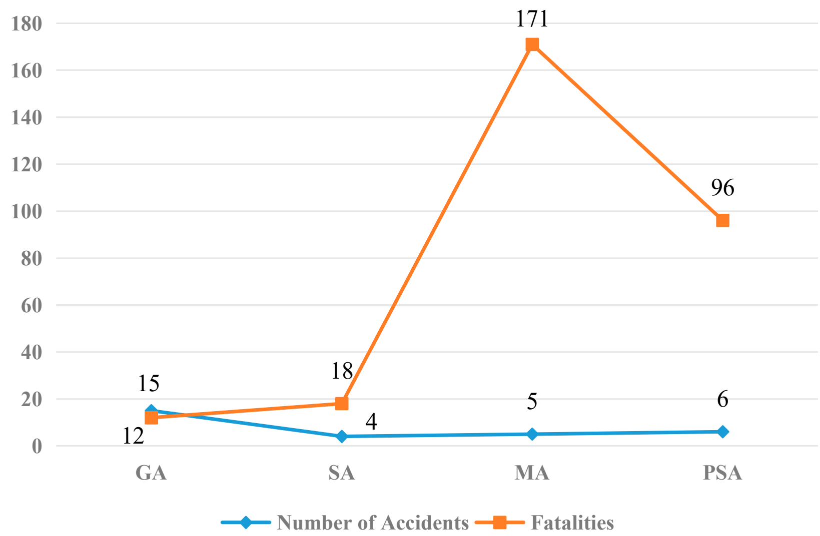

Figure 3. Numbers and fatalities of the accidents.

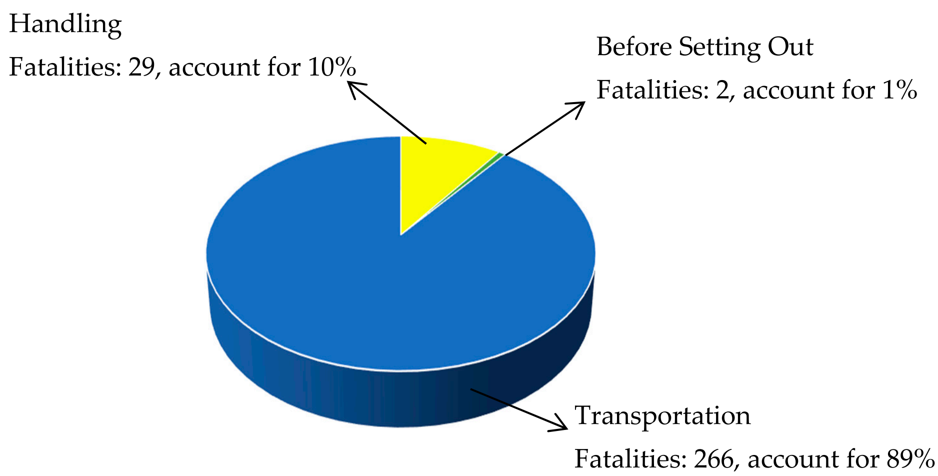

Figure 4. Proportion of fatalities in hazardous chemical transportation accidents.

3. Accident Process

This article collected 30 investigation reports of hazardous chemical transportation accidents with complete information and large impact in China from 2000 to 2018, and some hazardous chemical transportation accidents with incomplete information and less impacts were not counted.

In the case study, 30 accidents were collected and analyzed by the CREAM and 24Model separately to testify the method. Among them, one accident is shown in detail as follows for illustration purposes. Additionally, fictitious names are used in order to illustrate the accident analysis processes.

At 00:58, Tang, the driver of Linyi Jinyu Logistics Co., Ltd., after driving a liquefied gas transport vehicle for a long distance, entered the company, ready to unload. After Tang got off the vehicle, he connected the gas–liquid quick-connect interface of the No. 10 loading and unloading arm to the vehicle unloading port, and the gas phase valve was opened to pressurize the tank. Then, the pressure of the vehicle tank increased from 0.6 MPa to more than 0.8 MPa.

At 00:59, when Tang opened the liquid-phase valve of the tank, the liquid-phase connection nozzle was suddenly disconnected, and a large amount of liquefied gas was sprayed out and rapidly vaporized and diffused. Operators on duty failed to effectively handle the situation, which resulted in the leakage of liquefied gas for up to 2 min and 10 s. The leaked liquefied gas mixed with air to form an explosive mixture. Then, the mixture contacted the ignition source, an explosion occurred, and the tanks of accident vehicles and other vehicles were ignited, which caused continuous explosion.

The accident investigation report is issued by the Department of Emergency Management of Shandong Province, China. Some causes of the accident included in the case study can be obtained from the accident investigation report. For example, the accident investigation report states that the accident causes include the company's imperfect operating procedures, the lack of strict unloading procedures, the company's chaotic daily management, the lack of attention to the safety management of the loading and unloading process, driver fatigue, and so forth. In addition, some information can be inferred from the investigation report. For example, the investigation report mentions that the driver has dangerous goods driver qualification and dangerous goods escort qualification; we can infer that the driver has strong driving ability and driving experience.

It should be noted that the details of the accident are based on the facts in the accident investigation report issued by the investigation team of the major "6·5" tanker leakage explosion and fire accident of the Department of Emergency Management of Shandong Province. All analysis is also based on reasonable extrapolations from this.

3.1. Analysis of the CREAM Model

3.1.1. Identify the Human Event

Considering the above accident process, we analyzed that there was a key human error event in the accident: the driver did not reliably connect the quick-connect interface to the liquid discharge tube of the vehicle, which caused liquefied natural gas leakage.

3.1.2. Retrospective Analysis Process of the Human Event

Analysis and Determination of the Error Mode

The most immediate cause of the human error is that the driver in the preparatory stage of the unloading operation missed the step of checking the quick-connect interface and liquid-phase discharge pipe of the vehicle or deliberately skipped it to complete the unloading task in advance. The accident investigation report issued by the Department of Emergency Management of Shandong Province stated that "the driver was running long distances and working continuously, and during the midnight liquefied gas unloading operation did not strictly implement the unloading procedures and made serious operational errors, resulting in the failure to reliably connect the quick-connect interface to the tanker's liquid-phase discharge pipe". Therefore the disconnection is attributed to human error.

Therefore, the error mode of the event is determined as a sequence (missing, jumping forward).

Identify Possible General Causes

According to the "antecedent category name table" [25] provided by the CREAM model, combined with the content of the accident investigation report, "The driver of the vehicle in the accident was travelling long distance and working continuously (work for a long time). When discharging Liquefied Natural Gas, he did not strictly follow the unloading rules and made serious operation mistakes". The error mode sequence (missing, jumping forward) in this accident corresponds to the following four possible antecedents:

A. False observation: the driver who caused the accident checked the connection of the fast interface and found no abnormality;
B. Memory failure: the driver forgot to pick up the connection before unloading the truck;

C. Inattention: the driver who caused the accident was unloading by himself and did not carefully confirm the connection of the quick-connect interface;
D. Inadequate procedure: Jinyu Petrochemical Co., Ltd. (hereinafter referred to as Jinyu), has not formulated complete operation procedures for unloading vehicles and the handling site without the unloading management personnel.

Consequence–Antecedent Analysis

We take the four types of general antecedents summarized above (A–D) as the consequences, determine their general antecedents and specific antecedents in the consequence–antecedent chain, select the general antecedents as the consequences, and look for general antecedents and specific antecedents, which form a cyclic analysis. Finally, the last antecedent of each branch is the root cause of the human error of the driver who caused the accident.

Take A: False observation as an example to illustrate below. Since the analysis process of antecedents B, C, and D are the same as A, only the analysis process of antecedent A is elaborated.

A: False observation is analyzed as a consequence. In the accident case, the safety consciousness of the driver is weak, and illegal driving behaviors such as speeding and fatigue often occur. The driver who caused the accident failed to concentrate during the journey. Therefore, E: Distraction is chosen as the general antecedent. Additionally, there are no suitable specific antecedents.

Continue to use E: Distraction as a consequence to analysis. According to the description of the accident case, "The company has not carried out dynamic monitoring on the actual management of the accident vehicles, and failed to discover and correct the driver's fatigue driving behavior in time". "The company has not been equipped with road dangerous goods transportation handling management personnel according to law." It is known that the company and supercargo failed to form good team cooperation, so it has a general antecedent F: Inadequate team support.

Continue to use F: Inadequate team support as a consequence to analysis. In the description of the accident case, "The daily safety management is chaotic. The company's safety inspection and hidden trouble investigation and management are not thorough and in-depth, safety education and training are a mere formality, and the employees' safety consciousness is poor"; and "the company's emergency management is flawed, failure to formulate targeted emergency response plans, fail to regularly organize practitioners to carry out emergency rescue drills, and inadequate emergency response education and training for drivers". Thus, Jinyu Logistics Co., Ltd., has chaotic management, so we select the general antecedent G: Management problem. Additionally, the team members are not coordinated and can be identified as a specific antecedent.

The analysis process of A: False observation as show in Figure 5.

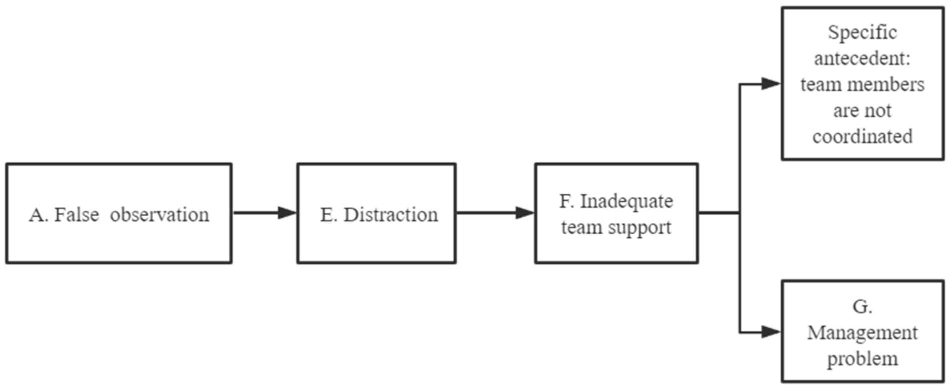

Figure 5. Analysis of A: False observation.

Through the above analysis, the results of the "sequence (missing, jumping forward)" retrospective analysis process and the two error modes are displayed in Figure 6.

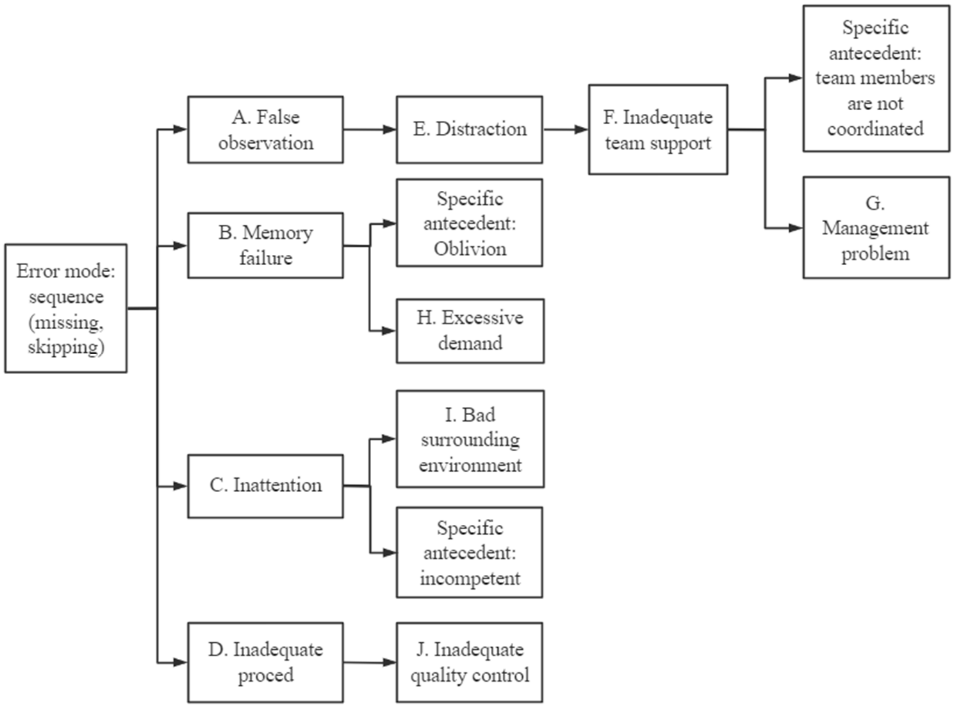

Figure 6. Trace analysis results of the root cause of human error event 1.

3.1.3. Statistics of 30 Accident Results

The CREAM model was used to analyze 30 hazardous chemical transportation accidents, and the statistical results are shown in Table 2. The first horizontal row in Table 2 means the accident level. The classification and explanation of the accident level are given in Table 1. The first vertical column represents the classification of accident causes as human error, human-related antecedents, technology-related antecedents, and organization-related antecedents, according to the CREAM. The meaning of the numbers in Table 2 is the frequency quantity of 30 accidents, that is, the frequency quantity of each cause in general accidents, serious accidents, major accidents, and particularly serious accidents. For example, 19 represents 30 accidents in which human error related to general accidents appeared 19 times, and the other figures in Table 2 have the same meaning.

Table 2. Statistical results of the CREAM model analysis of 30 chemical transport accidents.

Accident Level / Reason	General Accident	Serious Accident	Major Accident	Particularly Serious Accident
Human error	19	5	8	6
Human-related antecedent	75	17	20	12
Technology-related antecedent	25	7	10	7
Organization-related antecedent	88	20	25	14

Note: The data in the above table represent the number of various causes in 30 accidents.

3.2. Analysis of the 24Model

To compare the differences between the two models in analyzing accidents, this part adopts the 24Model to analyze the same accident. The analysis process and results are as follows:

3.2.1. Immediate Causes

Unsafe acts are actions that cause an accident or significantly affect the accident [26]. By analyzing this accident, the following unsafe acts are found, as shown in Table 3.

Table 3. Accident analysis of unsafe acts in Jinyu explosion.

Number	Action Originator	Details
1	Zhifeng Tang, the driver in the accident	Long journey, tired driving.
2		The connection between the quick loading interface and the discharge line of the tank truck is not reliable enough during handling.
3		Arranging for Huihai Chen to go home to rest, and implementing the unloading operation alone.
4	Jinyu logistics company management staff	Henan highway transportation vehicles without actual monitoring.
5		Failure to supervise the management of road dangerous goods transportation and unloading.
6	Remaining 3 drivers	When leakage happened, it was not handled correctly and evacuation was not performed in time.
7	Management staff of Jinyu	Command illegal construction team to start construction.
8	Operator on duty	Failure to detect the misoperation of the driver in time.
9	On-site employees (drivers, special equipment management, and operators)	Self-contained air breathing apparatus not worn.
10		Failure to close the emergency shut-off valve and ball valve in time after the leak.

An unsafe state may be caused by unsafe behavior or habitual behavior, and it may also be inherent in the accident [26]. The following unsafe conditions were found through the accident investigation report and related data, as shown in Table 4.

Table 4. Accident analysis of unsafe conditions of Jinyu explosion.

Numbering	Category	Details
1	Operating environment	More than 10 tank trucks entered the handling site at the same time, and the safety risk in the handling area was high
2	Protective equipment	Lack of emergency equipment and supplies
3	Equipment and facilities	The material of the control room wall does not meet the design requirements
4		Non-explosion-proof electrical appliances for long-term use in the duty room

3.2.2. Indirect Causes

According to the 24Model, indirect causes include the knowledge, consciousness, habits, mental state, and physical condition related to the immediate causes [26]. The indirect causes of this accident are shown in Table 5.

Table 5. Accident analysis of indirect causes of Jinyu explosion.

Indirect Causes Analysis	Type of Indirect Causes
1. Under a state of extreme exhaustion, the driver's physiological condition is not good, leading to illegal operations 2. A serious error in the driver's operation under severe fatigue	Adverse physiological states
1. Flaws in safety habits cause the driver to not check carefully while unloading 2. Employees have not worn respirators for a long time and formed bad habits	Flaws in safety habits
1. Managers are not aware of the risks of continuous operations 2. The driver is not aware of the importance of following the operating regulations 3. Employees did not realize the importance of wearing a respirator 4. On-site employees did not make emergency response in time 5. Managers lack awareness of the importance of using explosion-proof electrical appliances 6. Managers lack awareness of the importance of house safety intensity 7. Managers are unaware that working at night will cause employees to lose concentration and fatigue, resulting in operational errors 8. The management personnel did not realize that the lack of emergency equipment and materials will affect rescue in an emergency 9. Managers are not aware of the importance of qualifications	Flaws in safety consciousness
1. Employees lack the corresponding emergency rescue safety knowledge 2. Employees lack knowledge about safe operations 3. On-site employees lack corresponding emergency rescue safety knowledge 4. Managers lack safety knowledge of electrical explosion protection 5. Managers lack safety knowledge related to building structure design 6. Managers lack understanding of safety inputs 7. Management lacks safety knowledge related to special operations qualification	Flaws in safety knowledge

3.2.3. Radical Causes and Root Causes

The radical causes are the deficiencies in the safety management system in the organization where the accident initiator is located [26]. The specific results of this accident are shown in Table 6.

The root causes of the accident are the deficiencies in safety culture at the organizational level [26]. The safety culture is the guiding ideology of the organization's safety work. The safety culture affects the safety management system of the organization, which affects the habitual behavior of the members of the organization and ultimately affects the behavior and conditions.

The literature [5,27] proposed 32 types of safety culture elements, and the literature [28] designed a comprehensive evaluation index system to evaluate the level of enterprise safety culture construction based on the elements. The 32-element safety culture table also has specific applications in the quantitative measurement of safety culture [27]. According to the table of safety culture elements, specific deficiencies in safety culture elements (i.e., the root causes) are provided in Table 6. The numbers in Table 6 correspond to the numbers of safety cultural elements in [5,27].

According to Table 6, in this case, the safety culture has the following deficiencies: 1–12, 16, 19, 22, 29, 30, 32.

Table 6. Accident analysis of radical causes and root causes of Jinyu explosion.

Radical Causes Analysis	Defective Elements of Safety Culture (Serial Number)
Safety policy such as "safety first" has not been established	1, 3, 4, 16

Failure to establish safety production education and training procedures	1, 5, 6, 9, 30
Not manned by special personnel for handling dangerous goods	1, 3, 4, 10, 30
The management procedure of handling of hazardous chemicals has not been formulated strictly	1, 8, 11, 19, 30
Failure to establish a special emergency rescue organization according to law	1, 3, 11, 22
Employees not regularly organized to carry out emergency rescue drills	1, 6, 7, 12, 29, 32
Failure to establish the qualification assessment system for special operators	1, 4, 5, 8, 16, 19, 30
Failure to formulate hazard identification, risk assessment, and control measures	1, 4, 16, 30
The radical cause analysis	Defective elements of safety culture (serial number)
Failure to formulate targeted emergency response plans	1, 6, 10, 30, 32

Through the analysis of the Jinyu hazardous chemical transportation explosion accident cases, the causes of accidents at the organizational and personal levels were identified from on aspects: immediate causes, indirect causes, radical causes, and root causes. Figure 7 depicts the complete chain of accident causes.

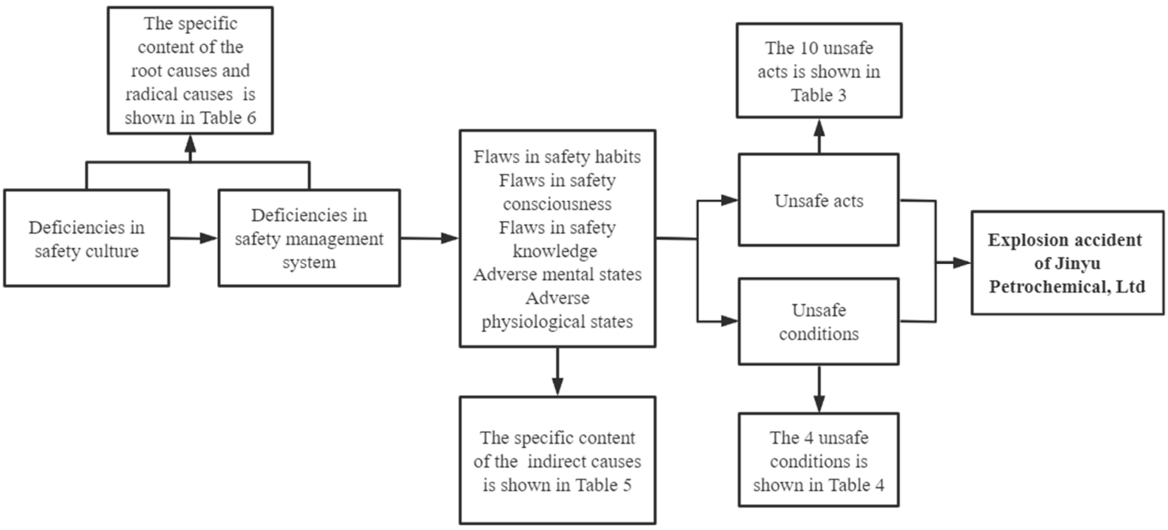

Figure 7. Accident analysis of chain of causes of the Jinyu explosion.

3.2.4. Statistics of 30 Accident Results

Using the above analysis steps to analyze the 30 hazardous chemical transportation accidents, the statistical results are shown in Table 7. The first horizontal row in Table 7 means the accident level. The classification and explanation of the accident level are given in Table 1. The first vertical column represents the classification of accident causes into unsafe acts, unsafe conditions, habitual unsafe behavior, deficiencies in safety management system, and deficiencies in safety culture according to the 24Model. Based on the analysis of 30 accidents, the frequency of each cause in general accidents, serious accidents, major accidents, and particularly serious accidents was obtained. For example, 82 represents 30 accidents in which unsafe acts related to general accidents occurred 82 times, and the other figures in Table 7 have the same meaning.

Table 7. Statistical results of the 24Model analysis of 30 chemical transport accidents.

Reason \ Accident Level	General Accident	Serious Accident	Major Accident	Particularly Serious Accident
Unsafe acts	82	88	33	27
Unsafe conditions	25	7	10	9
Habitual unsafe behavior	118	31	46	41
Deficiencies in safety management system	43	12	17	14
Deficiencies in safety culture	214	57	86	71

Note: The data in Table 7 represent the number of various accident causes in 30 accidents.

4. Results and Discussion

4.1. Preliminary Comparison of Analysis Results

For the Jinyu explosion accident case, the impact objects and accident analysis modules of hazardous chemical transportation accidents analyzed by the two model methods are compared. The results of the preliminary comparison of the two models are shown in Table 8.

Table 8. Comparison of analysis modules and objects.

Model \ Comparison	Objects Affected by the Accident in the Model	Accident Analysis Module
24Model	People, equipment, social wealth, environment, and other impacts	Human factors, material factors, organizational factors
CREAM model	People, equipment, social wealth, environment, and other impacts	Human, technical, and organizational factors

The comparison shows that the CREAM and 24Model specify the objects of accident impact, including personnel, equipment, social wealth, environment, and other influences. The CREAM is similar to the 24Model in this respect.

However, in terms of the analysis module of the model, the two models have their own focus. The CREAM model includes human, technical, and organizational factors in the analysis of human error events, but does not include external factors. The 24Model takes into account external factors, such as material factors, in its analysis.

To further analyze the focus of the two models in the analysis of accident causes, the gray relational analysis and regression analysis are used to conduct an in-depth discussion on the correlation of each analysis cause in the qualitative analysis.

4.2. Quantitative Comparison of Analysis Results

4.2.1. Grey Relational Analysis and Results Comparison

In this part, the gray relational analysis is used to conduct in-depth research on the statistical results of the 24Model and CREAM model analysis. The gray relational analysis method is based on the similarity or difference of the development trend among factors, which is the "gray relational degree", to measure the relational degree among factors. To correctly understand and effectively control the information of the system operation, the relational degree is the degree of geometric difference between the curves [29].

Establishment of the Index System of Influencing Factors

In the accident cause chain of the 24Model, unsafe acts are affected by unsafe conditions, habitual unsafe behavior, deficiencies in safety management system, and deficiencies in safety culture, so unsafe acts are selected as reference sequence X_1; unsafe conditions, habitual unsafe behavior, deficiencies in safety management system, and deficiencies in safety culture are comparison sequences X_2, X_3, X_4, and X_5, respectively. The statistical results of the 24Model analysis of 30 accidents were taken as sample data, as shown in Table 9.

Table 9. Statistics of influencing factors of unsafe acts of the 24Model.

	Unsafe Acts X_1	**Unsafe Conditions X_2**	**Habitual Unsafe Behavior X_3**	**Deficiencies in Safety Management System X_4**	**Deficiencies in Safety Culture X_5**
General accident	82	25	118	43	214
Serious accident	22	7	31	12	57
Major accident	33	10	46	17	86
Particularly serious accident	27	9	41	14	71

Similarly, in the CREAM model, human error is selected as the reference sequence X_1; the human-related antecedent, technology-related antecedent, and organization-related antecedent are selected as comparison sequences X_2, X_3, and X_4, respectively; and the statistical results of the CREAM model analysis of 30 accidents are taken as sample data, as shown in Table 10.

Table 10. Statistics of the influencing factors of the CREAM model human error.

	Human Error X_1	**Human-Related Antecedent X_2**	**Technology-Related Antecedent X_3**	**Organization-Related Antecedent X_4**
General accident	19	75	25	88
Serious accident	5	17	7	20
Major accident	8	20	10	25
Particularly serious accident	6	12	7	14

Note: The data in Tables 9 and 10 represent the number of various causes.

Relational Degree Analysis and Research

To make the calculation results accurate and effective, the subsequent steps are implemented using the DPS (Data Processing System) software [30]. The DPS software was used to process the data in Tables 9 and 10. Tables 11 and 12 are the corresponding results.

Table 11. Results of the relational degree analysis of the influencing factors of unsafe acts in the 24Model.

Averaging Transformation Result:				
1.9608	2.0000	2.0000	2.0000	2.0000
0.5490	0.5254	0.5581	0.5327	0.5366
0.7843	0.7797	0.7907	0.8037	0.8049
0.7059	0.6949	0.6512	0.6636	0.6585
The absolute difference between X_1 and other factors:				
X_2	0.0392	0.0124	0.0206	0.0473
X_3	0.0000	0.0112	0.0252	0.0364
X_4	0.0000	0.0216	0.0142	0.0074
X_5	0.0000	0.0039	0.0011	0.0050
Maximum difference Δmax = 0.04735				
Relation coefficient: G (1,2) = 0.47513 G (1,3) = 0.63950 G (1,4) = 0.72783 G (1,5) = 0.90965				

Relation order: $X_5 > X_4 > X_3 > X_2$

The data in Table 11 were obtained by inputting the data in Table 9 into the DPS (Data Processing System). The meanings of X_1~X_5 are shown in Table 9. G(1,2), G(1,3), G(1,4), and G(1,5) represent the correlation coefficients of X_1 and X_2, X_3, X_4, and X_5, respectively. Relation order represents the order of X_2~X_5 and X_1.

The analysis results in Table 11 show that the relational degree between safety culture X_5 and unsafe act X_1 is the largest, which is 0.90965. The relational degree between X_2 and unsafe act X_1 is the smallest, which is 0.47513.

Table 12. Results of the relational degree analysis of human error influencing factors in the CREAM model.

Averaging Transformation Result:				
2.4194	2.0408	2.3946	2.0000	
0.5484	0.5714	0.5442	0.5263	
0.6452	0.8163	0.6803	0.8421	
0.3871	0.5714	0.3810	0.6316	
The absolute difference between X_1 and other factors:				
X_2	0.4194	0.0221	0.1969	0.2445
X_3	0.0408	0.0451	0.0258	0.0602
X_4	0.3946	0.0179	0.1618	0.2506
Maximum difference Δmax = 0.41935				
Relation coefficient: G (1,2) = 0.55386 G (1,3) = 0.83190 G (1,4) = 0.57207				
Relation order: $X_3 > X_4 > X_2$				

The data in Table 12 were obtained by inputting the data in Table 10 into the DPS (Data Processing System). The meanings of X_1~X_4 are shown in Table 10. G(1,2), G(1,3), and G(1,4) represent the correlation coefficients of X_1 and X_2, X_3, and X_4, respectively. Relation order represents the order of X_2~X_4 and X_1.

The analysis results in Table 12 show that the correlation between technology-related antecedent X_3 and human error X_1 is at most 0.83190, followed by organization-related antecedent X_4 at 0.57207, and finally, human-related antecedent X_2 is 0.55386.

4.2.2. Comparison of Regression Analysis

Regression analysis is a statistical analysis method that can determine the quantitative relationship between two or more variables [31].

Establishment of the Regression Analysis Data Table

In the analysis results of the 24Model of 30 accidents (Table 9), set the unsafe acts as the dependent variable and record it as X_1; the unsafe conditions, habitual unsafe behavior, deficiencies in the safety management system, and deficiencies in safety culture are independent variables denoted as X_2, X_3, X_4, and X_5, respectively, and a regression analysis data table is constructed.

Similarly, in the analysis results of the CREAM model of 30 accidents (Table 10), human error is set as the dependent variable and denoted as X_1. The human-related antecedent, technology-related antecedent, and organization-related antecedent are independent variables denoted as X_2, X_3, and X_4, respectively, and a regression analysis data table is constructed.

The format of the two data tables in this section is similar to that of Tables 9 and 10. Therefore, these two tables are no longer listed.

Regression Analysis Results

The DPS data processing software was used to conduct a regression analysis of the dependent variables and independent variables in the analysis results of the two models. The results are shown in Tables 13 and 14.

Table 13. Results of regression analysis of the 24Model.

Correlation Coefficient	X_2	X_3	X_4	X_5	X_1	Significance Level p
X_2	1.0000	1.0000	0.9990	0.9994	0.9992	0.0008
X_3	1.0000	1.0000	0.9989	0.9994	0.9992	0.0008
X_4	0.9990	0.9989	1.0000	0.9997	0.9997	0.0003
X_5	0.9994	0.9994	0.9997	1.0000	1.0000	0.0001
X_1	0.9992	0.9992	0.9997	1.0000	1.0000	0.0001
	t-test	p				
(X_1, X_3)	−0.552	0.679				
(X_1, X_4)	1.716	0.329				
(X_1, X_5)	43.327	0.015				

Table 14. Results of regression analysis of the CREAM model.

Correlation Coefficient	X_2	X_3	X_4	X_1	Significance Level p
X_2	1.0000	0.9947	0.9998	0.9867	0.0133
X_3	0.9947	1.0000	0.9960	0.9978	0.0022
X_4	0.9998	0.9960	1.0000	0.9883	0.0117
X_1	0.9867	0.9978	0.9883	1.0000	0.0001
	t-test	p			
(X_1, X_3)	6.4274	0.0234			
(X_1, X_4)	2.6275	0.1194			

$p = 0.015 < 0.05$ indicates that the linear relationship of the regression equation is significant. Table 13 shows that the unsafe act X_1 has the highest correlation with the deficiencies in safety culture X_5, and X_2 is excluded due to error. Table 14 shows that human error X_1, and technology-related antecedent X_3 has the highest significance. X_2 is excluded due to error.

Based on the results of the gray correlation analysis and regression analysis, the correlations between the unsafe behaviors/human error and the respective causal factors in the two models are depicted in the Pareto chart below.

In Figures 8 and 9, the column represents the gray correlation analysis, with higher values indicating a higher correlation between X_1 and the other factors. Additionally, the line represents the regression coefficient, with lower values indicating a significant linear relationship between X_1 and the other factors. Thus, in both figures it can be seen that the degree of association is consistent with significance. This mutually corroborates the validity of the analysis results. In the 24Model and CREAM, X_1, X_2, X_3, X_4, and X_5 represent different meanings, respectively; see Tables 9 and 10. Additionally, there is no X_5 in the CREAM. X_2 is removed due to errors in the regression analysis.

The gray relational analysis shows that in the analysis results of the 24Model, safety culture has the highest relational degree with unsafe acts and the lowest relational degree with unsafe conditions. Among the analysis results of the CREAM model, human errors have the highest relational degree with the technology-related antecedent and the lowest relational degree with the human-related antecedent. The regression analysis results are consistent with the gray relational analysis results, which verifies the correctness of the analysis.

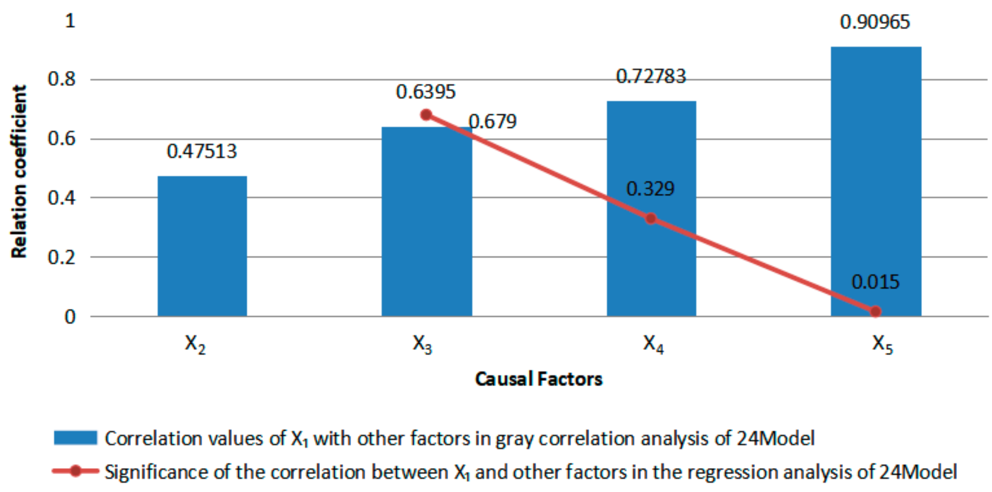

Figure 8. Correlations Pareto chart for the 24Model.

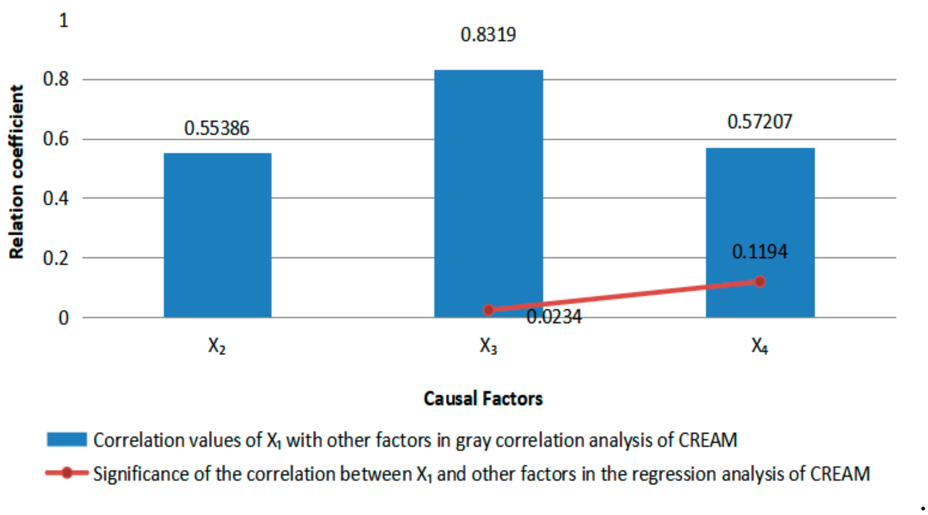

Figure 9. Correlations Pareto chart for the CREAM.

4.3. Discussion

According to the analysis results in Figures 6, a total of 13 petrochemical accident causes in four categories were identified by the CREAM. Additionally, 61 accident causes were derived from four major categories by the 24Model in Figure 7. It can be seen that when two models are used to analyze the same accident, the number of the accident causes analyzed by the 24Model is higher than that by the CREAM. This is probably because the 24Model does not classify the causes of accidents in detail, leaving more freedom for analysts, whereas the CREAM provides a detailed classification of accident causes, limiting the depth and breadth of the analysis.

Gray correlation analysis was used to further study the focus of the two models. According to the results in Tables 11 and 12, the maximum correlation between technology-related precondition X_3 and human error was 0.83190 in the CREAM analysis results; meanwhile, the maximum correlation between safety culture and unsafe acts was 0.90965 in the 24Model analysis results. The closer the correlation is to 1, the higher is the correlation. That means that the CREAM focuses more on the technical aspects of production, and the 24Model focuses more on the safety culture of the company when it comes to analyzing the human causes of accidents. People are influenced by the prevailing equipment, technology, and so forth, before they finally make a decision, so the CREAM focuses more on the analysis of the technical aspects of the reasons. Similarly, safety culture is the root cause of accidents in the 24Model. The two models have different analytical focuses, affecting the perspective of the analysis, thus making the results of the cause analysis appear different.

According to the results of regression analysis in Tables 13 and 14, through regression analysis of human error and other influencing factors in 30 accidents by the CREAM, it is concluded that the maximum correlation coefficient between technology-related antecedent X_3 and human error is 0.9978; the 24Model conducted a regression analysis of unsafe actions and other influencing factors, which shows a maximum correlation coefficient of 1.0000 between safety culture and unsafe acts. The results shown are highly correlated. Additionally, the regression analysis results are consistent with the results of the gray correlation analysis, further validating the results of the gray correlation analysis.

This study contributes to the research on the CREAM and 24Model. The focus of the two models in accident analysis is given through accident analysis and quantitative calculations. The focus of the models obtained from the study is similar to the results of the study of Fu et al. (2013). The results of the study are supported by the results of the study of Fu et al. (2013). Furthermore, according to the limited literature available to us, no literature has been found that quantifies a comparison of the correlation analysis of accident causes and the concerns in different models.

5. Conclusions

A statistical analysis of the causal factors of 30 hazardous chemical transportation accidents using the 24Model and CREAM revealed that both models include the impacts of accidents on personnel, equipment, social wealth, and the environment and other impacts. However, the CREAM does not include factors external to the organization. Using the 24Model for accident analysis, the cause numbers were more than those for the CREAM model, which shows the difference in the perspective of accident analysis between the two models.

The gray correlation analysis results inferred that the results obtained from accident analysis using the 24Model showed the highest correlation between safety culture and unsafe acts and the lowest correlation between unsafe conditions, whereas in the CREAM, human error and technology-related antecedents had the highest correlation and human-related antecedents had the lowest correlation. The results of the regression analysis validated the results of the gray correlation analysis.

This study will provide a reference for subsequent analysts using the CREAM and 24Model to focus on their accident analysis, and will help analysts to target their analysis according to the model characteristics, or to make reasonable improvements to enhance the analysis results. For an accident, the 24Model should be chosen if the researcher wants to obtain more information about the causes of the accident in terms of safety culture, and the CREAM model if the researcher wants to obtain more information about the causes of the accident in terms of technology.

For future research, applications between different models could be explored from other perspectives, and other scenarios could be explored to test the hypothesis. In addition, as a limitation, there are only 30 case reports of hazardous chemical transportation accidents in this study, and more data samples could be collected to obtain the more common accident causes of hazardous chemical transportation accidents. Additionally, further combine with the on-site investigation of hazardous chemical transportation accidents, carry out quantitative prediction research on hazardous chemical transportation accidents, and better achieve the goal of sustainable development.

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