Classification Evaluation and Control Analysis for Multi-dimensional Safety Risks of Port Storage Tanks

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Abstract. The Port, as a transportation hub, possesses a strong function of gathering and evacuating, facing a high risk of serious production safety accidents. Especially, port storage tanks involve diverse safety hazards, such as oil spills, leakage, fire, and explosion, due to their wide area covered as well as relatively large equipment and facilities. Given the centralized and connected layout of most port storage tank areas, the leakage of a certain storage tank can easily lead to a chain accident, eventually resulting in serious consequences. In this regard, this research identifies and analyzes the potential safety production risks faced by port storage tanks through case analysis of typical accidents and comprehensive identification of related risks. Based on the identified safety production risks, this research further establishes a multi-dimensional risk evaluation index system suitable for port storage tanks by utilizing an analytic hierarchy process (AHP), constructing a risk evaluation model characterized by all-parameter interaction and coupling, with the indexes of core criteria layer and factor layer being optimized and determined. Moreover, this research comprehensively applies relevant theories and methods of safety engineering systems represented by AHP to implement the fuzzy comprehensive evaluation of safety production risks, thereby obtaining the high-risk points and overall risk index of storage tanks in each port involved. In this foundation, this research ultimately determines the weak links of storage tank supervision as well as the key points of safety supervision.

Keywords: Port storage tank; Risk identification; Multi-dimensional indexes; Classification evaluation.

1 CONSTRUCTION OF EVALUATION INDEX SYSTEM FOR MULTI-DIMENSIONAL SAFETY RISKS OF PORT STORAGE TANKS

1.1 Background

Recently, accidents in storage tank safety production still occur occasionally. In particular, major and extraordinarily serious accidents, the painful cost in terms of human life, coupled with huge economic losses, has attracted great attention from the nation

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al government. Against this backdrop, it is imperative to clarify the safety production risk base of port storage tanks, thereby establishing a comprehensive and scientific classification evaluation method for the safety production risks of port storage tanks.

The academic circles worldwide have proposed extensive evaluation methods for safety production risks [1-3]. Yet, each evaluation method presents its characteristics, scope of application, application conditions, and corresponding advantages and disadvantages [4,5]. Specifically, qualitative evaluation methods typically reveal defects that are significantly influenced by subjectivity, whereas quantitative evaluation methods generally involve a large amount of calculation. Furthermore, the index method faces challenges in obtaining complete data. Concurrently, quantitative risk evaluation involves not only natural science but also various related knowledge of social science such as management and logic [6,7]. Besides, the selection of risk evaluation indexes, along with their weights, is closely related to diversified factors encompassing production technology level, safety management level, quality of producers and managers, and social and geographical background [8-10]. Regarding a huge and intricate system, the index evaluation process also involves issues concerning fuzziness and uncertainty. Hence, it is of great significance to improve the existing evaluation methods and establish a feasible classification mechanism for safety production risks as per the types of port-based enterprises.

To this end, this research establishes multi-dimensional risk evaluation technical methods suitable for port storage tanks, including evaluation index system, evaluation criteria, and quantitative evaluation methods. In this way, this research systematically addresses the difficulties in quantitative technical evaluation, calculating the high-risk points and overall risk index of the storage tank area. On these grounds, this research further analyzes and determines the risk level and risk distribution of production safety, thereby realizing multi-dimensional accurate evaluation and classified management and control of related risks.

1.2 Hierarchical Structure of Evaluation Index System for Multi-dimensional Safety Production Risks of Port Storage Tanks

Numerous factors affect the possibility of accidents as well as the severity of accident consequences, with their influence degree being different. This research, therefore, employs the analytic hierarchy process (AHP) to decompose the safety production risk factors at all levels of enterprises according to the requirements of integrity, unity, pertinence, comparability, simplicity, and practicality, thereby constructing a multi-dimensional safety production risk evaluation index system applicable to port storage tanks. In accordance with the “objects, personnel, and management” involved in the operation process of storage tanks, this research focuses on the risk factors of port enterprises with hazardous chemicals storage tanks, thus establishing an evaluation index system for the safety production risk of storage tanks.

Unsafe States of Objects. As a rule, hazardous chemical substances stored and transported by enterprises exhibit various dangerous properties such as flammability, explosiveness, and toxicity. During loading, unloading, transportation, and storage, they may cause great potential danger to people around them. Consequently, hazardous chemical substances are regarded as the energy sources that lead to diverse large-scale casualties such as fire, explosion, and poisoning.

The operating equipment within the storage tank area is primarily composed of storage tanks and pipelines. In this connection, a plurality of factors contribute to the rupture of tanks and pipelines, as well as the leakage of hazardous chemical substances during storage and transportation. These factors include cracking of the tank bottom, tank wall, pipe wall, welding bead, and other parts due to corrosion and perforation, lax sealing of valve flange seal components due to wear and aging, failure of protective functions of safety accessories and safety protection devices such as safety valve, breathing valve, and liquid level alarm, uneven settlement of tank and pipeline infrastructure, etc.

Unsafe Behaviors of Relevant Personnel. As a whole, the unsafe behaviors of the relevant personnel can be summarized as follows: a) the failure to install fire-proof facilities for vehicles entering the factory, smoking by the relevant personnel in no-smoking areas, etc.; b) unsafe scenarios in which some front-line operators may not work strictly in accordance with the safety operation regulations or strictly implement the safety management system; and, c) emergency personnel's incompetence or unskilled mastery of emergency rescue knowledge and procedures, lack of emergency rescue practical ability, improper utilization of emergency rescue equipment, etc.

Management Defects. Overall, safety management defects within enterprises primarily encompass: a) non-compliance with legal requirements for qualifications and certifications of enterprises; b) inadequate structuring of safety management institutions; c) failure to implement a robust safety production responsibility system; d) inadequacies in safety operation procedures and management systems; e) insufficient organization of educational training for personnel in diverse positions; f) failure of safety management personnel, specialized operators, and others to obtain required certifications for their respective roles; g) failure to adhere to prescribed schedules for the regular inspection and calibration of equipment and facilities; h) untimely maintenance and upkeep of equipment and facilities; and, i) lapses in the fulfillment of safety management duties by safety personnel and inspection officers, inability to promptly identify and rectify violations by on-site workers.

Specifically, the primary indexes affecting the risk target system of storage tank safety production comprise eight ones, including equipment and facilities, operation activities, operation conditions, safety management, safety performance, safety culture, personnel qualifications, and direct determination of major risks. Furthermore, the secondary indexes consist of 24 ones, encompassing storage tanks, loading platforms, pipelines, storage operations, hazardous operations, pipeline transportation operations, automation control level, annual turnover rate, loading & unloading cargo types, safety production standardization, historical accidents, and safety culture demonstration enterprises, etc. Concurrently, a total of 45 tertiary indexes are further determined based on the secondary indexes. Through further refinement of the tertiary indexes, this research lists the corresponding index layers, with the scores of indexes at all levels being divided into five grades. Notably, each individual criterion is rated on a scale of 10 points, with respective feature values of 10, 8, 6, 4, and 2, as illustrated in Table 1. Building upon this framework, this research ultimately formulates a classification evaluation criterion specifically tailored to the safety production risks associated with storage tanks.

Table 1. Classification Evaluation Index System and Evaluation Criteria for Safety Production Risks of Storage Tanks.

Target layer	Primary indexes	Secondary indexes	Tertiary indexes	Evaluation criteria	Scores
Safety production risks (A)	Equipment and facilities (B_1)	Storage tanks (C_{11})	Number of storage tanks (number * size) (D_1)	≥ 50	10
				[10, 50)	6
				< 10	2
			Storage tank types (D_2)	Cryogenic tanks	10
				Pressure tanks	8
				Atmospheric tank (including low-pressure tank)	6
			Detection situation (D_3)	Unqualified (not regularly verified as required)	10
				Qualified (regularly verified as required)	6
			Interval between storage tanks (D_4)	Non-compliance	10
				Compliance	4
			Whether the fire dike of corrosive storage tanks such as acid and alkali is treated with anti-corrosion (D_5)	No	10
				Yes	6
				Uninvolved	0
		Loading platforms (C_{12})	Quantity (D_6)	≥ 6	10
				[3, 6)	6
				< 3	2
			Loading stack technology (D_7)	Upper-level loading	10
				Lower-level loading	8
				Lower-level loading (including closed loading and quantitative loading)	4
		Pipelines (C_{13})	Quantity (D_8)	≥ 15	10
				[5, 15)	6
				< 5	2
			Pipe diameter (D_9)	≥ 600 mm	10
				[300, 600) mm	8
				< 300 mm	4
			Flow rate (pressure) (D_{10})	$P > 10$ MPa	10
				$1.6 < P \leq 10$ MPa	8
				$0.1 \leq P \leq 1.6$ MPa	6
			Temperature (D_{11})	Above normal temperature	10
				Below normal temperature	8
				Normal temperature	6
	Operation activities (B_2)	Storage operations (C_{21})	Tank entry operations (D_{12})	Involved	10
				Uninvolved	0
			Tank exit operations (D_{13})	Involved	10
				Uninvolved	0
			Loading operations (D_{14})	Involved	10
				Uninvolved	0
			Tank emptying operations (D_{15})	Involved	10
				Uninvolved	0
			Tank cleaning operations (D_{16})	Involved	10
				Uninvolved	0
		Hazardous operations (C_{22})	Hazardous operation situation (D_{17})	≥ 12 times/year	10
				< 12 times/year	6
				Uninvolved	0
		Pipeline transportation operations (C_{23})	Multi-point (including round trip) transportation (D_{18})	Involved	10
				Uninvolved	0
			Single fixed-point (including round trip) transportation (D_{19})	Involved	6
				Uninvolved	0
		Automation control (C_{24})	Automation control level (D_{20})	Low (safety protection devices such as video monitoring, automatic alarm, automatic interlock, and emergency cut-off are not equipped or equipped	10

				at a limited level).	
				Medium (most enterprises are equipped with effective safety protection devices such as video monitoring, automatic alarms, automatic interlock, and emergency cut-off).	8
				High (video monitoring, automatic alarm, automatic interlock, emergency cut-off, and other safety protection devices are basically complete and effective)	6
		Major hazard sources (C_{25})	Levels of major hazard sources (D_{21})	Level 1	10
				Level 2	8
				Level 3	6
				Level 4	4
				No	0
	Operation conditions (B_3)	Annual turnover (C_{31})	Annual turnover rate (annual turnover/total storage capacity) (D_{22})	≥ 15	10
				[10, 15)	8
				[5, 10)	6
				<5	2
		Loading & unloading goods (C_{32})	Danger of fire and explosion of goods (D_{23})	A_A	10
				A_B	8
				B_A	6
				B_B	4
				C_A, C_B	2
			Toxicity of goods (D_{24})	Extremely toxic	10
				Highly toxic	8
				Moderately toxic	6
				Generally toxic	4
		Surrounding environment (C_{33})	Location selection of enterprises in chemical industry park (chemical industry concentration area) (D_{25})	No	10
				Yes	8
	Safety performance (B_4)	Emergency management (C_{41})	Equipped with a full-time fire emergency team (D_{26})	No	10
				Yes	6
			Complete publicity and education of emergency rescue plan, emergency materials, training plans, relevant schemes, and summary (D_{27})	Completely incomplete	10
				Partially complete	8
				Complete	4
		Risk management and control (C_{42})	Hazard source identification and risk evaluation for operation activities, equipment and facilities, working environment, and auxiliary facilities to determine the name, category, and grade of risks (D_{28})	Failure in hazard source identification	10
				Incomplete identification and evaluation	8
				Complete identification	4
		Potential risks identification and mitigation (C_{43})	Whether to formulate a potential risk identification plan and establish relevant potential risk identification and mitigation accounts and files (D_{29})	Not formulated	10
				Formulated but incomplete	8
				Yes	4
		Safety production standardization (C_{44})	Levels of safety production standardization (D_{30})	Not qualified	10
				Level 3	8
				Level 2	6
				Level 1	4
	Safety performance (B_5)	Safety performance level (C_{51})	Historical accidents (D_{31})	One major safety accident occurred within three years (D_{45})	10
				One safety accident that resulted in one or two deaths occurred within three years (D_{46})	8
				Safety accidents with social impact such as explosion, fire, and poisoning occurred within three years, without any casualty being caused (D_{47})	6
				No safety accident occurred within three years (D_{47})	4
	Safety culture (B_6)	Safety culture level (C_{61})	Safety culture demonstration enterprises (D_{32})	None (D_{48})	8
				District and county level (D_{49})	6
				Provincial and municipal level (D_{50})	4
				National level (D_{51})	2
	Personnel qualifications (B_7)	Safety management organizations (C_{71})	Number of practitioners in enterprise's safety management organizations (D_{33})	≥ 5	6
				[3, 5)	8
				< 3	10
		Person in charge of enterprises (C_{72})	Educational background of the first person in charge of enterprise safety production (person in charge of enterprise) (D_{34})	High school and technical secondary school	10
				Junior college	8
				Bachelor degree	6
				Master degree or above	4

			Major of the first person in charge of enterprise safety production (person in charge of enterprise) (D_{35})	Chemistry and chemical engineering/safety	6
				Port/machinery/electrical engineering	8
				Others	10
			Whether the first person in charge of enterprise safety production has been engaged in safety management full-time (D_{36})	No	10
				Yes	8
		Person in charge of the enterprise's safety management organization (C_{73})	Educational background of the person in charge of the enterprise's safety management organization (D_{37})	High school and technical secondary school	10
				Junior college	8
				Bachelor degree	6
				Master degree or above	4
			Major of the person in charge of the enterprise's safety management organization (D_{38})	Chemistry and chemical engineering/safety	6
				Port/machinery/electrical engineering	8
				Others	10
			Working years of the person in charge of the enterprise's safety management organization in safety management (D_{39})	≥ 10	6
				[5, 10)	8
				< 5	10
			Certification of the person in charge of the safety management organization (D_{40})	Registered fire engineer	6
				Certified safety engineer	6
				Safety assessor	6
				Others	8
		Enterprise security management personnel (C_{74})	Professional matching of enterprise safety management personnel (D_{41})	Chemistry and chemical engineering/safety accounting for 100%	0
				Proportion of chemistry and chemical engineering/safety $\geq$ 75%	4
				50% $\leq$ proportion of chemistry and chemical engineering/safety < 75%	6
				Proportion of chemistry and chemical engineering/safety < 50%	10
			Number of intermediate certified safety engineers within enterprises (D_{42})	$\geq 1/3$	6
				[1/6, 1/3)	8
				$< 1/6$	10
Enterprises with one of the following conditions are directly judged as red (i.e., the highest risk level)					
	Direct determination of major risks (B_8)	Accidents (C_{81})	Major or above safety accidents that have occurred within three years, or two major safety accidents that occurred within three years, or two or more general safety accidents involving deaths that occurred in the past year (D_{43})		
		Personnel (C_{82})	The main person in charge of enterprises, safety production management personnel, loading & unloading management personnel without valid credentials for employment, and hazardous chemical specialized operators without valid credentials or failing to attain an educational level equivalent to or above high school (D_{44})		
		Scope of permission (C_{83})	Loading & unloading of goods beyond the scope of business license (D_{45})		

2 CALCULATION OF INDEX WEIGHT BY AHP

In this section, the AHP is used to calculate the weights of indexes at each level, which are compared based on the judged matrix scale. Meanwhile, this section employs the sum-product algorithm to synthesize the weight results of the calculated indexes, ultimately determining the composite weight of each index.

Based on the hierarchical structure model constructed, this research utilizes the 1-9 scale method (with specific meanings as shown in Table 2 below) to pairwise compare the importance of indexes at each level, thereby determining the judgment matrix for these indexes.

Table 2. Relative Importance Scale.

b_{ij}, as the importance of comparing B_i with B_j, is equal to B_i/B_j	**Scale** (*the index in the corresponding row of* ***a certain position in the table is more important than*** *the index in the corresponding column*)	**Scale** *(the index in the corresponding column of* ***a certain position in the table is more important than*** *the index in the corresponding row)*
Equally important	1	1
Slightly important	3	1/3
Obviously important	5	1/5
Strongly important	7	1/7
Absolutely important	9	1/9
In the case where B_i is not as important as B_j, the corresponding scales should be 1/3, 1/5, 1/7, and 1/9. In the case where the importance of B_i and B_j is between different levels, the corresponding scale should be one of 2, 4, 6, and 8 (or its reciprocal).		

By means of the sum-product algorithm, the weight of each index is determined by calculating the eigenvalues and eigenvectors of the judgment matrix. Assuming that the n-order judgment matrix B=[bij], where j=1,2,3…,n, the elements of each column of the judgment matrix B are added and normalized to determine the matrix Q:

$$\mathrm{q}_{i1} = \frac{\mathrm{b}_{i1}}{\sum_{i=1}^{n} b_{i1}}, i = 1,2,3,\cdots,n \tag{1}$$

Additionally, the eigenvector can be obtained by adding and normalizing the rows of the matrix *Q*:

$$\begin{gathered} \mathrm{b}_i = \sum_{j=1}^{n} q_{ij}, j = 1,2,3,\cdots,n \\ w_i = b_i \Big/ \sum_{\mathrm{i}=1}^{m} b_i, i = 1,2,3,\cdots,n \end{gathered} \tag{2}$$

From Equation (2), the eigenvector W of the judgment matrix B can be expressed as [w1, w2, ..., wn]T. The characteristic equation of the judgment matrix B is utilized to calculate its maximum eigenvalue λmax:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{\sum_{j=1}^{n} b_{ij} w_j}{w_i} \right) \tag{3}$$

With regard to determining the index weight of the evaluation system, this research invited 12 industry-related experts to put forward relevant opinions on the index weight. Through the comparison as per the judged matrix scale, this research further employs the sum-product algorithm to calculate the questionnaire of each expert to determine the weight of each index and synthesize the results, ultimately deriving the synthetic weight of each index. In addition, by calculating the analytic hierarchy comparison given by experts one by one, the weights of the primary, secondary, and tertiary indexes within the index system are acquired in this research, as shown in Table 2. Notably, the weight calculation of the direct determination of major risks (B8) is no longer implemented. Cases with major risks are directly determined as the highest risk level.

Table 3. Weight Sets of Primary and Secondary Indexes

Primary indexes	Weights	Secondary indexes (serial number)	Weights	Tertiary indexes (serial number)	Weights
Equipment and facilities (B_1)	0.1655	C_{11}	0.0414	D1	0.0146
				D2	0.0079
				D3	0.0104
				D4	0.0037
				D5	0.0048
		C_{12}	0.0828	D6	0.0552
				D7	0.0276
		C_{13}	0.0414	D8	0.0068
				D9	0.0051
				D10	0.0122
				D11	0.0173
Operation activities (B_2)	0.2838	C_{21}	0.0501	D12	0.0147
				D13	0.0076
				D14	0.0131
				D15	0.0104
				D16	0.0043
		C_{22}	0.0888	D17	0.0888
		C_{23}	0.0280	D18	0.0187
				D19	0.0093
		C_{24}	0.0280	D20	0.0280
		C_{25}	0.0888	D21	0.0888
Operation conditions (B_3)	0.1677	C_{31}	0.0499	D22	0.0499
		C_{32}	0.0904	D23	0.0603
				D24	0.0301
		C_{33}	0.0275	D25	0.0275
Safety performance (B_4)	0.1401	C_{41}	0.0265	D26	0.0177
				D27	0.0088
		C_{42}	0.0491	D28	0.0491
		C_{43}	0.0491	D29	0.0491
		C_{44}	0.0513	D30	0.0513
Safety performance (B_5)	0.0573	C_{51}	0.0573	D31	0.0573
Safety culture (B_6)	0.0573	C_{61}	0.0573	D32	0.0573
Personnel qualifications (B_7)	0.1282	C_{71}	0.0206	D33	0.0206
		C_{72}	0.0123	D34	0.0019
				D35	0.0030
				D36	0.0074
		C_{73}	0.0355	D37	0.0037
				D38	0.0057
				D39	0.0141
				D40	0.0121
		C_{74}	0.0597	D41	0.0193
				D42	0.0386

The consistency test reveals that the CR of judgment matrix A is less than 0.1. Hence, its consistency is acceptable.

3 CLASSIFICATION EVALUATION FOR SAFETY PRODUCTION RISKS OF PORT STORAGE TANKS

Based on the established evaluation index system, this research conducts the fuzzy comprehensive evaluation of the tertiary indexes, the secondary indexes, and the primary indexes successively, thereby obtaining the comprehensive evaluation results of indexes at each level respectively.

Moreover, according to the established evaluation criteria, this research implements the single-factor fuzzy evaluation for the tertiary indexes, ultimately determining the fuzzy evaluation rank matrix $R = UV$ .The membership degree of the factor ui to the j-th element v_j is r_{ij}. Accordingly, the fuzzy comprehensive evaluation index bi can be given by multiplying the weight set by the single-factor membership matrix.

$$\mathrm{B{=}A}R=\left(a_1,a_2,\ldots,a_n\right)\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}=\left(b_1,b_2,\ldots,b_m\right) \tag{1}$$

Through the classification evaluation of the safety production risks of storage tanks for six enterprises in a certain domestic port, this research obtains the scores of safety production risks of storage tanks as well as the scores of various indexes, as outlined in Figure 1.

The risk analysis results in Figure 1 reveal that A5 demonstrates the highest risk score among the six enterprises, whereas A6 exhibits the lowest risk score, with other enterprises presenting moderate risks. Based on the above analysis, this research clarifies the overall security risk classification of each enterprise, without further analyzing the reasons for high risks. Hence, this research analyzes the primary-index scores of safety risks to determine the safety risk classification of each enterprise's storage tanks as well as the reasons leading to high risks. It can be observed that the operation activity risk value of A1 is significantly higher than that of other enterprises. Meanwhile, the risk value of A6 in terms of equipment and facilities is high, while its other safety risks are significantly low.

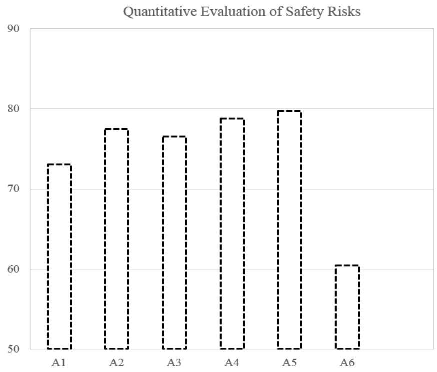

Fig. 1. Quantitative Evaluation Results of Safety Risks of Storage Tanks for 6 Enterprises

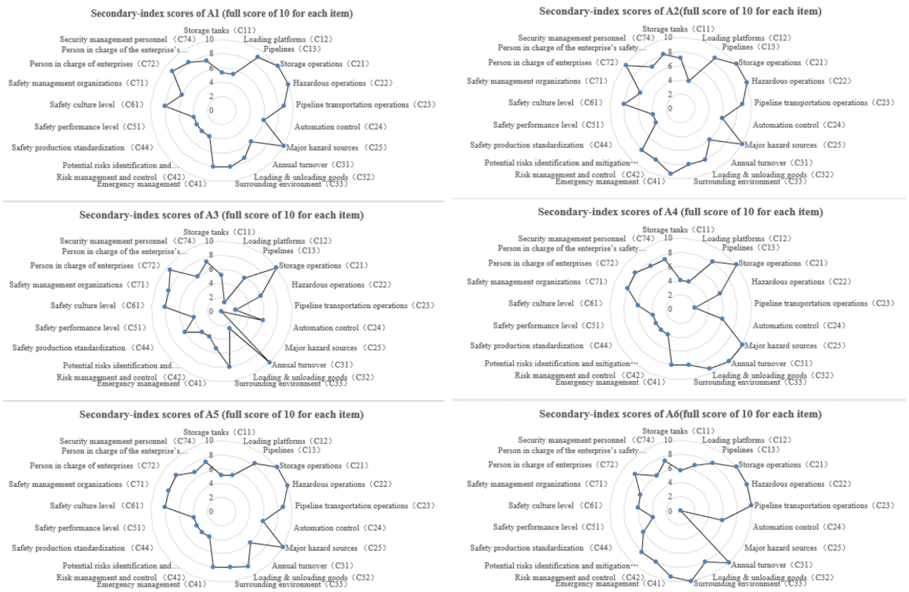

Fig. 2. Radar Chart of Safety Risk Classification for Storage Tanks of 6 Enterprises

For further determining the more detailed high-risk points of each enterprise, this research further analyzes the scores of secondary indexes of each enterprise, drawing the radar chart of safety risk classification, as depicted in Fig.2.

As can be seen from Fig.2, A1 shows a high-risk value regarding major hazard sources, storage operations, and hazardous operations, while A2 presents a high-risk value regarding emergency management, storage operations, and hazardous operations. Secondly, A3 exhibits a high-risk value regarding the person in charge of enterprises, storage operations, and annual turnover. By contrast, A4 presents a high-risk value regarding loading & unloading goods, storage operations, and annual turnover. Additionally, A5 presents a high-risk value regarding storage operations, hazardous operations, and loading & unloading goods. Lastly, A6 demonstrates a high-risk value regarding storage operations, hazardous operations, pipeline transportation operations, annual turnover, and the surrounding environment. Simply put, the detailed high-risk points of each enterprise can be determined through the foregoing analysis. Accordingly, these enterprises are required to further strengthen the supervision and control of high-risk points.

4 CONCLUSIONS

To sum up, this research initially analyzes a host of factors, such as the industry characteristics of port storage tanks, the severity and possibility of the consequences of production safety accidents, and the identification of typical production safety accidents and production safety risks within port areas. On these grounds, according to the principles of relative integrity, unity, pertinence, comparability, simplicity, and practicality, this research establishes an index system for safety production risk classification by AHP, thereby proposing the corresponding risk evaluation methods.

Through analyzing the key factors affecting the safety production risks of port storage tanks as well as establishing classification evaluation methods for the safety production risks of port enterprises. Concurrently, this research is beneficial to determine the classification and actual risk distribution of port enterprises' safety production risks and clarify the risk management and control measures that need to be continuously strengthened in view of the current situation of safety production risks of port enterprises. By this means, relevant enterprises can effectively establish a classified management and control model as well as a feasible classified supervision mechanism for port safety risks. More importantly, this research facilitates port administrative management departments in achieving grid-based, differentiated, and precise supervision of port safety risks.

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