Future Sustainability
Open Access Journal
ISSN 2995-0473

February 2026| Volume 04 | Issue 01 | Pages 37-44

Journal homepage: https://fupubco.com/fusus

https://doi.org/10.55670/fpll.fusus.4.1.4

Future Publishing LLC

Article

Research on safety risk assessment of polyimide foam production line based on AHP-FCE method

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ARTICLE INFO

Article history:
Received 19 September 2025
Received in revised form
10 November 2025
Accepted 01 December 2025

Keywords:
Polyimide foam, Safety risk assessment, Analytic hierarchy process, Fuzzy comprehensive evaluation, Index system, Risk management

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DOI: 10.55670/fpll.fusus.4.1.4

ABSTRACT

Polyimide foam, as a high-performance sandwich composite material, is widely used in high-tech manufacturing industries such as aviation and aerospace. Nevertheless, its production process involves numerous hazardous chemicals and sophisticated machinery, which is extremely hazardous to the system itself. Today, the overall assessment tools for multidimensional safety risks on the production line are unsatisfactory. To address this, this paper developed a safety risk assessment system comprising five dimensions: equipment, materials, personnel, environment, and management. The study applied the Analytic Hierarchy Process (AHP) to calculate indicator weights and the Fuzzy Comprehensive Evaluation Method (FCE) to assess safety risk in a polyimide foam line. The results show that the overall risk level of this production line is Relatively High, and the main sources of risk are equipment factors and process-material factors. Simultaneously, personnel and safety management factors should also be considered. Based on the evaluation findings, specific risk control measures are offered, with both theoretical background and methodological underpinning for the safety design and operational management of polyimide foam production lines.

1. Introduction

Polyimide foam material possesses extensive opportunities of application in aviation, aerospace, and other high-end equipment manufacturing industries because it has excellent high-temperature resistance, light weight, high strength, and good chemical stability [1-4]. As high-performance sandwich composites are in demand for model products, the industrialization of polyimide foam is advancing rapidly [5,6]. Nevertheless, its manufacturing process requires numerous hazardous chemicals and equipment, including flammable solvents (tetrahydrofuran and methanol) and hazardous processes (high-temperature, high-pressure foaming, microwave radiation, and dust crushing). This puts the production line at several safety risks during operation, such as fire, explosions, poisoning, and mechanical injuries. Currently, studies on polyimide foam materials are conducted at both the local and international levels, with the main emphasis on maximizing performance and expanding applications [7-10]. On the contrary, studies on assessing system safety risks and control measures in the production process are lacking. The possible deficiency of systematic evaluation techniques and technical assistance in the overall assessment of safety risks across the entire process and its many dimensions is particularly relevant to realizing large-scale industrialization at the domestic level. Current safety evaluation systems are not without problems, such as the use of incomplete indicators, subjective weighting distributions, vague evaluation outcomes in the application to production systems with complex process characteristics, and numerous risk couplings. In a bid to overcome this, this study aims to discuss the construction of a polyimide foam production line. By incorporating relevant technical documentation, we created a safety risk assessment framework comprising five dimensions: equipment, materials, personnel, environment, and management. The weights of all risk factors were decided using the Analytic Hierarchy Process (AHP). Simultaneously, the Fuzzy Comprehensive Evaluation Method (FCE) was applied to address uncertainties and indeterminate information during the evaluation process, yielding a similar quantitative analysis of the production line's safety risks. This study will provide scientific foundations and risk management methods for safety in polyimide foam production lines and, thereby, contribute to the safe, controlled industrial development of these high-risk process lines.

2. Research methods

To systematically and scientifically evaluate safety risks in polyimide manufacturing lines, this study uses a complex assessment tool combining qualitative and quantitative evaluation. Specifically, the Analytic Hierarchy Process (AHP) is initially used to create an evaluation index for safety risks and to compute the weights of each indicator, reflecting the relative significance of various factors in the comprehensive risk. Based on this, the Fuzzy Comprehensive Evaluation (FCE) technique is presented to address the inherent two-sidedness and uncertainty in safety risk assessment and to convert the expert's experience and judgment into quantitative assessment outcomes. The combined use of AHP and FCE can not only ensure the scientific validity and consistency of indicator weights but also provide an opportunity to conduct a thorough quantitative assessment of complex risk factors and to support the methodological support for further risk analysis and decision-making [11].

2.1 Hierarchy analysis method

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making technique that uses both quantitative and qualitative methods to compare the relative significance of elements, assign weights at various levels, and rank and select the best alternative [12,13]. This method was proposed by the American operations researcher, T. L. Saaty. It has found extensive application across most fields and has been demonstrated to be effective and universal in making complex decisions [14]. The steps for implementing the AHP analysis method are shown in Figure 1.

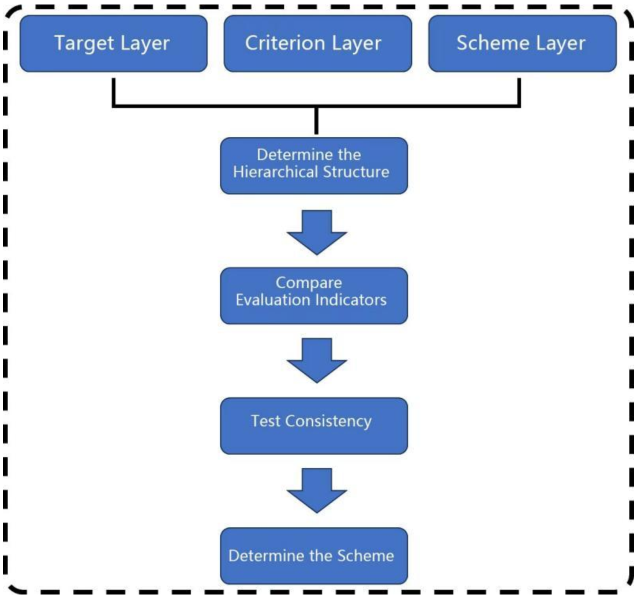


Figure 1. Steps in the analytic hierarchy process (AHP) analysis

It is possible to divide the AHP weighting process into four steps:
(1) Build a hierarchical organization: Compare the relationships between the elements of evaluation to create a hierarchical system. Based on a precise grasp of the essence of the problem, clarify the decision-making objectives, decompose the problem into different levels, and determine the target level, criterion level, and solution level.
(2) Constructing the judgment matrix: Using the 1-9 proportional scale [15] as shown in Table 1, pairwise comparisons are conducted between elements within the same level, with appropriate scale values selected based on their relative importance. Judgment matrices are then constructed for each criterion level according to the pairwise comparison results.
(3) Determine the maximum eigenvalue λ_{max} and its corresponding eigenvector ω of the judgment matrix.
(4) Consistency check. Calculate the consistency index CI as shown in Equation (1).

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

Here, λ_{max} denotes the maximum eigenvalue of the judgment matrix, while n represents the matrix's order. The Consistency Index (CI) measures the internal consistency of the matrix.
Then calculate the random consistency ratio (CR) as shown in Equation (2).

$$CR = \frac{CI}{RI} \quad (2)$$

Relative Importance (RI) represents the average random consistency index of the judgment matrix at the corresponding order. The Consistency Ratio (CR), typically set at 0.1, is used to assess whether the matrix demonstrates acceptable consistency. The CR < 0.1 implies that the matrix satisfies the consistency requirements. When this happens, the eigenvector ω, which is the eigenvalue of the largest eigenvalue λ_{max}, is scaled to get the evaluation index weights. On the other hand, when CR is greater than 0.1, it indicates high levels of inconsistency in the judgment matrix, requiring that the pairwise comparisons be re-examined and tweaked iteratively until a tolerable level of consistency is attained.

Table 1. Meaning of the 1-9 scale

Scale	Definition
1	The *i* factor is as important as the *j* factor.
3	The *i* factor is slightly more important than the *j* factor.
5	The *i* factor is more important than the *j* factor
7	The *i* factor is significantly more important than the *j* factor.
9	The *i* factor is absolutely more important than the j factor.
2, 4, 6, 8	The comparison result between the *i* and *j* factors falls within the median of the adjacent judgments listed above.
Count backwards	Compare factor *j* with factor *i* to obtain the judgment value $a_{ji} = 1/a_{ij}$.

2.2 Fuzzy comprehensive evaluation method

The Fuzzy Comprehensive Evaluation Method (FCE) is a quantitative measurement based on fuzzy mathematics. It is practical in nature, as it applies the principle of fuzzy relation synthesis to measure factors whose boundaries in the system are unclear, thereby providing a complete evaluation [16,17]. The basic steps of the fuzzy comprehensive evaluation method are as follows:

(1) Determine the set of evaluation factors: Identify all evaluation factors for the subject. Assuming n factors influencing safety assessment, the critical factors set is obtained:

$$U = (u_1, u_2, \dots u_n) \tag{3}$$

(2) Determine the evaluation level set: Set evaluation levels, typically divided into multiple categories such as severe, relatively severe, moderate, relatively weak, and no impact. These evaluation levels form a set:

$$V = (v_1, v_2, \dots v_n) \tag{4}$$

(3) Determine the weight set: In fuzzy evaluation of various factors, the determination of weight is the key to evaluation. According to the importance of evaluation factors, the weight of evaluation indicators is determined to form a weight set:

$$A = (a_1, a_2, \dots a_n) \tag{5}$$

The value $\sum_{i=1}^{n} a_i\, a_i u_i$ of 1 represents the weight of the evaluation factor, which can be determined through the Analytic Hierarchy Process (AHP).

(4) Establish the fuzzy relation matrix R: The membership degree reflects the extent to which an evaluated object belongs $r_{ij} u_i v_i$to a specific evaluation level under a given factor, denoted as, where represents the membership degree of the factor in the level. All factor membership degrees collectively form a fuzzy evaluation matrix:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{6}$$

(5) Fuzzy comprehensive evaluation: The fuzzy comprehensive evaluation result B is:

$$B = AR = (a_1, a_2, \dots a_m) \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} = (b_1, b_2, \dots b_m) \tag{7}$$

Here, B denotes the membership vector, with bi representing the membership degree of the comprehensive evaluation result in the i-th evaluation level.

(6) Processing of evaluation results: Based on the fuzzy comprehensive operation result B, the final rating of the evaluated object can be determined using either the maximum membership principle or the weighted average method. The maximum membership principle selects the highest corresponding rating in bi as the evaluation result, while the weighted average method calculates the weighted average of all evaluation ratings to obtain the final result. In practice, the AHP and FCE methods can be implemented effectively using specialized software tools for efficient, accurate computation and analysis. The implementation platform of this study was Yaahp software. First, we prepared a survey questionnaire based on the hierarchical structure of the AHP, in which we invited experts to make pairwise comparisons and score indicators at each level. After collecting the data from the questionnaires, the data were processed in Yaahp to obtain judgment matrices, calculate indicator weights, and test consistency. Based on this, we have integrated the software's fuzzy overall analysis capability. To determine the final assessment results, we multiplied the experts' scores for subordinate factors by the weights derived using AHP. All calculations of weight and the total FCE evaluation process went along smoothly with the assistance of Yaahp. Such an approach was not only the most effective in enhancing research efficiency and standardization but also in rendering risk assessment results scientifically valid and reliable.

3. Construction of the safety evaluation index system

Science and a rational risk assessment system are the basis of accurate safety risk analysis. To make the assessment results effectively and impartially illustrate the safety situation in the production lines of polyimide foams, this study systematically analyzed the production process, the properties of hazardous substances, and the types of accidents that may occur in the manufacturing lines. Our analysis of project documentation and related literature enabled us to develop a multi-level, multi-dimensional system of safety risk evaluation indices.

3.1 Basis and principles of indicator system construction

To develop a comprehensive and precise evaluation index system for safety risks in polyimide foam production line, it must be grounded in solid theoretical foundations and clear design principles [18]. This study, after comprehensively examining domestic and international chemical process safety standards (e.g., GB 45673-2025) and the characteristics of polymer material synthesis processes, established the following four core principles to guide the scientific construction of the index system:

(1) Systematic principle: The index system should be able to comprehensively cover the key safety dimensions, such as "people-machine-material-method-environment", ensure that the factors are relatively independent and have internal logical connections, and constitute a hierarchical and complete organic whole, to avoid the omission or repeated evaluation of important risk sources.

(2) Scientific principle: The selection, definition, and hierarchical attribution of each indicator must have a solid theoretical basis (such as accident causation theory, system engineering principles) or come from the clear support of industry standards and technical specifications, to ensure that it can accurately and objectively reflect the essence and impact path of a specific risk.

(3) Operability Principle: Indicators must be observable, measurable, and comparable. The required data for evaluation should be obtained through feasible methods, such as on-site inspections, reviewing equipment operation records, querying safety management archives, and expert on-site assessments, to ensure the evaluation work can be effectively implemented.

(4) The principle of dynamism and orientation: The index system is not only used for static risk status assessment, but also should pay attention to the dynamic process of risk management, guide enterprises to pay attention to the continuous improvement of safety management, and provide directional guidance for future risk early warning and prevention and control priorities.

3.2 Construction of safety evaluation index system

First, by systematically reviewing domestic and international literature on chemical process safety and polymer production process safety, we identified common risk factors, including equipment reliability, hazardous chemical management, and personnel safety behavior [19-22]. Secondly, we conducted an in-depth analysis of safety design documents, operating procedures, and safety management regulations related to polyimide foam production lines. This enabled us to identify specific risk points unique to polyimide foam manufacturing, including radiation control in microwave foaming processes, fire/explosion risks associated with solvents like tetrahydrofuran, and interlock controls during high-pressure vulcanization. Building on this foundation, we applied the Analytic Hierarchy Process (AHP) methodology to decompose complex safety risk issues into three hierarchical levels: objectives, criteria, and indicators. This resulted in a clear hierarchical structure model. The specific risk evaluation index system for polyimide foam production lines is detailed in Table 2.

4. Risk assessment

4.1 Indicator weighting

This study developed an expert survey questionnaire on risk indicators for polyimide foam production lines, based on the established risk assessment framework. Industry experts were invited to complete the questionnaire. Using the collected data, judgment matrices were constructed in Yaahp software to aggregate expert opinions through group decision-making, ultimately determining the final weights of each indicator. First, based on the risk index evaluation system for polyimide foam production lines, a hierarchical model was constructed in the Yaahp software, as shown in Figure 2.

The expert data was then imported into the Yaahp software to construct judgment matrices for each expert. All matrices demonstrated a consistency ratio (CR) below 0.1, passing the consistency test to ensure the scientific validity and rationality of the weight distribution. The final weight allocation results are presented in Table 3. As shown in Table 3, the key risk points with higher weights constitute the primary risk profile of this production line. The top three factors are all equipment-related: B11 Core Equipment Stability and Reliability Design (0.1068), B12 Safety Interlock and Protective Device Effectiveness (0.0994), and B14 Electrostatic Protection and Grounding System Reliability (0.0780). Following closely are B42 Safety Layout of Hazardous Materials Production Facilities (0.0557), B13 Compliance of Special Equipment Safety Accessories (0.0547), B21 Management of Hazardous Chemical Storage and Usage (0.0450), B51 Coverage of Safety Education and Specialized Training (0.0405), and B31 Management of Workers' Physical and Mental Health Status (0.0407). This clearly identifies the priority areas for risk control resource allocation.

4.2 Fuzzy comprehensive evaluation

After determining the weights of each indicator, experts were invited to rate the relevance

V= {Low Risk 1, Relatively Low Risk 2, General Risk 3, Relatively High Risk 4, High Risk 5}

of all secondary indicators in the evaluation set. The results were imported into the Yaahp software, which performed fuzzy calculations to generate a comprehensive safety risk assessment score for the polyimide foam production line. The final evaluation report is shown in Figure 3.

The overall safety risk assessment score for the polyimide foam production line is 3.7246, as shown in Figure 3. This score is considered a Relatively High Risk according to the set-out evaluation scale. This means the entire safety scenario in the production line is critical, and the management should take urgent action and implement effective measures. The most significant factors were equipment-related (B1) and process material (B2), with scores of 4.05 and 3.98, respectively, and were all considered high risk. This not only confirms the findings of the AHP weight analysis but also establishes these two dimensions as the main factors contributing to high overall risk levels. The scores for personnel factors (B3), safety management factors (B5), and environmental risk factors (B4) were 3.46, 3.30, and 3.2,5, respectively, which are within the upper band of General Risk and on the border of Relatively High Risk. These results reveal a significant lack in these fields that cannot be ignored.

4.3 Recommendations for countermeasures

This section will present a detailed safety risk analysis of the polyimide foam production lines and an indicator-weighted fuzzy overall assessment. It will offer specific risk-prevention and improvement suggestions in five main areas: equipment and facilities, process materials, personnel management, safety management, and environmental control. These are measures to improve overall safety management capabilities and mitigate systemic risks.

(1) Strengthen the inherent safety of equipment and facilities, focusing on high-weight risk points

1. Enhancement of the reliability of core equipment: To develop and actively introduce a preventative maintenance and life cycle maintenance system for major equipment (such as high-temperature pressure tanks and microwave foaming furnaces), as well as the implementation of equipment-based monitoring technology, to detect the trend of equipment deterioration in advance.

2. Assurance of the functionality of combustible gas alarm interlocks and mechanical protective devices: The functionality of combustible gas alarm interlocks and mechanical protective devices should be regularly checked and inspected to be responsive and effective. Create an interlock system management ledger that has well-established maintenance responsibilities and cycles.

3. Comprehensive electrostatic protection system: Have periodic tests and maintenance of the grounding resistance of all equipment and pipelines that carry any of the flammable and explosive media to offer continuous and dependable grounding. The use of anti-static materials and humidification in processes is likely to generate static, such as during crushing and conveying.

(2) Optimize the risk control of process materials and strictly prevent the loss of control of hazard sources

1) Accurate control over hazardous chemicals: Introduce the one book one label system (safety data sheets and safety labels) of all substances, standardize storage and usage conditions of solvents, including tetrahydrofuran and methanol, and enhance integrity checks in leak prevention facilities.

Table 2. Risk assessment index system for polyimide foam production line

Evaluation goal	Primary indicator	Secondary indicator	Subdivide secondary indicators
Polyimide Foam Wire Production Line Safety Risk Assessment A	Device Factor B1	Core Equipment Stability and Reliability Design B11	Design life, failure rate, and maintenance cycle of high-temperature pressure tanks, microwave foaming furnaces, vulcanizing machines, etc., as well as material selection and system design for pressure-bearing pipelines
		Safety interlock and protective device effectiveness B12	The combustible gas detector is interlocked with the emergency ventilation system, while the fire damper is interlocked with the corresponding air conditioner. Protective measures are implemented for mechanical processing equipment such as vulcanizing machines and cutting machines.
		Special Equipment Safety Accessories Compliance B13	Pass rate of pressure gauge, safety valve, and quick-opening interlock device inspection
		Electrostatic Protection and Grounding System Reliability B14	Electrostatic grounding of crushing equipment, pipelines, fans, etc.
		Explosion-proof Electrical Equipment Selection and Installation Compliance B15	Explosion-proof marking, explosion-proof clearance, and cable sealing devices meet the standards
		Completeness of the equipment online monitoring and early warning system B16	Coverage of real-time electrical fire monitoring, vibration monitoring, and temperature/pressure collection
	Process Material Factor B2	Hazardous Chemicals Storage and Use Management B21	Storage conditions and anti-leakage measures for polyimide resin, tetrahydrofuran, methanol, alcohol, isocyanate, etc.
		Asphyxiation gas risk prevention and control B22	Nitrogen leak detection, accident ventilation and alarm interlock
		Control of combustible gas and dust concentration B23	Dust and steam concentration monitoring and control in crushing, foaming and oven processes
		High-temperature and high-pressure interlock control B24	Temperature and pressure dual-limit interlock and over-limit protection for pressure vessels and other equipment
		Fire Prevention in Cleaning Operations B25	Fire and explosion prevention facilities, anti-static flooring, and ventilation in alcohol consumption areas
		Waste gas and harmful substance control B26	Hydrogen fluoride, methanol, and cyclopentadiene emissions purification and compliance monitoring
	Personnel Factor B3	Workforce Health Management B31	Health examination and fatigue monitoring before high temperature, high altitude and confined space operations
		Compliance with operating procedures and violation control B32	Violation of regulations and operation
		Job Qualifications and Skill Set B33	Certification rates for special operations, explosion-proof electrical maintenance, and pressure vessel operation
		Job standard compliance rate B34	The wearing rate of work protective equipment, the implementation rate of the "three certificates" in confined spaces, and the orderly arrangement of items and tools in the workplace
		Security awareness and risk identification ability B35	Can you identify the risks of chemicals, poisoning, explosion and other risks specific to this process
		Emergency response capability B36	Emergency response proficiency for on-site fires, leaks, and explosions
	Environmental risk factor B4	Noise hazard control B41	Noise levels of vacuum pumps and cooling systems ≤85 dB, along with the proportion of ear protection worn.
		Safety Layout of Hazardous Materials Production Facilities B42	The location, evacuation distance, and fire prevention distance of Class A operation area comply with the specifications
		Fire Protection Facilities: Configuration and Effectiveness B43	The completeness rate of fire hydrants, fire extinguishers, fireproof roller shutters, and fire water sources
		Microwave radiation control B44	Microwave oven cavity shielding effect pass rate
		Evacuation corridor accessibility B45	No items in the channel. The indicator light is working properly.
		Ventilation and Dust Removal System Performance B46	Local exhaust and accident ventilation air volume compliance rate
		Environmental temperature and humidity and chemical stability B47	The temperature and humidity control records in the storage and production areas meet the process requirements
	Safety management factor B5	Safety education and specialized training coverage rate B51	Training ratio for high-temperature, high-pressure, confined space, explosion-proof areas, and chemical operations
		Safety responsibility system implementation B52	Workplace safety responsibility signing rate and assessment results
		Emergency Plan Development and Drill B53	Fire, explosion, leakage, electric shock and other special plans and exercise frequency
		Operational Procedures and System Completeness B54	Update and operability of core equipment and hazardous work procedures
		Closed-loop management of safety inspections and hazard rectification B55	Monthly inspection frequency and closed-loop rectification rate

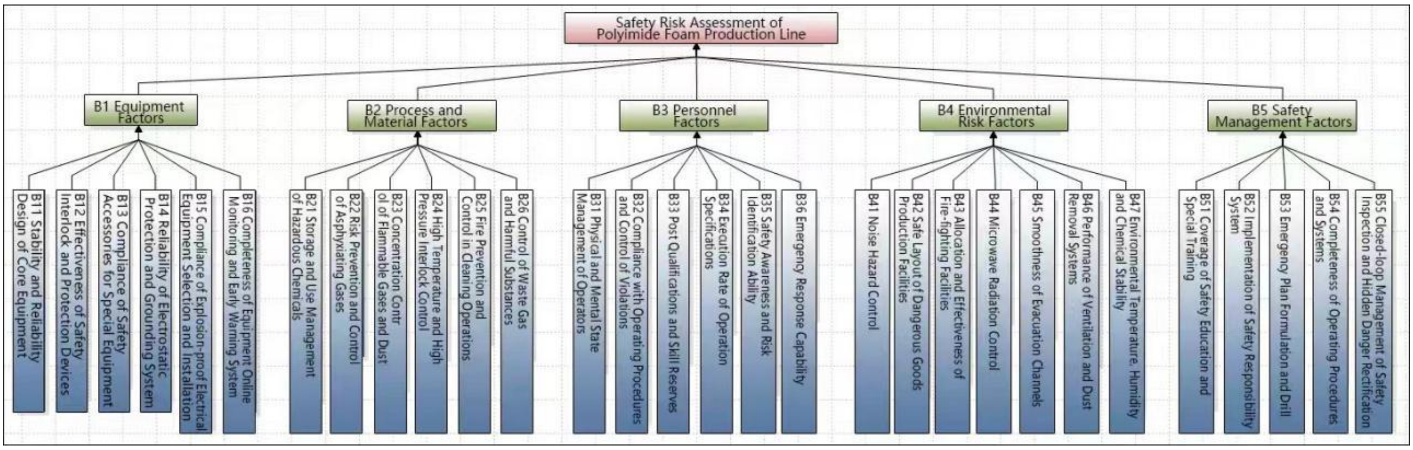
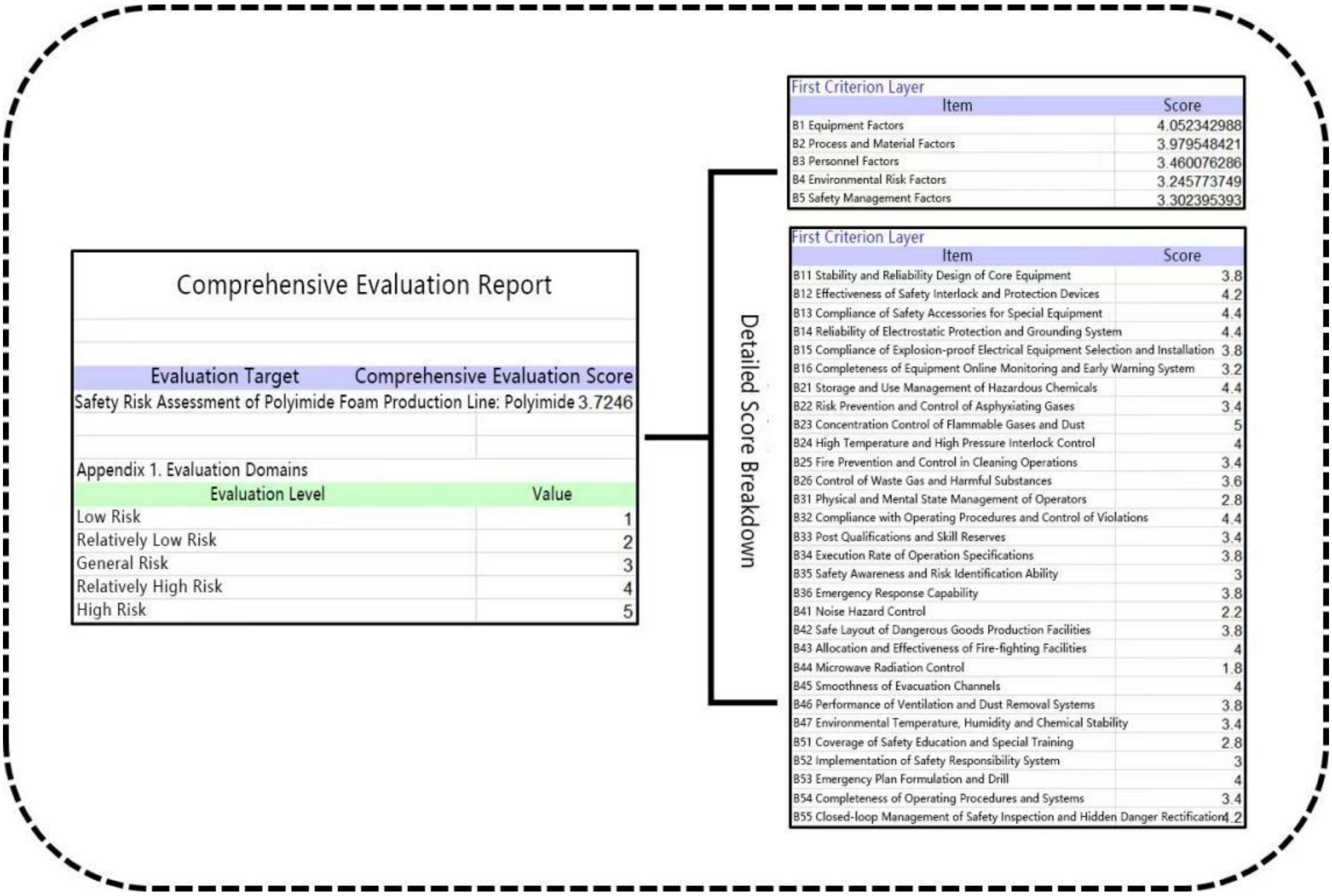


Figure 2. Hierarchical structure model



Comprehensive Evaluation Report

Evaluation Target	Comprehensive Evaluation Score
Safety Risk Assessment of Polyimide Foam Production Line: Polyimide	3.7246

Appendix 1. Evaluation Domains

Evaluation Level	Value
Low Risk	1
Relatively Low Risk	2
General Risk	3
Relatively High Risk	4
High Risk	5

Detailed Score Breakdown

First Criterion Layer

Item	Score
B1 Equipment Factors	4.052342988
B2 Process and Material Factors	3.979548421
B3 Personnel Factors	3.460076286
B4 Environmental Risk Factors	3.245773749
B5 Safety Management Factors	3.302395393

First Criterion Layer

Item	Score
B11 Stability and Reliability Design of Core Equipment	3.8
B12 Effectiveness of Safety Interlock and Protection Devices	4.2
B13 Compliance of Safety Accessories for Special Equipment	4.4
B14 Reliability of Electrostatic Protection and Grounding System	4.4
B15 Compliance of Explosion-proof Electrical Equipment Selection and Installation	3.8
B16 Completeness of Equipment Online Monitoring and Early Warning System	3.2
B21 Storage and Use Management of Hazardous Chemicals	4.4
B22 Risk Prevention and Control of Asphyxiating Gases	3.4
B23 Concentration Control of Flammable Gases and Dust	5
B24 High Temperature and High Pressure Interlock Control	4
B25 Fire Prevention and Control in Cleaning Operations	3.4
B26 Control of Waste Gas and Harmful Substances	3.6
B31 Physical and Mental State Management of Operators	2.8
B32 Compliance with Operating Procedures and Control of Violations	4.4
B33 Post Qualifications and Skill Reserves	3.4
B34 Execution Rate of Operation Specifications	3.8
B35 Safety Awareness and Risk Identification Ability	3
B36 Emergency Response Capability	3.8
B41 Noise Hazard Control	2.2
B42 Safe Layout of Dangerous Goods Production Facilities	3.8
B43 Allocation and Effectiveness of Fire-fighting Facilities	4
B44 Microwave Radiation Control	1.8
B45 Smoothness of Evacuation Channels	4
B46 Performance of Ventilation and Dust Removal Systems	3.8
B47 Environmental Temperature, Humidity and Chemical Stability	3.4
B51 Coverage of Safety Education and Special Training	2.8
B52 Implementation of Safety Responsibility System	3
B53 Emergency Plan Formulation and Drill	4
B54 Completeness of Operating Procedures and Systems	3.4
B55 Closed-loop Management of Safety Inspection and Hidden Danger Rectification	4.2

Figure 3. Comprehensive evaluation report

Table 3. Weight ranking of risk indicators

Risk indicator	Weight
B11 Core Equipment Stability and Reliability Design	0.1068
B12 safety interlock and protection device effectiveness	0.0994
B14 Static protection and grounding system reliability	0.0780
B42 Safety layout of hazardous materials production facilities	0.0557
B13 Compliance of Safety Accessories for Special Equipment	0.0547
B21 Management of storage and use of hazardous chemicals	0.0450
B31 Personnel physical and mental state management	0.0407
B51 safety education and special training coverage	0.0405
B41 Noise hazard control	0.0346
B15 Explosion-proof Electrical Equipment Selection and Installation Compliance	0.0345
B16 equipment online monitoring and early warning system completeness	0.0295
B22 Asphyxiating gas risk prevention and control	0.0295
B52 Safety responsibility system implementation	0.0279
B26 Waste gas and harmful substance control	0.0269
B44 Microwave Radiation Control	0.0254
B32 Compliance with Operating Procedures and Violation Control	0.0252
B53 Emergency Plan preparation and exercise	0.0245
Fire prevention in B25 cleaning operations	0.0238
B54 Operational Procedures and System Completeness	0.0225
B23 combustible gas and dust concentration control	0.0213
B43 Fire protection facilities and effectiveness	0.0213
B46 ventilation and dust removal system performance	0.0212
B24 High-temperature and high-pressure interlock control	0.0188
B34 Work Specification Compliance Rate	0.0182
B33 Job Qualifications and Skill Set	0.0164
B45 evacuation channel accessibility	0.0162
B47 Environmental temperature and humidity and chemical stability	0.0127
B55 closed-loop management for safety inspection and hazard rectification	0.0106
B35 Safety Awareness and Risk Identification	0.0103
B36 Emergency response capability	0.0080

2) Enhanced process safety parameter interlock: Re-examine and optimize alarm and interlock settings for critical process parameters (temperature, pressure, concentration) to ensure automatic downgrading or shutdown procedures when limits are exceeded, preventing accident escalation.

(3) Improve personnel safety literacy and behavioral norms

1) Special training and capacity building: Develop special training modules for the risks of the polyimide foam production process and adopt the combination of case teaching and practical exercise to improve the risk identification and emergency response ability of employees.

2) Operation process supervision and behavior correction: Promote the "behavior safety observation" activity, and use video surveillance and other technical means to strengthen remote supervision of high-risk operations (such as limited space, high temperature cleaning), timely intervention in violation of rules, and analysis of root causes.

(4) Improve the safety management system and promote closed-loop management

1) Link the implementation of the responsibility system with performance assessment: include safety performance indicators (such as the rate of hidden danger rectification and the number of violations) into the annual assessment of departments and individuals, clarify the rules of rewards and punishments, and enhance the safety responsibility awareness of all staff.

2) Closed-loop optimization of hazard identification and management: Through digital systems (e.g., mobile inspection apps), the entire process of hazard reporting, rectification, and verification is tracked, ensuring timely resolution and feedback for each identified issue, thereby forming a closed-loop management system.

(5) Improve working environment and emergency support conditions

1) Layout optimization and emergency facility maintenance: Regularly review fire separation distances between Class A zones and adjacent facilities to ensure unobstructed evacuation routes. Establish a monthly inspection system for fire protection facilities to maintain their readiness at all times.

2) Improvement of local environmental control ability: optimize the airflow organization of local exhaust hood for dust (gas) production processes, such as foaming and crushing, and regularly measure the air volume and air speed to ensure that the capture efficiency meets the occupational exposure limit requirements.

5. Conclusion

This paper mathematically constructs a multidimensional assessment model that includes five aspects, such as equipment, materials, personnel, environment, and management, to evaluate the degree of safety risks in polyimide foam manufacturing lines. The paper uses the Analytic Hierarchy Process (AHP) and the Fuzzy Credibility Evaluation (FCE) method to provide quantitative risk assessment and classification. The key findings are as follows:

(1) Through AHP weight analysis, the identification of key risk factors such as the stability and reliability design of core equipment, the effectiveness of safety interlock and protective devices, and the reliability of the electrostatic protection and grounding system are the priority areas of risk control.

(2) The comprehensive evaluation based on FCE indicates that the production line's overall risk is classified as "Relatively High Risk". The highest scores were attributed to equipment and process material factors, which are the primary contributors to the elevated risk level.

(3) Although the personnel, environment, and safety management factors are at the level of "General Risk", they are still close to the threshold of "Relatively High Risk", indicating that there are obvious shortcomings in the risk prevention and control system, which need to be strengthened systematically.

(4) Based on the evaluation results, specific risk prevention and control measures are put forward from the aspects of equipment inherent safety, process parameter control, personnel behavior management, closed-loop system operation, and environmental emergency support, which provide an operational practice path for the safe operation and continuous improvement of the polyimide foam production line.

This study provides methodological support for risk identification, classification, and the formulation of control strategies in high-risk production systems. Future research may further incorporate dynamic risk-monitoring data and intelligent early-warning technologies to improve the real-time and prospective character of risk assessment.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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