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Research on Fuzzy Comprehensive Evaluation of Fire Safety Risk of Battery Pack Production Process Based on DEMATEL-ANP Method

Yunfei Xia [1], Qingming Guo [2], Lei Lei [1,3,*], Jiong Wu [2], Xin Su [1] and Jianxin Wu [2]

[1] School of Fire Protection Engineering, China People's Police University, Langfang 065000, China; 2023909002@cppu.edu.cn (Y.X.); 2023909010@cppu.edu.cn (X.S.)
[2] Huizhou Desay Intelligent Storage Technology Co., Ltd., Huizhou 516000, China; guoqm@desay.com (Q.G.); wujiong@desay.com (J.W.); wujx_dc@desay.com (J.W.)
[3] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, China
* Correspondence: leilei@cppu.edu.cn; Tel.: +86-13582798312

Abstract: A new safety risk assessment model for battery pack production processes was developed using the DEMATEL-ANP method to analyze the impact and complex relationships of risk-influencing factors. Initially, five major risk-influencing factors were identified, leading to the construction of a 15-factor indicator system. Through the DEMATEL method, these factors were categorized into cause and result factors. Subsequently, by combining the DEMATEL and ANP methods, key risk-influencing factors were identified by comparing ANP weights with hybrid weights adjusted through the DEMATEL-ANP method. Finally, integrating the DEMATEL-ANP method with the fuzzy comprehensive evaluation method allowed us to assess the overall fire safety risk level. Our findings highlighted "hazards in the test process" and "fire hazards" as critical risk factors needing control and elimination in the highly hazardous battery pack production process. This method offers dynamic evaluation and valuable insights for safety management in battery pack production.

Keywords: lithium-ion battery; battery pack production process; fire safety risk; influence factors; DEMATEL-ANP; fuzzy comprehensive evaluation

Academic Editors: Shenshi Huang, Yubo Bi and Mingjun Xu

Received: 25 November 2024
Revised: 6 January 2025
Accepted: 15 January 2025
Published: 17 January 2025

Citation: Xia, Y.; Guo, Q.; Lei, L.; Wu, J.; Su, X.; Wu, J. Research on Fuzzy Comprehensive Evaluation of Fire Safety Risk of Battery Pack Production Process Based on DEMATEL-ANP Method. *Fire* **2025**, *8*, 31. https://doi.org/10.3390/fire8010031

1. Introduction

In the context of globalization and rapid technological development, battery packs, as crucial components for energy storage, require the utmost safety in their manufacturing, processing, and assembly. The production process of battery packs involves multiple stages, each of which may introduce safety risks. On 14 August 2016, a fire broke out in the plant of LG Chem New Energy Battery Co., in Nanjing, the point of origin was the lithium battery production equipment, and the fire took nearly three hours to be extinguished [1]. On 5 April 2020, a flash explosion occurred in the acetone recovery system of the battery separator project at Zhuhai Weixun Technology Development Co., Ltd., and the cause of the fire was illegal ignition spot welding, resulting in one death and one injury [2]. On 24 June 2024, a major fire broke out at the Aricell battery plant in Korea, and the fire started on the second floor of Building 3, where the packaging and welding work of the batteries occurred. The cause of the fire, which may have been caused by the overheating of a large number of lithium batteries, lasted about 22 h and killed 23 people [3]. Therefore, it is necessary to comprehensively identify and evaluate the safety risks in the battery pack production process and explore the complex relationship between the influencing factors of safety risks and the degrees of their impact.

In recent years, many scholars have conducted many studies on the safety risk evaluation of battery production [4], operation [5], and energy storage [6] applications. Niu H et al. [7] employed the risk assessment method (RAC method) to identify, analyze, and evaluate the fire risks involved in the storage of the product and production and storage of lithium-ion battery raw materials. Xiao Yong et al. [8] developed a comprehensive risk evaluation system that considers six aspects, including basic battery properties, battery operating conditions, and external stimuli. The authors combined the weights derived from the Analytic Hierarchy Process and the Entropy Weight Method and employed the TOPSIS method to evaluate the risk of battery safety operations in a holistic manner. Huang Hui et al. [9] used the LEC rating method to assess the magnitude of the risk level of induced accidents and to identify the main causes of induced battery safety accidents. Zhang Mengdi et al. [10] applied the DEMATEL-ANP model to quantitatively evaluate the impact relationship and intensity among various security objectives and measures in the power Internet of Things, effectively solving the problem that the risks are difficult to quantify in the existing power Internet of Things risk assessment. Duan Yunlong et al. [11] proposed the DEMATEL-ANP model for evaluating the innovation capability of strategic emerging industries. The study identified management innovation ability and technological innovation ability as key factors in determining the innovation capability of strategic emerging industries. Che Luping et al. [12] verified the applicability of the DEMATEL-ANP model to the risk assessment of transportation facility PPP projects and extracted the key factors affecting the risk of transportation facility PPP projects as the market and operation handover periods. Ji, Y et al. [13] established a model (software factors, hardware factors, environmental factors, parties and other factors, SHEL) to identify 15 risk factors in 4 categories that affect urban complex fire events. Using the Decision Testing and Evaluation Laboratory Method (DEMATEL) and Interpretive Structural Modeling (ISM) methods, the first three critical factors were identified, and eight critical paths with the greatest impact on the fire were identified. Taeho Kim et al. [14] conducted a risk assessment of the battery recycling process based on the RAC (Risk Assessment Code) matrix method. The results show that the use of H_2SO_4 in the extraction of Li during the leaching process has the highest risk, and the disassembly and heat treatment have the lowest risk. In summary, in recent years, domestic and international scholars have carried out a large number of studies on the safety of battery production, operational safety, energy storage safety, and other aspects of the application of safety risk assessment. Various fire risk assessment methods are employed, including the Risk Assessment Code (RAC), Interpretive Structural Modeling (ISM), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Life Cycle Evaluation (LEC), and Analytic Hierarchy Process (AHP). The RAC method has notable drawbacks, including strong subjectivity, potential information loss, and limitations in complex decision-making scenarios. On the other hand, ISM is characterized by high complexity and insufficient adaptability. Both TOPSIS and LEC face limitations related to distance calculation methods and struggle to address nonlinear problems effectively. Additionally, AHP presents challenges such as strong subjectivity and complicated calculations. The combination of assessment methods has become a research focus of safety risk assessment in the process of battery production, assembly, and recycling [15,16].

However, with the continuous development of modern industrial production in society, the process integration of battery pack manufacturing, processing, and assembly has attracted much attention, and the overall safety of the integrated process system has attracted more attention. At present, the safety risk evaluation research on the whole process integration system, such as battery pack manufacturing, processing, and assembly, is relatively weak. Based on this, different from most scholars' research on the safety risk assessment of individual processes in battery manufacturing, processing, and assembly, this paper uses the DEMATEL-ANP model to evaluate and study the overall safety risk of the whole process of battery pack manufacturing, processing, and assembly. By leveraging the strengths of the DEMATEL-ANP model, which is well suited for decision-making environments characterized by complex interactions among factors, this study quantified the intricate relationships among influential factors in the safety risk of the battery pack production process. This was achieved through the construction of a causal diagram and the calculation of mixed weights for the indicators. This approach enables decision makers to gain a deeper understanding of complex management problems, facilitating the identification of key factors and providing effective solutions. It can enhance the scientific and rational nature of decision making. It is expected to provide a practical risk management framework for the battery pack production industry and provide decision support for relevant enterprises and research institutions to formulate effective strategies and improvement measures.

2. Methods

The Decision-Making Trial and Evaluation Laboratory method (DEMATEL) is used to analyze the logical and direct influence relationships between various elements in a system, and in contrast to similar ISM methods [17], the DEMATEL method offers a refined and quantitative analysis of causal relationships. It can calculate the influence degree, affected degree, centrality degree, and causation degree of factors and represent the intensity and direction of these relationships by constructing causal diagrams. While identifying the key factors in the system and their causal relationships among each other, it provides more precise data support. The Analytic Network Process method (ANP) is an extension of the Analytical Hierarchy Process (AHP). In contrast to the AHP, in the ANP, not only can decision factors be directly compared but they can also take into account their mutual influence and dependence, forming a network of interconnected relationships rather than a one-way relationship in a hierarchical structure. The ANP uses expert ratings to calculate the relative importance and dependency of factors, and determines the final weights through the limit process of the hypermatrix. The DEMATEL-ANP method first uses DEMATEL to reveal the causal relationships between factors and then uses the ANP to calculate the weights of these factors. Compared to similar methods such as TOPSIS and LEC rating, the DEMATEL-ANP method can handle and quantify the causal relationships and dependencies in complex problems, reveal the interactions between different factors, and allocate resources or priorities based on the strength of these interactions. It can also handle the combination of qualitative and quantitative factors [18]. This method is particularly effective in complex decision-making problems, where the relationships between factors are complex and difficult to express using traditional hierarchical models. At present, the DEMATEL-ANP method has been successfully applied to many fields such as supply chain management [19], enterprise risk management [20], and service quality evaluation [21]. In this paper, the DEMATEL-ANP model is applied to the study of safety risk evaluation of the battery pack production process to deal with the complex relationship between the factors influencing the safety risk of the battery pack production process and then find the key causal factors.

The fuzzy comprehensive evaluation method is a multi-index evaluation approach that incorporates the principles of fuzzy mathematics. It is primarily employed to address uncertainty and vague information by converting qualitative indicators into quantitative metrics and integrating the effects of various evaluation factors. This process assists decision makers in making informed and scientific judgments. The integration of the fuzzy comprehensive evaluation method with the DEMATEL-ANP method allows for a systematic identification and evaluation of the roles and uncertainties associated with each factor.

This approach comprehensively accounts for the influence of multiple factors and their complex inter-relationships, thereby enhancing the systematization and reliability of the decision-making foundation. Furthermore, this combination enables a clear identification of the impact and weight of each factor, thereby optimizing the decision-making process and allowing for a targeted focus on addressing key issues. This ensures that decisions are well informed and strategically aligned with the underlying complexities of the situation at hand.

2.1. DEMATEL Method

Decision-Making Trial and Evaluation Laboratory (DEMATEL) was originally proposed by scholars A. Gabus and E. Fontela from the Battelle Laboratories in the United States in 1971 through the use of graph theory and matrix tools to determine the causal relationships between elements and each element's position in the system [22,23]. The principle and steps are shown in Figure 1.

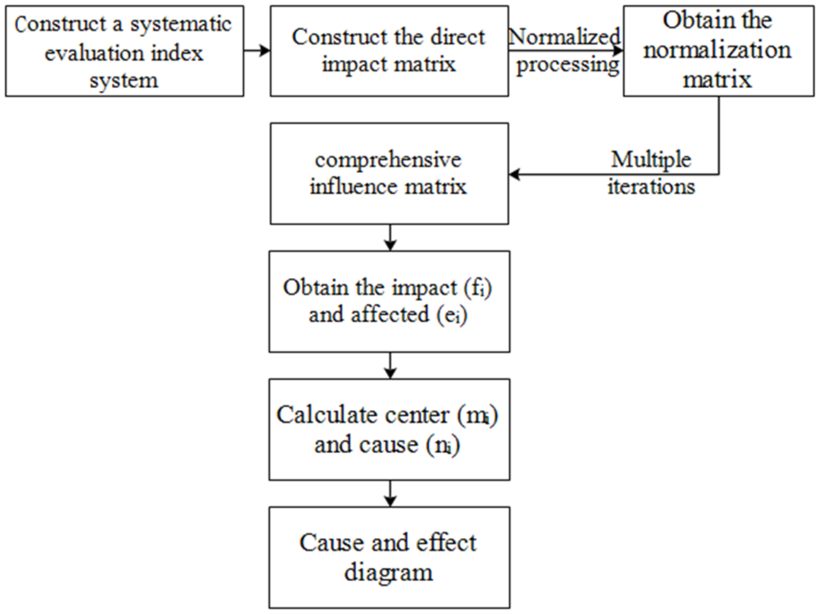


Figure 1. DEMATEL principle and calculation flowchart.

1. Construct a systematic evaluation indicator system through field research and a literature review and number indicators at all levels.
2. Construct the direct impact matrix. Determine the influence relationship between the two indicators through expert scoring. The influence of each factor is evaluated from the standpoint of fire safety risk. The degree to which one factor affects another can be interpreted as the extent to which the former factor contributes to an increase in the fire risk associated with the latter factor. Experts can use different scoring rules with the same basic criteria. For example, if factor A_i has no influence on factor A_j, it can be scored as 0; if the influence is small, it can be scored as 1; if the influence is moderate, it can be scored as 2; and if the influence is large, it can be scored as 3. Alternatively, a 1–9 scoring standard can be used, with specific scoring values and decision criteria, as shown in Table 1.

Table 1. Corresponding values and decision criteria of the scoring scale of the direct impact matrix.

Numerical Value	Decision Criteria
1	The former factors have a slight influence on the latter factors
3	The former factors have a bit more influence on the latter factors
5	The former factors have an influence on the latter factors
7	The former factors have a higher influence on the latter factors
9	The former factors have an extreme influence on the latter factors
2, 4, 6, 8	The degree of influence between adjacent values

Note: the impact between the same indicators is 0, e.g., A1 on A1.

And reflect the influence relationship of all indicators in the matrix based on expert scoring, i.e., obtain the direct influence matrix A, as shown below:

$$\boldsymbol{A} = \begin{bmatrix} 0 & x_{12} & \cdots & x_{1n} \\ x_{21} & 0 & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & 0 \end{bmatrix}, \tag{1}$$

where x_{ij} ($i = 1, 2, 3\ldots, n$; $j = 1, 2, 3\ldots$, n) represents the influence degree of influencing factor A_i on influencing factor A_j; if $i = j$, $x_{ij} = 0$.

3. Obtain the normalized matrix through normalization processing. The formula is as follows:

$$B = \frac{1}{max\sum_{j=1}^{n} x_{ij}} A, \tag{2}$$

i = 1, 2, 3. . ., n.

4. Calculate the comprehensive influence matrix. First, iteratively multiply the normalized matrix B by itself until the value in the matrix is close to 0, that is:

$$\lim_{k \to \infty} B^k = 0 \tag{3}$$

Then, calculate the comprehensive influence matrix T using the following formula:

$$T = B(I - B)^{-1} \tag{4}$$

I is the unit matrix.

5. Calculate the impact (c), affected (e_i), center (m_i), and cause (n_i) degrees based on the comprehensive impact matrix T. The calculation formulas are as follows:

$$f_i = \sum_{j=1}^{n} t_{ij}, (i = 1, 2 \ldots n) \tag{5}$$

$$e_i = \sum_{j=1}^{n} t_{ji}, (i = 1, 2 \ldots n) \tag{6}$$

$$m_i = f_i + e_i, (i = 1, 2 \ldots n) \tag{7}$$

$$n_i = f_i - e_i, (i = 1, 2 \ldots n) \tag{8}$$

6. Cause and effect diagram: the causality diagram can clearly show the relationship between indicators, in which the center degree (m_i) is the horizontal coordinate and the cause degree (n_i) is the vertical coordinate [24].

2.2. ANP Method

The Analytic Network Process (ANP) is an extension of the Analytic Hierarchy Process (AHP), proposed by Professor Thomas L. Saaty in 1996. The ANP considers the interaction between decision criteria and the influence of lower factors on higher factors and calculates the relative weights of each criterion through network analysis. It has been widely used in management science [25], economics [26], engineering [27], environmental science [28], and other fields. The principle and specific steps are shown in Figure 2.

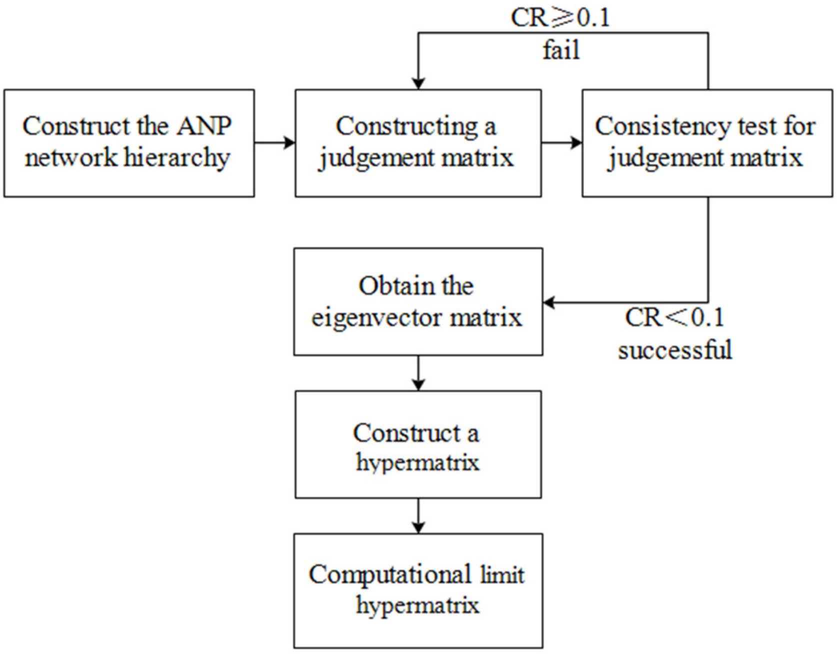


Figure 2. ANP principle and calculation flowchart.

1. Construct an ANP network hierarchy. Identify all the battery pack production process safety risk-influencing factors and clarify the mutual influence relationship between all the elements.
2. Construct the judgement matrix. Based on the mutual influence relationship between the elements, the judgement matrix is obtained through two-by-two comparison scoring of the indicators by experts. Likewise, the degree of importance is assessed from the perspective of fire safety. And the greater the fire safety risk of the factor, the more important it is. The specific values and decision criteria are shown in Table 2.

Table 2. Corresponding values and decision criteria of the scoring scale of the judgement matrix.

Numerical Value	Decision Criteria
1	Both factors are equally important
3	The former factor is slightly more important
5	The former factor is important
7	The former factor is very important
9	The former factor is extremely important
2, 4, 6, 8	The degree of importance between adjacent values

And through normalization processing, obtain the normalized eigenvector matrix W_{ij}:

$$W_{ij} = \begin{bmatrix} W_{i1}^{j1} & W_{i1}^{j2} & \cdots & W_{i1}^{jnj} \\ W_{i2}^{j1} & W_{i2}^{j2} & \cdots & W_{i2}^{jnj} \\ \vdots & \vdots & \cdots & \vdots \\ W_{ini}^{j1} & W_{ini}^{j2} & \cdots & W_{ini}^{jni} \end{bmatrix} \quad (9)$$

It is interpreted that there is an element set U_i, U_j, and element set U_i has an impact on element set U_j; then, the arrangement vector of the influence degree of elements in element set U_i on the elements in element set U_j is denoted as the column vector of matrix W_{ij}; if there is no influence, W_{ij} in matrix W_{ij} is denoted as 0.

3. Check the consistency of the matrix. When the Consistency Ratio (*CR*) value is less than 0.1, the consistency of the judgment matrix is considered to pass. The test formulas are as follows:

$$CI = (\lambda_{max} - n)/n - 1 \quad (10)$$

$$CR = CI/RI \quad (11)$$

CI (Consistency Index) is a quantitative index to judge the degree of matrix deviation from consistency;
λ_{max} is the maximum eigenvalue of the judgment matrix;
n is the dimension of the matrix;
RI (Random Consistency Index) is the average Consistency Index of several randomly generated judgment matrices;
CR (Consistency Ratio) is used to measure the consistency of the judgment matrix.

4. Construct the hypermatrix and calculate the limit hypermatrix. The normalized eigenvector matrix W_{ij} is used as the submatrix to form the hypermatrix, and the weighted hypermatrix is obtained using the normalized vector by column. The weighted hypermatrix is self-multiplied to form the limit hypermatrix *W*, and the indicators weights of each influencing factor are obtained.

2.3. Combination of the DEMATEL Method and the ANP Method

In the process of combining DEMATEL and the ANP, it is necessary to explain the following:

1. Compared with the traditional scoring method, this paper aims to achieve the purpose of making expert judgement bias as consistent as possible, mainly based on the DEMATEL method in the direct impact matrix of the direct impact of the relationship between the construction of the ANP judgement matrix. For example, in the direct influence matrix under the guidelines of the influence factor A1, if the influence factor A2 scoring scores "2", the influence factor A3 scoring scores "1", then, in the judgement matrix in the A2 rows and A3 columns, the value is "2", and the value of column A2 of row A3 is "1/2". This is used as a scoring guideline for each judgement matrix.

2. Calculate the hybrid weights of indicators. The specific formula is as follows:

$$Z = W + T \times W \quad (12)$$

Z is the hybrid weight matrix for each indicator after the combined use of DEMATEL and the ANP;

W is the matrix of indicator weights calculated using the ANP;

T is the comprehensive influence matrix in the DEMATEL method.

2.4. Fuzzy Comprehensive Evaluation Method

The fuzzy comprehensive evaluation method, a comprehensive evaluation approach grounded in fuzzy mathematics, was introduced by Chinese scholars in the early 1980s. This method primarily encompasses the following steps:

1. Create a factor set. Begin by constructing a comprehensive set of index factors that represent various evaluation research objects. This set will consist of multiple index factors, denoted as $u_1, u_2, u_3, \ldots u_n$. These factors will collectively form the evaluation criteria needed for the assessment. The factor set can be represented as follows:

$$U = \{u_1, u_2, u_3, \ldots, u_n\} \quad (13)$$

2. Establish an evaluation set. Construct an evaluation set that contains the evaluations made by the reviewers. The evaluation is divided into m levels, and each level is represented as $v_1, v_2, v_3, \ldots, v_m$, thus constituting a finite set of evaluations:

$$V = \{v_1, v_2, v_3, \ldots, v_n\} \quad (14)$$

3. Determine the weight set. Due to the different importance of each evaluation factor, its weight is also different, and the weight set is the set composed of the weight of each indicator factor. If there are n index factors, corresponding to n weights, respectively, use $a_1, a_2, a_3, \ldots, a_n$, to form a set of weights:

$$A = \{a_1, a_2, a_3, \ldots, a_n\} \quad (15)$$

4. Obtain the evaluation matrix R through expert scores, and then consider the importance of each factor, that is, the weight set A. Then, the fuzzy comprehensive evaluation model is as follows:

$$B = A \cdot R \quad (16)$$

5. Based on the principle of maximizing the degree of membership, this paper identifies the evaluation grade with the highest membership degree from set B as the final assessment of building risk. This approach ensures that the selected grade most accurately reflects the overall evaluation, providing a clear and definitive conclusion regarding the building's risk level.

3. Application and Results

3.1. Construct a Safety Risk Evaluation System for the Battery Pack Production Process

Based on site investigation and a literature review [4,5], the safety risk indicator system of the battery pack production process was sorted into five secondary indicators—hazardous source factor A, equipment and facilities factor B, personnel factor C, management factor D, and environmental factor E—and fifteen tertiary indicators, from A1 to E2, as shown in Table 3.

Table 3. Safety risk indicator system of battery pack production process.

Primary Indicator	Secondary Indicator	Tertiary Indicator
Battery pack production process safety risks	Hazardous source factor A	Hazard sources due to the battery itself A1 Hazards during testing A2 Fire hazard sources A3
	Equipment and facilities factor B	Production assembly equipment B1 Transport trans-shipment equipment B2 Fire-fighting equipment B3
	Personnel factor C	Individual protection of personnel C1 Familiarity of personnel with production processes C2 Physical and mental states of personnel C3 Personnel security awareness and skills C4
	Management factor D	Institution/building D1 Education, training, and emergency drills D2 Daily supervision, inspection and rectification of hidden dangers D3
	Environmental factor E	Building fire safety factor E1 Production environmental factor E2

3.2. Application of DEMATEL-ANP Method

Based on the DEMATEL-ANP method, the safety risk evaluation model of the battery pack production process is constructed as shown in Figure 3.

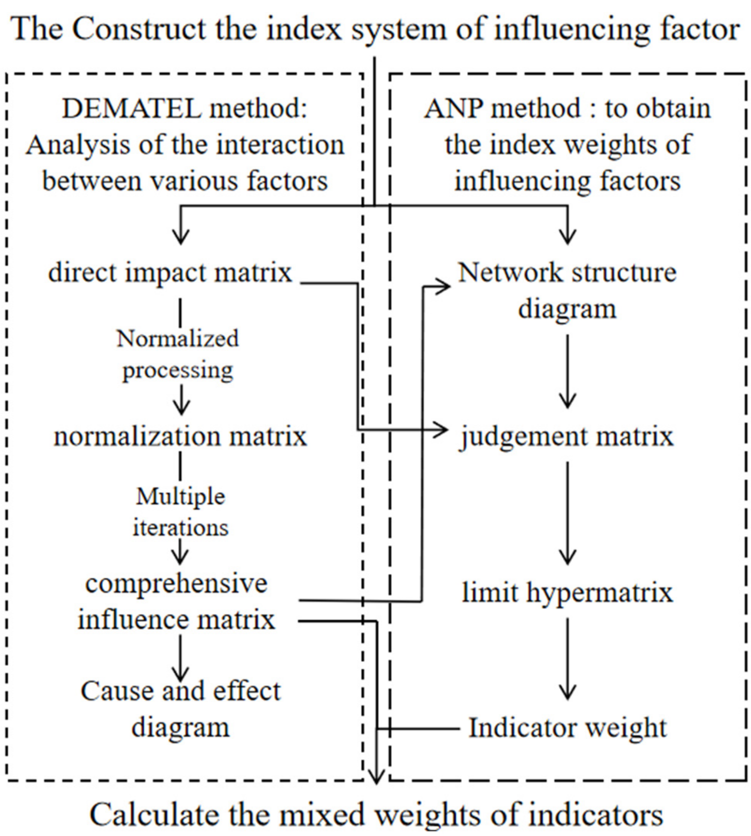


Figure 3. Battery pack production process safety risk evaluation model.

3.2.1. Application of the DEMATEL Method

Construction of the direct influence matrix: The direct influence matrix of the tertiary indicators in the safety risk evaluation system of the whole production process of the battery plant is distributed to the experts in the form of questionnaires and then collected and summarized in the research process. In order to refine the score and strengthen the accuracy of combining with the ANP, the 1–9 scale method is adopted to measure the interaction between indicators. The specific scoring values and decision criteria are shown in Table 1 of Section 2.1.

The questionnaire was effective, and We collected 20 evaluation questionnaires, using the arithmetic mean method to integrate the expert preferences of the 20 expert scoring situations, and the results obtained established a direct impact matrix of the tertiary indicators, with the results shown in Table 4.

Table 4. DEMATEL results: tertiary indicators direct impact matrix A.

NO.	A1	A2	A3	B1	B2	B3	C1	C2	C3	C4	D1	D2	D3	E1	E2
A1	0	8	7	4	4	0	3	5	5	2	5	3	5	4	3
A2	7	0	8	6	3	3	8	6	6	5	7	5	4	3	4
A3	7	6	0	7	7	8	9	6	3	7	7	7	8	7	4
B1	2	6	5	0	0	0	5	5	1	3	3	2	4	0	2
B2	5	0	7	0	0	3	5	2	4	3	3	2	3	0	0
B3	5	6	7	4	4	0	7	0	1	6	4	5	5	7	0
C1	0	2	4	3	2	0	0	0	3	1	2	1	0	0	0
C2	3	5	4	5	4	0	2	0	3	5	1	2	4	0	0
C3	1	6	5	1	2	0	1	1	0	1	0	2	1	0	0
C4	2	5	6	4	4	2	7	0	1	0	0	2	0	0	0
D1	0	1	6	4	4	7	6	6	2	5	0	5	7	6	7
D2	0	6	7	2	2	7	8	8	3	7	0	0	4	0	0
D3	4	6	8	7	7	8	6	5	3	5	3	3	0	5	5
E1	0	0	5	0	2	7	0	0	0	3	1	0	3	0	4
E2	7	5	7	5	5	6	2	0	1	0	1	2	4	3	0

Following the steps of the DEMATEL method, as outlined in Formulas (2)–(4), the integrated influence matrix T is derived. Building upon the results of this matrix, the influence degree, affected degree, centrality degree, and causation degree are determined using Formulas (5)–(8). The obtained results, along with the integrated influence relationship, are presented in Table 5.

Table 5. DEMATEL results: tertiary indicators composite impact relationships table.

Indicator	Influence Degree	Affected Degree	Centrality Degree	Centrality Sort	Causation Degree	Factor Attribute
A1	1.412	1.052	2.464	6	0.359	causal factor
A2	1.744	1.455	3.199	2	0.29	causal factor
A3	2.13	1.967	4.097	1	0.163	causal factor
B1	0.95	1.267	2.217	8	−0.316	outcome factor
B2	0.908	1.196	2.105	10	−0.288	outcome factor
B3	1.455	1.193	2.648	4	0.261	causal factor
C1	0.446	1.685	2.131	9	−1.239	outcome factor
C2	0.92	1.068	1.988	12	−0.148	outcome factor
C3	0.567	0.882	1.449	15	−0.314	outcome factor
C4	0.795	1.281	2.076	11	−0.486	outcome factor
D1	1.535	0.947	2.481	5	0.588	causal factor
D2	1.274	1.011	2.286	7	0.263	causal factor
D3	1.76	1.232	2.992	3	0.527	causal factor
E1	0.664	0.856	1.52	14	−0.192	outcome factor
E2	1.227	0.695	1.922	13	0.532	causal factor

Based on the results in Table 5, the causality of the influencing factors is plotted, as shown in Figure 4.

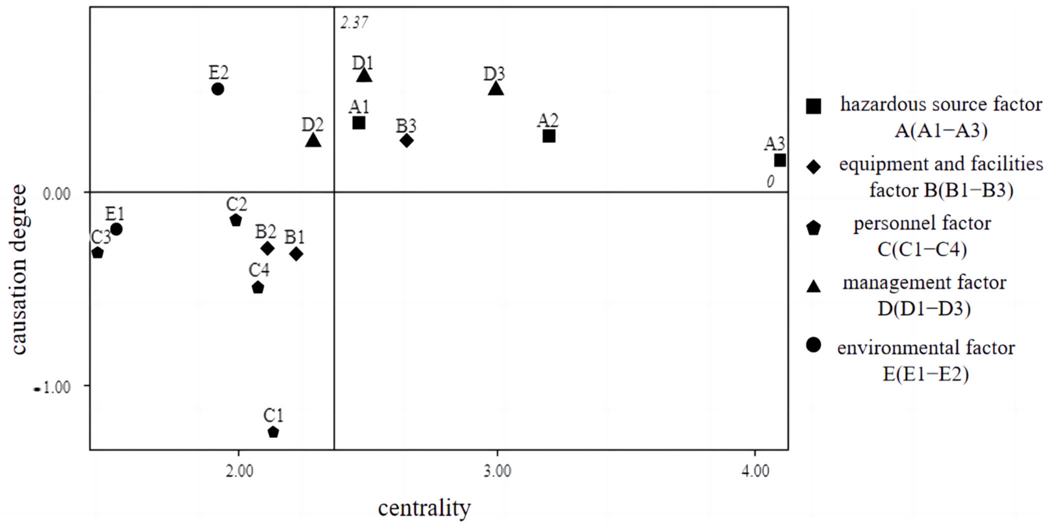


Figure 4. DEMATEL results: causality diagram for tertiary indicators.

The size of the centrality indicates the degree of influence of the influence factor in the evaluation system, and the size of the centrality is directly proportional to the degree of influence. As shown in Table 5, the degree of importance of the influencing factors in descending order is as follows: A3 (fire hazards sources), A2 (hazards during testing), D3, B3, D1, A1, D2, B1, C1, B2, C4, C2, E2, E1, and C3; Figure 4 clearly shows the attribute of each influencing factor. The influencing factors in the first and second quadrants are cause factors: the first quadrant indicates that the degree of cause and centrality are both high, so they are cause factors of high importance; the second quadrant indicates that the degree of centrality is low and that the degree of cause is high, so they are cause factors of low importance. The influence factors in the third and fourth quadrants are the result factors. The third quadrant indicates that the centrality and cause degrees are low, so it is a result factor of low importance. The fourth quadrant represents a high degree of centrality and a low degree of cause, so it is a result factor of higher importance.

3.2.2. Application of the ANP Method

When drawing the ANP network structure diagram, firstly, a threshold value α [18,19] is set to filter out factors with weaker associations while ensuring the overall integrity of the data. The threshold value α is the sum of the mean and variance of each influence value in the comprehensive influence matrix T. When the influence value α is less than the threshold, it is considered that there is no influence relationship, i.e., it is recorded as 0. When the influence value α is greater than the threshold, it is considered that there is an influence relationship. After calculating the threshold value α of 0.08, the fine-tuned integrated influence matrix T* is obtained, and the structure of the ANP network is drawn as shown in Figure 5.

Arrow lines are used to show the mutual influence relationship between the influencing factors, with the arrow pointing to represent that a factor group has an influence on another factor group (the curved arrow represents the existence of its own influencing factor mutual influence relationship), such as the two factor groups influencing each other; then, the arrow is bidirectional.

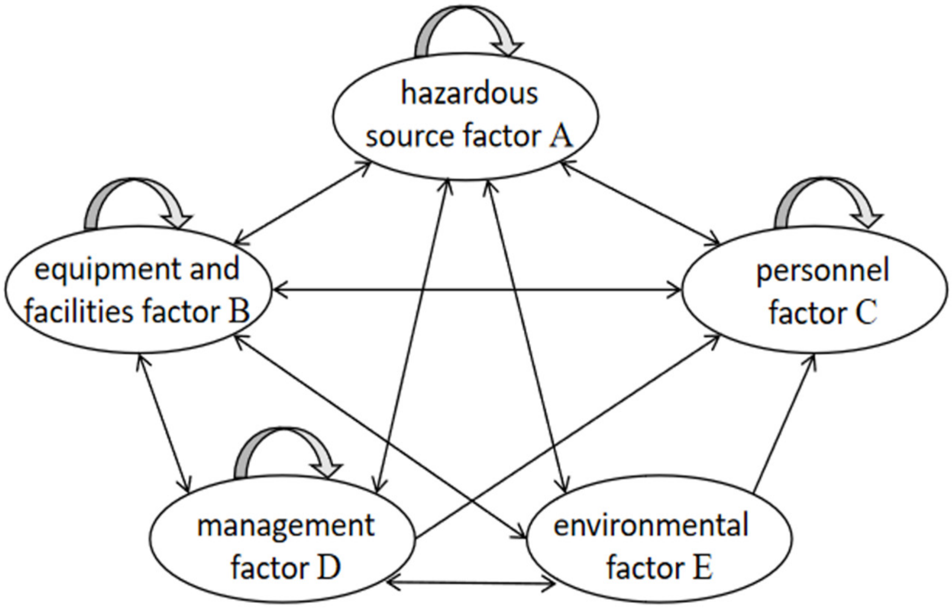


Figure 5. ANP interaction diagram.

Based on the tertiary indicator direct influence matrix *A* constructed in the DEMATEL method, the judgement matrix is constructed using the ANP method, a total of 80 judgement matrices are constructed, and the consistency test of the judgement matrices is carried out using the Formulas (10) and (11), with the results being that all of them pass the consistency test. A series calculation of all judgement matrices is performed to obtain the weights of each influence factor indicator, as shown in Table 6.

Table 6. ANP results: ANP indicator weights.

Secondary Indicator	Secondary Indicator Weight	Tertiary Indicator	Tertiary Indicator Weight
Hazardous source factor A	0.293	Hazard sources due to the battery itself A1 Hazards during testing A2 Fire hazard sources A3	0.062 0.099 0.132
Equipment and facilities factor B	0.207	Production assembly equipment B1 Transport trans-shipment equipment B2 Fire-fighting equipment B3	0.075 0.069 0.062
Personnel factor C	0.290	Individual protection of personnel C1 Familiarity of personnel with production processes C2 Physical and mental states of personnel C3 Personnel security awareness and skills C4	0.101 0.058 0.060 0.071
Management factor D	0.163	Institution/building D1 Education, training, and emergency drills D2 Daily supervision, inspection and rectification of hidden dangers D3	0.054 0.050 0.058
Environmental factor E	0.047	Building fire safety factor E1 Production environmental factor E2	0.025 0.022

According to Equation (12) and normalization, the hybrid weights of the indicators can be calculated after the combined use of DEMATEL and the ANP, as shown in Table 7.

Table 7. DEMATEL combined with ANP: hybrid weight.

Secondary Indicator	Normalized Hybrid Weight for Secondary Indicator	Tertiary Indicator	Normalized Hybrid Weight for Tertiary Indicator
Hazardous source factor A	0.290	Hazard sources due to the battery itself A1	0.071
		Hazards during testing A2	0.097
		Fire hazard sources A3	0.121
Equipment and facilities factor B	0.196	Production assembly equipment B1	0.064
		Transport trans-shipment equipment B2	0.059
		Fire-fighting equipment B3	0.073
Personnel factor C	0.218	Individual protection of personnel C1	0.059
		Familiarity of personnel with production processes C2	0.055
		Physical and mental states of personnel C3	0.046
		Personnel security awareness and skills C4	0.059
Management factor D	0.215	Institution/building D1	0.070
		Education, training, and emergency drills D2	0.064
		Daily supervision, inspection and rectification of hidden dangers D3	0.081
Environmental factor E	0.081	Building fire safety factor E1	0.032
		Production environmental factor E2	0.049

Combined with the results of Tables 6 and 7, the weight of the tertiary indicators obtained using the ANP method is compared with the hybrid weight of the tertiary indicators obtained by combining the DEMATEL method and ANP method, as shown in Table 8.

Table 8. Comparison of ANP weight and hybrid weight of tertiary indicators.

Tertiary Indicator	ANP Weight	Normalized Hybrid Weight
Hazard sources due to the battery itself A1	0.062	0.071
Hazards during testing A2	0.099	0.097
Fire hazard sources A3	0.132	0.121
Production assembly equipment B1	0.075	0.064
Transport trans-shipment equipment B2	0.069	0.059
Fire-fighting equipment B3	0.062	0.073
Individual protection of personnel C1	0.101	0.059
Familiarity of personnel with production processes C2	0.058	0.055
Physical and mental states of personnel C3	0.060	0.046
Personnel security awareness and skills C4	0.071	0.059
Institution/building D1	0.054	0.070
Education, training, and emergency drills D2	0.050	0.064
Daily supervision, inspection and rectification of hidden dangers D3	0.058	0.081
Building fire safety factor E1	0.025	0.032
Production environmental factor E2	0.022	0.049

3.3. Analysis of the Evaluation Results of the DEMATEL-ANP Method

3.3.1. Analysis of the Evaluation Results of the DEMATEL Method

The magnitude of centrality indicates the degree of importance of each influencing factor, and the magnitude of centrality is directly proportional to the degree of importance. The degree of cause reflects the tendency of the influencing factor to act as a cause or an effect.

According to the results in Table 5, the three tertiary indicators in “hazardous source factors A”, namely “hazard sources due to the battery itself A1”, “hazards during testing A2”, “fire hazard sources A3”, and the tertiary indicators in “management factor D” are the cause factors. “Fire hazard sources A3” and “hazards during testing A2” are the two most central influencing factors among all the influencing factors, indicating that they are not only an important cause factor but also have the most significant impact on the occurrence of safety accidents in the battery pack production process.

"Production assembly equipment B1", "transport trans-shipment equipment B2", and the four tertiary indicators in "personnel factor C" are the outcome factors. The centrality of the above outcome factors is low, indicating that they have less influence on the occurrence of safety accidents in the battery pack production process. However, they are all affected by the cause factors, of which "production assembly equipment B1" and "transport trans-shipment equipment B2" are the two factor indicators with the greatest degree of influence.

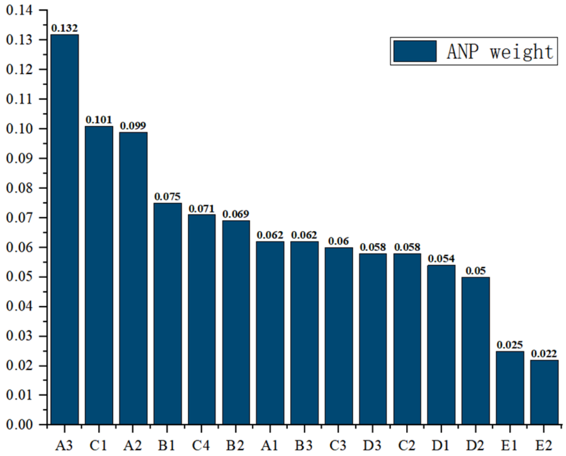
Influencing factors with a high degree of centrality in the cause factors and influencing factors with a high degree of influence in the outcome factors should be focused on and further investigated using different methods, so as to make targeted optimization recommendations.

3.3.2. Comparative Analysis of ANP Weights and Hybrid Weights for Influencing Factors

According to Tables 6 and 7, the weight of "hazardous source factor A" is the largest for both ANP weights and hybrid weights, which indicates that the control of "hazardous source factor A" is the most critical in preventing safety accidents in the battery pack production process, followed by "personnel factor C", whose ANP weight and hybrid weight are only second to that of "hazardous source factors A", so the optimization of "personnel factor C" is continuously strengthened; in the ANP weighting, "management factor D" is the most important factor in preventing safety accidents in the battery pack production process. In the ANP weighting, "management factor D" is second to "equipment and facilities factor B", and in the hybrid weighting, "equipment and facilities factor B" is second to "management factor D", which indicates that in the evaluation process, "management factor D" is second to "equipment and facilities factor B". In the hybrid weighting, "equipment and facilities factor B" is second to "management factor D", indicating that in the evaluation process, through the combination of the ANP method and DEMATEL method, the specific situation of the battery pack production process has been taken into consideration and analyzed, and targeted improvement measures should be strengthened for "management factor D"; "environmental factor E" is second to "equipment and facilities factor B" in the ANP weighting. "Environmental factor E" has the smallest weight in both the ANP and hybrid weights, but after the combination of the ANP and DEMATEL methods, its weight is increased accordingly, so improving the suitability of "environmental factor E" should not be neglected in preventing safety accidents in the production process of battery packs.

Combined with the results of the comparison between ANP weights and hybrid weights of the tertiary indicators in Table 8, the ANP weight order diagram and hybrid weight order diagram are plotted, respectively, as shown in Figure 6.

As can be seen from Figure 6, compared with the ANP weights, the hybrid weights: "hazards during testing A2" and "fire hazard sources A3" in "hazardous source factor A" are slightly weakened, but they are the two third-level indicator influencing factors with the greatest influence, so it is most important to strengthen the control and elimination of hazardous sources in the testing process and fire hazards at the site. The weight of the four tertiary indicators, such as "individual protection of personnel C1", in "personnel factor C" has been weakened. However, as a highly variable and highly complex factor, the personnel factor should also be paid special attention and optimized in combination with changes in production conditions and methods. The weight of "daily supervision, inspection and rectification of hidden dangers D3" has increased significantly, indicating that daily supervision and inspection and hidden danger rectification are the top priorities among daily management factors. Additionally, "fire-fighting equipment B3" has been enhanced, indicating that in combination with the actual situation, the risk of fixed equipment and facilities in the battery pack production process is relatively stable, and the configuration and reliability of fire protection facilities should be paid more attention. "Building fire safety factor E1" and "production environmental factor E2" have both been strengthened, reflecting the fact that there is still a relatively variable and complex relationship between environmental factors and production safety, and that the building structure should be further improved to make it meet the fire safety requirements and strengthened. The external environmental conditions for production should be improved.



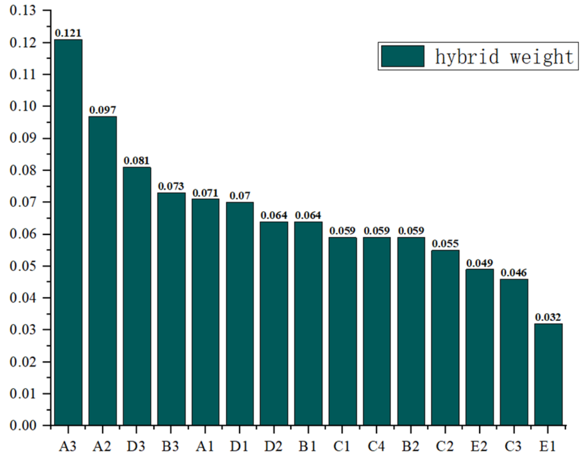


Figure 6. Plot of ANP weight and hybrid weight orders for the tertiary indicators: (**a**) ANP weight sequence diagram; (**b**) hybrid weight sequence diagram.

Upon further analysis of the influencing factors for the two most impactful third-level indicators, "fire hazard sources A3" and "hazards during testing A2", it becomes evident that in the actual production and assembly of battery packs, "fire hazard sources A3" predominantly includes materials such as plastic film, wood, and cardboard boxes that accumulate on-site, in addition to flammable and explosive lubricating sprays and the high-temperature surfaces of high-voltage equipment. These elements consistently pose risks to production safety. On the other hand, "hazards during testing A2" primarily involves the use of high-voltage test guns, the improper use of insulation equipment during testing, and potential failures of test equipment. Additionally, the presence of flammable and explosive substance leakage—resulting from fires and explosions associated with high-temperature equipment—along with equipment malfunctions due to electric shock, introduces further safety risks. Addressing these factors is critical for enhancing safety in the production and testing processes.

3.4. Combined Application and Result Analysis of Fuzzy Comprehensive Evaluation Method and DEMATEL-ANP Method

In this paper, the indicators at all levels to evaluate the safety risks of the battery pack production process were determined, and the ANP weights and hybrid weights of the indicators at each level were calculated through the application of the DEMATEL-ANP method. Based on this, the fuzzy comprehensive evaluation method is combined with the ANP weight and the mixed weight, respectively, to evaluate and analyze the safety risk of the battery pack production process and the influence of its influencing factors.

3.4.1. Application of Fuzzy Comprehensive Evaluation Model

1. Determine the set of factors:

Based on the established evaluation indicator system (Table 3), the set of factors for establishing the safety risk indicator of the battery pack production process is as follows:

$U = \{U_1, U_2, U_3, U_4, U_5\}$ = {hazardous source factor A, equipment and facilities factor B, personnel factor C, management factor D, and environmental factor E};

$U_1 = \{u_{11}, u_{12}, u_{13}\}$; $U_2 = \{u_{21}, u_{22}, u_{23}\}$; $U_3 = \{u_{31}, u_{32}, u_{33}, u_{34}\}$;

$U_4 = \{u_{41}, u_{42}, u_{43}\}$; $U_5 = \{u_{51}, u_{52}\}$.

Among them, u_{11}, u_{22}, and u_{33}, respectively, correspond to the tertiary indicator in hazardous source factor A, and the other factor sets also correspond to each other.

2. Determine the set of evaluations:

According to the actual needs of the safety risk assessment of the battery pack production process, the safety risk level is divided into five levels: "very safe", "safe", "relatively safe", "relatively dangerous", and "very dangerous".

$V = \{v_1, v_2, v_3, v_4, v_5\}$ = {very safe, safe, relatively safe, relatively dangerous, and very dangerous}.

3. Determine the weight sets:

The weight sets can be determined from the ANP weight results in Table 6 and the hybrid weight results in Table 7, and the ANP weight sets of factors set U_1, U_2, U_3, U_4, and U_5 are as follows:

$A = (a_1, a_2, a_3, a_4, a_5) = (0.293, 0.207, 0.290, 0.163, 0.047)$;

$A_1 = (a_{11}, a_{12}, a_{13}) = (0.212, 0.338, 0.450)$;

$A_2 = (a_{21}, a_{22}, a_{23}) = (0.362, 0.333, 0.300)$;

$A_3 = (a_{31}, a_{32}, a_{33}, a_{34}) = (0.348, 0.200, 0.207, 0.245)$;

$A_4 = (a_{41}, a_{42}, a_{43}) = (0.331, 0.307, 0.356)$;

$A_5 = (a_{51}, a_{52}) = (0.532, 0.468)$.

The hybrid weight sets of factors set U_1, U_2, U_3, U_4, U_5 are as follows:

$A' = (a_1, a_2, a_3, a_4, a_5)' = (0.290, 0.196, 0.218, 0.215, 0.081)$;

$A_1' = (a_{11}, a_{12}, a_{13})' = (0.245, 0.334, 0.417)$;

$A_2' = (a_{21}, a_{22}, a_{23})' = (0.327, 0.301, 0.372)$;

$A_3' = (a_{31}, a_{32}, a_{33}, a_{34})' = (0.271, 0.252, 0.211, 0.271)$;

$A_4' = (a_{41}, a_{42}, a_{43})' = (0.326, 0.298, 0.377)$;

$A_5' = (a_{51}, a_{52})' = (0.395, 0.605)$.

(Note: because the calculation result retains three decimal places, there is a numerical deviation in the weight set, but the deviation is extremely small, and this paper considers it negligible.)

4. Expert evaluation:

In order to construct the evaluation matrix, a total of 20 valid questionnaires were collected. The 20 questionnaires were conducted by the same evaluators as those used above for the evaluation of the direct impact matrix. The numerical values in Table 9 represent the number of questionnaires out of the 20 that considered each factor to be at a particular level.

Table 9. Risk level evaluation table of single factors of safety risk in the battery pack production process.

Secondary Indicator	Tertiary Indicator	Very Safe	Safe	Relatively Safe	Relatively Dangerous	Very Dangerous
Hazardous source factor A	Hazard sources due to the battery itself A1	2	2	3	4	9
	Hazards during testing A2	1	2	2	5	10
	Fire hazard sources A3	1	1	2	6	10
Equipment and facilities factor B	Production assembly equipment B1	3	5	6	4	2
	Transport trans-shipment equipment B2	6	2	6	3	3
	Fire-fighting equipment B3	3	2	6	3	6
Personnel factor C	Individual protection of personnel C1	3	2	2	9	4
	Familiarity of personnel with production processes C2	3	3	3	8	3
	Physical and mental states of personnel C3	4	3	3	7	3
	Personnel security awareness and skills C4	2	3	5	7	3
Management factor D	Institution/building D1	3	5	2	4	6
	Education, training, and emergency drills D2	5	3	3	6	3
	Daily supervision, inspection and rectification of hidden dangers D3	3	2	3	8	4
Environmental factor E	Building fire safety factor E1	6	7	2	3	2
	Production environmental factor E2	4	8	4	2	2

According to the results in Table 9, the results of risk membership are shown in Table 10.

Table 10. Single-factor membership table of safety risk in the battery pack production process.

Secondary Indicator	Tertiary Indicator	Very Safe	Safe	Relatively Safe	Relatively Dangerous	Very Dangerous
Hazardous source factor A	Hazard sources due to the battery itself A1	0.1	0.1	0.15	0.2	0.45
	Hazards during testing A2	0.05	0.1	0.1	0.25	0.5
	Fire hazard sources A3	0.05	0.05	0.1	0.3	0.5
Equipment and facilities factor B	Production assembly equipment B1	0.15	0.25	0.3	0.2	0.1
	Transport trans-shipment equipment B2	0.3	0.1	0.3	0.15	0.15
	Fire-fighting equipment B3	0.15	0.1	0.3	0.15	0.3
Personnel factor C	Individual protection of personnel C1	0.15	0.1	0.1	0.45	0.2
	Familiarity of personnel with production processes C2	0.15	0.15	0.15	0.4	0.15
	Physical and mental states of personnel C3	0.2	0.15	0.15	0.35	0.15
	Personnel security awareness and skills C4	0.1	0.15	0.25	0.35	0.15
Management factor D	Institution/building D1	0.15	0.25	0.1	0.2	0.3
	Education, training, and emergency drills D2	0.25	0.15	0.15	0.3	0.15
	Daily supervision, inspection and rectification of hidden dangers D3	0.15	0.1	0.15	0.4	0.2
Environmental factor E	Building fire safety factor E1	0.3	0.35	0.1	0.15	0.1
	Production environmental factor E2	0.2	0.4	0.2	0.1	0.1

5. Establishment of an evaluation matrix R:

According to the data of the single-factor membership table of safety risk in the production process of battery pack in Table 10, the tertiary indicators under secondary indicator correspond to an evaluation matrix of R_1, R_2, R_3, R_4, and R_5, respectively, taking the evaluation matrix R_1 of "hazardous source factor A" as an example:

$$R_1 = \begin{bmatrix} 0.10 & 0.10 & 0.15 & 0.20 & 0.45 \\ 0.05 & 0.10 & 0.10 & 0.25 & 0.50 \\ 0.05 & 0.05 & 0.10 & 0.30 & 0.50 \end{bmatrix} \quad (17)$$

3.4.2. Combination of Fuzzy Comprehensive Evaluation Method and ANP Weights

Based on the fuzzy comprehensive evaluation model, the given weights for the factor set U_1, U_2, U_3, U_4, and U_5 will be calculated using the weighted average method. These weights will then be combined with the evaluation matrices R_1, R_2, R_3, R_4, and R_5. By performing the calculations, we can obtain the fuzzy comprehensive evaluation result. Let us take the factor set U_1 as an example:

$$B_1 = A_1 \cdot R_1 = \begin{pmatrix} 0.212 & 0.338 & 0.450 \end{pmatrix} \cdot \begin{bmatrix} 0.10 & 0.10 & 0.15 & 0.20 & 0.45 \\ 0.05 & 0.10 & 0.10 & 0.25 & 0.50 \\ 0.05 & 0.05 & 0.10 & 0.30 & 0.50 \end{bmatrix} = (0.06,\ 0.08,\ 0.11,\ 0.26,\ 0.49) \quad (18)$$

The fuzzy comprehensive evaluation results B_2, B_3, B_4, and B_5 of factor sets U_2, U_3, U_4, and U_5 are, respectively, as follows:

B_2 = (0.20, 0.15, 0.30, 0.17, 0.18);

B_3 = (0.15, 0.13, 0.16, 0.39, 0.17);

B_4 = (0.18, 0.16, 0.13, 0.30, 0.22);

B_5 = (0.25, 0.37, 0.15, 0.13, 0.10).

To sum up, the principle of maximum membership is used to judge the risk level. The risk levels of the secondary indicators obtained using the fuzzy comprehensive evaluation method combined with ANP weights are shown in Table 11.

Table 11. Risk level table of secondary indicators combined with fuzzy comprehensive evaluation method and ANP weights.

Secondary Indicator	Hazard Rating
Hazardous source factor A	very dangerous
Equipment and facilities factor B	relatively safe
Personnel factor C	relatively dangerous
Management factor D	relatively dangerous
Environmental factor E	safe

B_1, B_2, B_3, B_4, and B_5 constitute the total fuzzy comprehensive evaluation matrix R of the safety risk in the battery pack production process, which is as follows:

$$R = \begin{bmatrix} 0.06 & 0.08 & 0.11 & 0.26 & 0.49 \\ 0.20 & 0.15 & 0.30 & 0.17 & 0.18 \\ 0.15 & 0.13 & 0.16 & 0.39 & 0.17 \\ 0.18 & 0.16 & 0.13 & 0.30 & 0.22 \\ 0.25 & 0.37 & 0.15 & 0.13 & 0.10 \end{bmatrix} \quad (19)$$

The overall rating of the safety risk of the battery pack production process is as follows:

$$B = A \cdot R = \begin{pmatrix} 0.293 & 0.207 & 0.290 & 0.163 & 0.047 \end{pmatrix} \cdot \begin{bmatrix} 0.06 & 0.08 & 0.11 & 0.26 & 0.49 \\ 0.20 & 0.15 & 0.30 & 0.17 & 0.18 \\ 0.15 & 0.13 & 0.16 & 0.39 & 0.17 \\ 0.18 & 0.16 & 0.13 & 0.30 & 0.22 \\ 0.25 & 0.37 & 0.15 & 0.13 & 0.10 \end{bmatrix} = (0.14,\ 0.14,\ 0.17,\ 0.28,\ 0.27) \quad (20)$$

The risk level was determined using the principle of maximum membership, with the membership degree of "relatively dangerous" being the highest at 0.28. This indicates that the evaluation result of using the fuzzy comprehensive evaluation method, combined with ANP weights, to assess the safety risk of the battery pack production process was classified as "relatively dangerous".

3.4.3. Combination of Fuzzy Comprehensive Evaluation Method and Hybrid Weights

In a similar way, the weights given are calculated according to the weighted average type, and the hybrid weight sets of factor sets U_1, U_2, U_3, U_4, and U_5 are combined with the evaluation matrix R_1, R_2, R_3, R_4, and R_5 to calculate the fuzzy comprehensive evaluation results. Take factor set U_1 as an example:

$$B_1{}' = A_1{}' \cdot R_1 = \begin{pmatrix} 0.245 & 0.334 & 0.417 \end{pmatrix} \cdot \begin{bmatrix} 0.10 & 0.10 & 0.15 & 0.20 & 0.45 \\ 0.05 & 0.10 & 0.10 & 0.25 & 0.50 \\ 0.05 & 0.05 & 0.10 & 0.30 & 0.50 \end{bmatrix} = (0.06,\ 0.08,\ 0.11,\ 0.26,\ 0.49) \quad (21)$$

The fuzzy comprehensive evaluation results $B_2{}'$, $B_3{}'$, $B_4{}'$, and $B_5{}'$ of factor sets U_2, U_3, U_4, and U_5 are, respectively, as follows:

$B_2{}'$ = (0.20, 0.15, 0.30, 0.17, 0.19);
$B_3{}'$ = (0.15, 0.14, 0.16, 0.39, 0.16);
$B_4{}'$ = (0.18, 0.16, 0.13, 0.31, 0.22);
$B_5{}'$ = (0.24, 0.38, 0.16, 0.12, 0.10).

The principle of maximum membership is used to judge the risk level. The risk levels of the secondary indicators obtained using the fuzzy comprehensive evaluation method combined with hybrid weights are shown in Table 12.

Table 12. Risk level table of secondary indicators combined with fuzzy comprehensive evaluation method and hybrid weights.

Secondary Indicator	Hazard Rating
Hazardous source factor A	very dangerous
Equipment and facilities factor B	relatively safe
Personnel factor C	relatively dangerous
Management factor D	relatively dangerous
Environmental factor E	safe

$B_2{}'$, $B_3{}'$, $B_4{}'$, and $B_5{}'$ constitute the total fuzzy comprehensive evaluation matrix R' of the safety risk in the battery pack production process, which is as follows:

$$R = \begin{bmatrix} 0.06 & 0.08 & 0.11 & 0.26 & 0.49 \\ 0.20 & 0.15 & 0.30 & 0.17 & 0.19 \\ 0.15 & 0.14 & 0.16 & 0.39 & 0.16 \\ 0.18 & 0.16 & 0.13 & 0.31 & 0.22 \\ 0.24 & 0.38 & 0.16 & 0.12 & 0.10 \end{bmatrix} \quad (22)$$

The overall rating of the safety risk of the battery pack production process is as follows:

$$B' = A' \cdot R' = \begin{pmatrix} 0.293 & 0.196 & 0.218 & 0.215 & 0.081 \end{pmatrix} \cdot \begin{bmatrix} 0.06 & 0.08 & 0.11 & 0.26 & 0.49 \\ 0.20 & 0.15 & 0.30 & 0.17 & 0.19 \\ 0.15 & 0.14 & 0.16 & 0.39 & 0.16 \\ 0.18 & 0.16 & 0.13 & 0.31 & 0.22 \\ 0.24 & 0.38 & 0.16 & 0.12 & 0.10 \end{bmatrix} = (0.15,\ 0.15,\ 0.17, 0.27, 0.27) \tag{23}$$

The risk level was determined using the principle of maximum membership, wherein both "relatively dangerous" and "dangerous" had the same membership value of 0.27, which was the highest among all the categories. Therefore, the evaluation result of applying the fuzzy comprehensive evaluation method, combined with hybrid weights, to assess the safety risk of the battery pack production process falls between the categories of "relatively dangerous" and "dangerous".

3.4.4. Analysis of the Evaluation Results of the Fuzzy Comprehensive Evaluation Method

According to the application of fuzzy comprehensive evaluation method in combination with the ANP weights and mixed weights in DEMATEL-ANP model, respectively, the comprehensive evaluation results of "hazardous source factor A", "personnel factor C", and "management factor D" in the secondary indicators were "very dangerous", "relatively dangerous", and "relatively dangerous", respectively, which corresponded to the proportion of the ANP weights and hybrid weights in the DEMATEL-ANP method. These results indicate that these three influencing factors have a high risk. In conjunction with the actual production environment, a further analysis of "hazardous source factor A", which has been assessed to have a risk grade of "very dangerous", reveals critical insights. The hazard analysis during the testing process, as well as the fire hazard analysis associated with it, aligns with the findings detailed in Section 3.4. Furthermore, it is essential to evaluate the risk sources stemming from the intrinsic characteristics of the battery itself. These factors primarily include battery leakage, damage to the terminals, and damage to the protective blue film. Such issues can lead to an elevated risk of overheating and potential fire hazards due to short circuits at any given moment. Addressing these risks is crucial for ensuring the safety and reliability of battery production and use. The comprehensive evaluation results of "equipment and facilities factor B" and "environmental factor E" in the secondary indicators are "relatively safe" and "safe", respectively, also corresponding to the proportion of ANP weights and hybrid weights in the DEMATEL-ANP method. These results indicate that the risk of these two factors is relatively small, and they have certain safety. For the overall safety risk of battery pack production process, the evaluation result obtained by combining the fuzzy comprehensive evaluation method with ANP weights indicates a "relatively dangerous" level. On the other hand, the evaluation result obtained by combining hybrid weights falls between "relatively dangerous" and "dangerous", showing good consistency. This suggests that regardless of whether we consider the ideal scenario or the interdependencies among influencing factors, the battery pack production process carries a high level of risk.

4. Discussion

This paper proposes a novel safety risk assessment model for the production process of battery packs, integrating the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method with the Analytic Network Process (ANP) method. The model enables an in-depth investigation into the causal relationship and influence degree among the influencing factors. By extracting the key influencing factors and employing the fuzzy comprehensive evaluation method, a comprehensive evaluation of the overall safety risk of the battery pack production process, as well as the safety risks associated with each secondary indicator, is conducted. This approach allows for a comprehensive and detailed analysis of the safety risks involved in the production process of battery packs. It greatly enriches the theory and method of assessing the overall safety risk of the battery pack production process and effectively solves the problem that the overall safety risk of the battery pack production process is difficult to quantify. However, there are some shortcomings in this study.

When constructing the causal diagram and calculating weights through the judgment matrix, the opinions of experts may be limited by personal experiences and their knowledge level, which has strong subjectivity, resulting in a certain degree of subjective bias in the research results. In the follow-up research, the collection of scoring opinions of research experts in more research fields should be considered, and at the same time, combining them with objective weight calculation methods such as the Entropy Weight Method should be considered, so as to increase the universality and guidance of the research results.

The influencing factors in the battery pack production process will change with time and technological progress, and the DEMATEL-ANP model usually provides static evaluation with a certain lag. It mainly includes the following: First, the model is typically evaluated based on data collected at a specific moment in time, without taking into account the dynamic nature of data as it evolves over time. Second, it is assumed that the causal relationships remain constant throughout the evaluation period, overlooking potential external interferences and internal changes that may impact these relationships. So, the influencing factors in the safety risk of the battery pack production process should be continuously updated and improved in the follow-up research, and the DEMATEL-ANP model should be innovated to improve the adaptability and timeliness of the model in the dynamic environment.

5. Conclusions and Suggestions

5.1. Main Conclusions

Based on the evaluation of the influencing factors of the safety risk of the battery pack production process of the battery factory, this paper comprehensively evaluates the safety risks of the battery pack production process based on the DEMATEL-ANP method and fuzzy comprehensive evaluation method and draws the following conclusions:

1. Through the application of the DEMATEL method, the centrality and causality of the influencing factors were calculated, revealing the degree of importance of the influencing factors and the causal relationship between them, identifying the key points for control improvement and the dynamic interactions and causal chains between the influencing factors, thus providing a strong basis for the development of more effective strategies and interventions.
2. Through the comparison and combination of ANP weights and hybrid weights, "hazardous source factor A" is determined to be the secondary indicator with the largest weight, especially "hazards during testing A_2" and "fire hazard sources A_3", which are at the top of both ANP weights and hybrid weights. In addition, "individual protection of personnel C_1" and "daily supervision, inspection and rectification of hidden dangers D_3" are at the top of the ANP and hybrid weights, respectively. In the corresponding fuzzy comprehensive evaluation method, the comprehensive evaluation results of "hazardous source factor A", "personnel factor C", and "management factor D" are, respectively, "very dangerous", "more dangerous", and "more dangerous".
3. By combining the DEMATEL-ANP method with the fuzzy comprehensive evaluation method, it was found that there is a high level of risk in the overall production process

of the battery pack. This combined approach also demonstrated the ability of the DEMATEL-ANP method to identify and assess the real-time dynamic relationships between the influencing factors, thereby optimizing the weights assigned to each factor accordingly. This highlights the effectiveness of the methodology in accurately evaluating and managing the risks associated with the battery pack production process.

5.2. Policy Recommendations

Based on the research results of these influencing factors and the results of fuzzy comprehensive evaluation, countermeasures and suggestions for the safety of the battery pack production process are put forward as follows:

1. Focus on the strict control of all kinds of hazards. Clean up fire hazards, such as combustibles and flammable and explosive materials, around the production environment in a timely manner, such as cartons, plastic shells, etc. Regularly inspect production, assembly, and testing equipment and tools to meet safety standards and regularly carry out professional maintenance of equipment and fire-fighting facilities, such as automatic welding machines, fire hydrants, fire extinguishers, etc., to eliminate potential safety hazards in equipment and facilities.
2. Strengthen the standardization of personnel operations and strict management. Regularly conduct safety training for production operators and management personnel and wear personal protective equipment, such as safety helmets and insulating gloves, in strict accordance with the requirements. Strengthen daily supervision and the inspection and rectification of hidden dangers, formulate detailed inspection plans, and implement hidden danger checklists, such as equipment inspections, personnel operation safety inspections, and environmental safety inspections.
3. Optimize the fire protection structure and production environment of the building. Optimize the safety performance of the building structure by using materials with good fire performance, design an environmental safety monitoring system with a modular and scalable architecture, and use data analysis technology to realize the early prediction of environmental safety hazards.

Author Contributions: Conceptualization, Y.X., L.L. and X.S.; Data curation, Y.X.; Investigation, Y.X., Q.G., L.L., J.W. (Jiong Wu) and J.W. (Jianxin Wu); Methodology, Y.X. and X.S.; Project administration, Q.G., J.W. (Jiong Wu) and J.W. (Jianxin Wu); Resources, Q.G. and J.W. (Jianxin Wu); Supervision, Q.G. and L.L.; Validation, Y.X. and L.L.; Visualization, Y.X. and L.L.; Writing—original draft, Y.X.; Writing—review and editing, L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the university-level key research project "Intelligent evaluation and early warning Technology of Fire Risk based on Big Data Analysis" of China People's Police University, subject number ZDZX202102.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank the anonymous reviewers for their valuable comments and suggestions.

Conflicts of Interest: Authors Qingming Guo, Jiong Wu and Jianxin Wu are employed by the company Huizhou Desay Intelligent Storage Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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