

## Research Article

# A Fast Diagnosis Method of Escalator Reversal Faults Based on Dynamic Information and Multiattribute Decision-Making

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Received 23 August 2021; Revised 21 October 2021; Accepted 2 December 2021; Published 20 December 2021

Academic Editor: Jia-Bao Liu

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There are many reasons for escalator reversal failure, and the reasons are distributed in different locations. It is difficult to locate the specific location of the fault in the actual fault troubleshooting. At the same time, the information related to the failure is not used in the troubleshooting, so there is a problem of inefficient troubleshooting. To this end, this paper proposes a multiattribute decision-making method that integrates dynamic information and gives the optimal troubleshooting order to improve the efficiency of the troubleshooting. First of all, according to the structure of the escalator components, the escalator reversal fault tree is established. Secondly, a static decision matrix is established by comprehensively considering the failure probability, search cost, and influence degree of the bottom event of the fault tree. Finally, the influence matrix of information on each attribute is given by the dynamic information obtained in troubleshooting, the static decision fusion influence matrix determines the dynamic decision matrix, the dynamic decision matrix is weighted and normalized, and the Technique for Order Preference by Similarity to Ideal Solution is used to determine the optimal troubleshooting order. Taking the reversal failure of a certain type of escalators as an example, the method of multiattribute decision-making of fusion dynamic information is used to shorten the troubleshooting time, improve the efficiency of troubleshooting, and verify the effectiveness of this method.

## 1. Introduction

Escalator is a kind of fixed electric drive equipment with circular running rungs, which is mainly used to transport passengers up or down. It can continuously transport passengers. At present, escalators are widely used and have become an indispensable part of public transportation, and escalators are widely used in crowded locations, especially shopping malls, stations, and subways [1, 2]. With the increase in the number of escalators, the safety problems of escalators have become increasingly prominent. In 2019, there occurred 130 accidents and related accidents involving special equipment, resulting in 119 deaths and 49 injuries. Among them, elevator accidents accounted for 33, with 29 deaths, accounting for 25.38% of the total number of accidents, and the number of accidents ranked second. Among escalator accidents, escalator reversal accidents account for a

relatively large proportion, resulting in serious consequences such as passengers falling and squeezing [3]. Therefore, it is important to trace the cause of the failure and quickly troubleshoot the failure after an escalator reversal accident.

Many methods have been used in the field of fault diagnosis and troubleshooting, and the fault tree analysis has been widely used in the field of reliability analysis and fault diagnosis of engineering systems [4–6]. In order to analyze the causes and preventive measures of home elevator accidents, Cheng et al. use fault tree analysis to diagnose home elevators [7]. The method used above lacks sufficient consideration of the search sequence of the cause of the fault and is blind, resulting in low diagnosis efficiency. In order to improve the efficiency of fault diagnosis, Wang et al. use the importance of the bottom events to obtain the gray correlation degree and then calculate the probability of various failure modes of the escalator, so as to sort the bottom fault

event [8]. Liu et al. calculate the structural importance of the basic event of elevator trouble, so as to carry out a rapid and comprehensive inspection of the elevator system after the failure of trapped people [9]. However, these methods only rely on a single indicator to troubleshoot, ignoring the importance of fault search cost in troubleshooting. In order to consider the failure probability, search cost, and influence degree in troubleshooting, He et al. study multiattribute decision-making methods and calculate the fault search path of the crane hydraulic system by the multiattribute decision-making method before troubleshooting [10]. However, this method is only calculated once before troubleshooting, so the search path provided is immutable, and it does not fully consider the impact of dynamic information that may appear during the troubleshooting on the fault search path. When dynamic information is obtained from the investigation of the bottom event, the search sorting of the remaining bottom events changes accordingly.

In view of the existing escalator troubleshooting work and combined with other mechanical equipment troubleshooting research work, this paper applies the multiattribute decision-making method to the escalator fault troubleshooting work for the first time and, at the same time, fuses the dynamic information obtained, gives the optimal troubleshooting order by the Technique for Order Preference by Similarity to Ideal Solution, improves the efficiency of troubleshooting, and supports the rapid diagnosis of escalator reversal fault.

## 2. Establishment of Escalator Reversal Fault Tree

Escalator is a kind of complex transportation equipment with very close mechanical and electrical integration, so it is necessary to understand the composition structure of the escalator before establishing the reversal fault tree [11]. At present, there are many types of escalators used in public places. Although their electrical control systems and rung systems are different, their main structures are the same, including trusses, rung systems, armrest systems, rail systems, handrails, safety protection devices, and electrical control devices [12–14]. The structure diagram of the escalator studied in this paper is shown in Figure 1.

Fault tree analysis is a logical method of graphical deduction. It takes the most undesired state of the system as the goal of logical analysis and finds out all the reasons why this failure state can occur [15–17]. Through the statistics of escalator reversal accidents, the cause of the accident was fully investigated, and it was found that the faults mainly occurred in the grid voltage fluctuations, reversal protection devices, and the host, drive chain, and cascade chains in the rung system. Take the escalator reversal failure as the top event, and take the 10 causes of the reversal failure such as overload, insufficient grid voltage, gear meshing failure of the gearbox, and damaged rung chain as the bottom event. The established fault tree is shown in Figure 2, and the event code is shown in Table 1.

## 3. Multiattribute Troubleshooting with Dynamic Information

### 3.1. Establishment of Dynamic Multiattribute Decision Matrix

**3.1.1. Establishment of Static Multiattribute Decision Matrix.** In the fault tree, the cut set is a collection of some bottom events that can cause the top event to occur. If any bottom event in the cut set does not occur, the top event will not occur, so the cut set is called the minimum cut set [18]. This paper uses the ascending method to divide the fault tree to obtain the minimum cut set. The minimum cut set provides a search scheme to be checked for the static decision matrix. Therefore, the escalator reversal fault tree search scheme is  $\{X_1\}, \{X_2\}, \{X_3\}, \{X_4\}, \{X_5\}, \{X_6\}, \{X_7\}, \{X_8\}, \{X_9\}, \{X_{10}\}$ .

Suppose there are  $n$  search schemes to be checked after the system fails, and  $m$  attributes that affect the search scheme need to be considered. These attributes include failure probability, search cost, and influence degree. Here,  $X = (X_1, X_2, \dots, X_n)$  represents the set of search schemes to be checked. Use  $Y_i = (Y_{i1}, Y_{i2}, \dots, Y_{im})$  to represent the set of attribute values in the  $i$ -th search scheme, where  $Y_{ij}$  is the value of the  $j$ -th attributes in the  $i$ -th search scheme [19–22]. The attribute value of each search plan to be checked can be represented by the static multiattribute decision matrix  $A$ , which provides basic information for analyzing the static fault decision sequence [23–26].

$$A = \begin{matrix} & S_1 & S_2 & \cdots & S_j & \cdots & S_m \\ \begin{matrix} X_1 \\ X_2 \\ \vdots \\ X_i \\ \vdots \\ X_n \end{matrix} & \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1j} & \cdots & Y_{1m} \\ Y_{21} & Y_{22} & \cdots & Y_{2j} & \cdots & Y_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{i1} & Y_{i2} & \cdots & Y_{ij} & \cdots & Y_{im} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nj} & \cdots & Y_{nm} \end{bmatrix} \end{matrix}, \quad (1)$$

where  $X_i$  is the optional plan and  $S_j$  is the attribute of the optional plan.

### 3.1.2. Construction of a Dynamic Information Impact Matrix.

After the escalator reverses the fault, dynamic information will appear during the troubleshooting. It is to obtain information that has different effects on the attribute values of the bottom events through human perception, instrument measurement, and other means when troubleshooting. Therefore, it is instructive for the next troubleshooting. When troubleshooting the cause of the fault, it is necessary to fully consider the impact of dynamic information that appears on the fault search path. The impact of dynamic information can be represented by the impact matrix  $B$ , which provides real-time updated information for dynamic fault decision sequence.

When troubleshooting escalator reversal faults, different information has different effects on the property values of the bottom events due to the wide range and variety of information. The structure of the escalators is closely related,

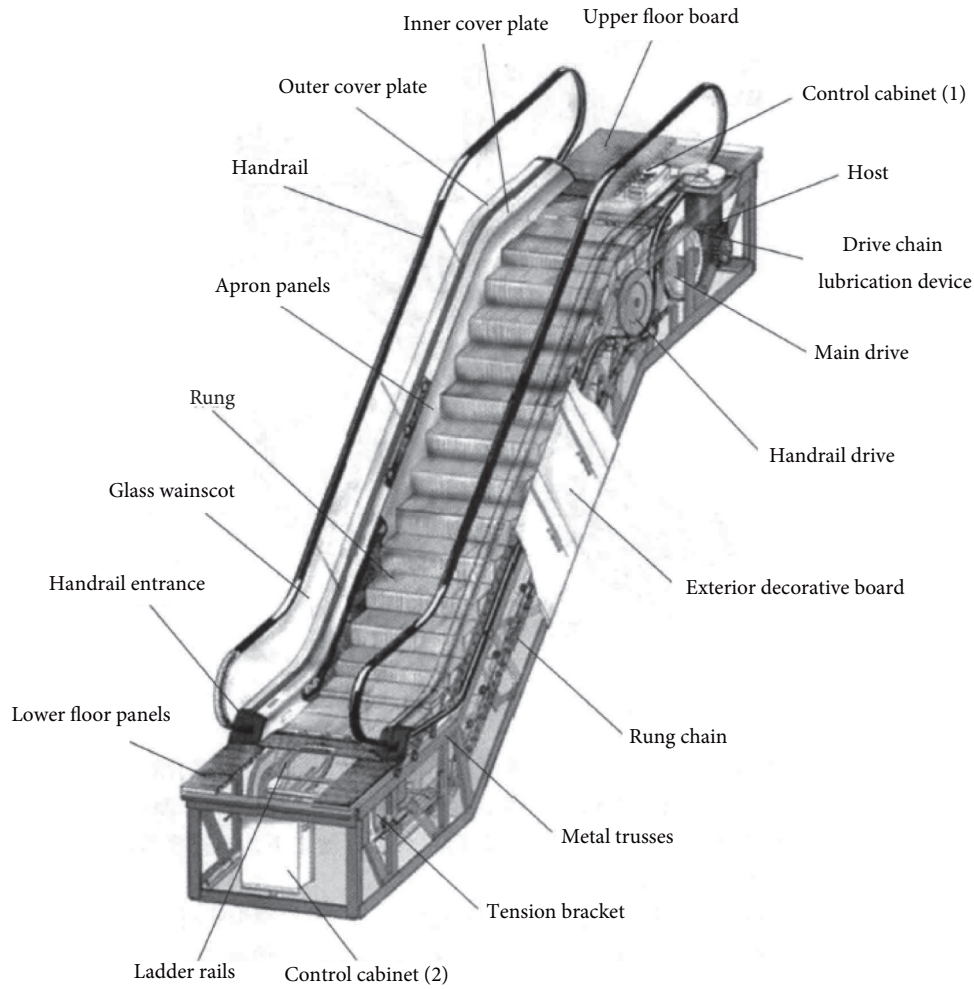


FIGURE 1: A diagram of the escalator structure.

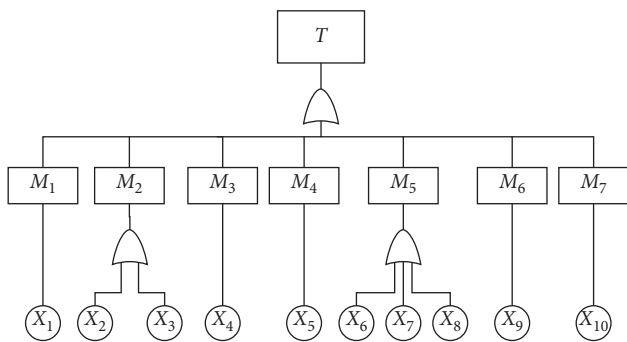


FIGURE 2: Escalator reversal fault tree.

the motors in the rung system are directly connected to the drive chain, the rung chains are indirectly connected to the drive chain, and the main engine of the escalators is composed of gearboxes, brakes, and motors, so dynamic information will be obtained during maintenance. Therefore, before determining the impact matrix  $B$ , the dynamic

TABLE 1: Event code.

| Event symbol | Event name                               |
|--------------|------------------------------------------|
| $T$          | Escalator reversal                       |
| $M1$         | Nonmanipulative reversal                 |
| $M2$         | Torque chain instability or broken chain |
| $M3$         | Voltage fluctuation                      |
| $M4$         | Underpowered                             |
| $M5$         | Power drive chain broken                 |
| $M7$         | Traction chain broken                    |
| $M8$         | Insufficient braking friction            |
| $X1$         | Overload                                 |
| $X2$         | Gear meshing failure of gearbox          |
| $X3$         | Damaged gearbox bearings                 |
| $X4$         | Insufficient grid voltage                |
| $X5$         | Motor power is too small                 |
| $X6$         | Reversal protection device fails         |
| $X7$         | Deformation and damage of drive chain    |
| $X8$         | Loose host position                      |
| $X9$         | Damaged rung chain                       |
| $X10$        | The brake is not working properly        |

information obtained during the troubleshooting of the escalator reversal failure should be classified and summarized. The dynamic information obtained is shown in Table 2.

The construction of the dynamic information impact matrix also needs to determine the optional bottom events, which are determined by the bottom events affected by the dynamic information. By the escalator system structure and composition correlation, the bottom event correlation diagram affected by the dynamic information is shown in Figure 3.

After classifying and summarizing dynamic information and exploring the bottom events affected by the dynamic information, three attributes that affect the search plan are considered: failure probability, search cost, and degree of impact. The influence matrix  $B$  can be determined according to the analysis of the attributes of the three influence search schemes considered by the escalator, the dynamic information obtained, and the bottom events affected by the dynamic information.

$$B = \begin{matrix} & \begin{matrix} N_1 & N_2 & \cdots & \cdots & N_j & \cdots & \cdots & N_k \end{matrix} \\ \begin{matrix} X_1 \\ X_2 \\ \vdots \\ X_i \\ \vdots \\ X_n \end{matrix} & \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} & B_{15} & B_{16} & \cdots & \cdots & B_{1\ 3j-2} & B_{1\ 3j-1} & B_{1\ 3j} & \cdots & \cdots & B_{1\ 3k-2} & B_{1\ 3k-1} & B_{1\ 3k} \\ B_{21} & B_{22} & B_{23} & B_{23} & B_{25} & B_{26} & \cdots & \cdots & B_{2\ 3j-2} & B_{2\ 3j-1} & B_{2\ 3j} & \cdots & \cdots & B_{2\ 3k-2} & B_{2\ 3k-1} & B_{2\ 3k} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \cdots & \vdots & \vdots & \vdots & \cdots & \cdots & \vdots & \vdots & \vdots \\ B_{i1} & B_{i2} & B_{i3} & B_{i4} & B_{i5} & B_{i6} & \cdots & \cdots & B_{i\ 3j-2} & B_{i\ 3j-1} & B_{i\ 3j} & \cdots & \cdots & B_{i\ 3k-2} & B_{i\ 3k-1} & B_{i\ 3k} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \cdots & \vdots & \vdots & \vdots & \cdots & \cdots & \vdots & \vdots & \vdots \\ B_{n1} & B_{n2} & B_{n3} & B_{n4} & B_{n5} & B_{n6} & \cdots & \cdots & B_{n\ 3j-2} & B_{n\ 3j-1} & B_{n\ 3j} & \cdots & \cdots & B_{n\ 3k-2} & B_{n\ 3k-1} & B_{n\ 3k} \end{bmatrix} \end{matrix}, \quad (2)$$

$$\begin{matrix} S_1 & S_2 & S_3 & S_1 & S_2 & S_3 & \cdots & \cdots & S_1 & S_2 & S_3 & \cdots & \cdots & S_1 & S_2 & S_3 \end{matrix}$$

where  $X_i$  represent optional solutions,  $S_1, S_2,$  and  $S_3$  are the three attributes in the search optional solutions, and  $N_j$  is the partitioned matrix of the influence of the acquired dynamic information on  $S_1, S_2,$  and  $S_3$  in the search scheme  $X_i$ .

3.1.3. Establishment of the Dynamic Decision Matrix. The dynamic decision matrix  $C$  proposed in this paper is determined by the fusion of dynamic information impact

matrix  $B$  on the basis of static decision matrix  $A$ . In the search scheme  $X_i$  to be checked, dynamic information  $N_1, N_2, \dots, N_p$  is obtained and the influence matrix  $B$  is determined. According to the established static multiattribute decision matrix  $A$ , multiply the columns  $S_1, S_2,$  and  $S_3$  in matrix  $A$  and the partitioned matrices  $N_1, N_2, \dots, N_p$  in matrix  $B$  to obtain dynamic multiattribute decision matrix  $C$ .

$$C = A \bullet N_1 \bullet N_2 \bullet \cdots \bullet N_p = \begin{matrix} & \begin{matrix} S_1 & S_2 & S_3 \end{matrix} & \begin{matrix} N_1 \\ N_2 \\ \vdots \\ N_p \end{matrix} \\ \begin{matrix} X_1 \\ X_2 \\ \vdots \\ X_i \\ \vdots \\ X_n \end{matrix} & \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ \vdots & \vdots & \vdots \\ Y_{i1} & Y_{i2} & Y_{i3} \\ \vdots & \vdots & \vdots \\ Y_{n1} & Y_{n2} & Y_{n3} \end{bmatrix} \bullet \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ \vdots & \vdots & \vdots \\ B_{i1} & B_{i2} & B_{i3} \\ \vdots & \vdots & \vdots \\ B_{n1} & B_{n2} & B_{n3} \end{bmatrix} \bullet \begin{bmatrix} B_{14} & B_{15} & B_{16} \\ B_{23} & B_{25} & B_{26} \\ \vdots & \vdots & \vdots \\ B_{i4} & B_{i5} & B_{i6} \\ \vdots & \vdots & \vdots \\ B_{n4} & B_{n5} & B_{n6} \end{bmatrix} \bullet \cdots \bullet \begin{bmatrix} B_{1\ 3p-2} & B_{1\ 3p-1} & B_{1\ 3p} \\ B_{2\ 3p-2} & B_{2\ 3p-1} & B_{2\ 3p} \\ \vdots & \vdots & \vdots \\ B_{i\ 3p-2} & B_{i\ 3p-1} & B_{i\ 3p} \\ \vdots & \vdots & \vdots \\ B_{n\ 3p-2} & B_{n\ 3p-1} & B_{n\ 3p} \end{bmatrix} \end{matrix}$$

$$= \begin{matrix} X_1 \\ X_2 \\ \vdots \\ X_i \\ \vdots \\ X_n \end{matrix} \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ \vdots & \vdots & \vdots \\ C_{i1} & C_{i2} & C_{i3} \\ \vdots & \vdots & \vdots \\ C_{n1} & C_{n2} & C_{n3} \end{bmatrix}, \quad (3)$$

TABLE 2: Dynamic information obtained.

| Maintenance position  | Dynamic information                    |                             |                           |                                        |
|-----------------------|----------------------------------------|-----------------------------|---------------------------|----------------------------------------|
| <i>Gearbox</i>        | Motor vibration                        | Motor temperature           | Host position shift       | The amount of brake compression spring |
|                       | Brake arm movement distance            | Damaged protection device   | Drive chain wear          | —                                      |
| <i>Brake</i>          | Motor vibration                        | Motor temperature           | Host position shift       | Gearbox vibration                      |
|                       | Drive chain wear                       | Damaged protection device   | —                         | —                                      |
| <i>Electric motor</i> | The amount of brake compression spring | Brake arm movement distance | Host position shift       | Gearbox vibration                      |
|                       | Drive chain wear                       | Damaged protection device   | —                         | —                                      |
| <i>Drive chain</i>    | Motor vibration                        | Motor temperature           | Host position shift       | The amount of brake compression spring |
|                       | Brake arm movement distance            | Gearbox vibration           | Damaged protection device | Drive chain wear                       |
| <i>Rung chain</i>     | Drive chain wear                       | Damaged protection device   | —                         | —                                      |

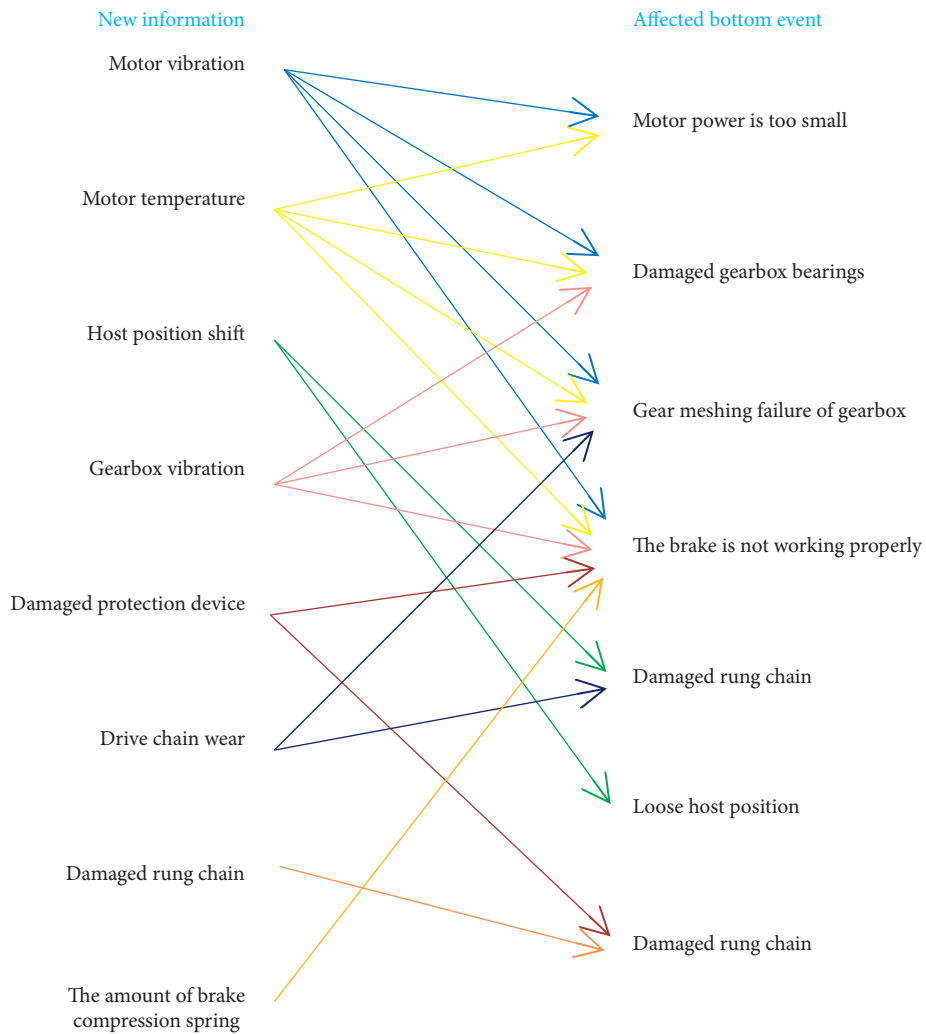


FIGURE 3: Bottom events affected by dynamic information.

where  $X_i$  represent optional solutions,  $S_1, S_2,$  and  $S_3$  are the three attributes in the search optional solutions, and  $N_1, N_2, \dots, N_p$  are the partitioned matrix of the influence of the acquired dynamic information  $j$  on  $S_1, S_2,$  and  $S_3$  in the search scheme  $X_i$ .

**3.2. Composition of the Weighted Normalization Matrix.** We map the three attribute values of failure probability, search cost, and influence degree to the range of 0 to 1, so that attribute values of different units or magnitudes can be compared and weighted. Therefore, using multi-attribute values to make decisions, each attribute data set needs to be normalized. The vectorization specification is a linear change, which can make the sum of the squares of the same attribute value of each scheme be 1. This paper uses vector normalization, and the normalized matrix  $Z$  is

$$z_{ij} = \frac{C_{ij}}{\sqrt{\sum_{i=1}^m C_{ij}^2}} \quad (4)$$

where  $z_{ij}$  is the element of the normalized matrix  $Z$ .

The ordinary least square method is used to determine the weight of each target. First, compare the importance of the goals in pairs. If there are  $n$  goals, then  $C_n^2 = (1/2)n(n-1)$  times are needed to be compared. Mark the relative importance of the  $i$ -th goal to the  $j$ -th goal as  $d_{ij}$ , which is the approximate value of the ratio of the weight  $w_i$  of attribute  $i$  to the weight  $w_j$  of attribute  $j$ ,  $d \approx w_i/w_j$ . The result of the pairwise comparison of  $n$  targets is matrix  $D$ .

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \approx \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix}. \quad (5)$$

If  $d_{ij}$  can be accurately estimated, then

$$d_{ij} = \frac{1}{d_{ji}}, \quad d_{ij} = d_{ik} \cdot d_{kj}, \quad (\forall i, j, k \in J), \quad (6)$$

$$d_{ii} = 1 \text{ and } \sum_{i=1}^n d_{ij} = \frac{\sum_{i=1}^n w_i}{w_j}.$$

When  $\sum_{i=1}^n w_i = 1$ ,

$$w_j = \frac{1}{\sum_{i=1}^n d_{ij}}. \quad (7)$$

If the estimation of  $d_{ij}$  is inaccurate, the equal sign in the above formulas should be approximate. Use the ordinary least squares method to find  $w$ . The instant solution is

$$\min \left\{ \sum_{i=1}^n \sum_{j=1}^n (d_{ij}w_j - w_i)^2 \right\}. \quad (8)$$

Subject to  $\sum_{i=1}^n w_i = 1$  and  $w_i > 0 (i = 1, 2, \dots, n)$ .

Using the Lagrange method to solve the constrained scalar optimization problem, the Lagrange function is

$$L = \sum_{i=1}^n \sum_{j=1}^n (d_{ij}w_j - w_i)^2 + 2\lambda \left( \sum_i w_i - 1 \right). \quad (9)$$

$L$  finds the partial derivative of  $w_l (l = 1, 2, \dots, n)$  and sets it to 0 to obtain  $n$  algebraic equations:

$$\sum_{i=1}^n (d_{il}w_l - w_i)d_{il} - \sum_{j=1}^n (d_{lj}w_j - w_l) + \lambda = 0. \quad (10)$$

From the  $n+1$  equations combined by equation (10) and  $\sum_{i=1}^n w_i = 1$ , where there are  $n+1$  variables in  $X_1, X_2, \dots, X_n$  and  $\lambda$ , we can get  $W = [w_1, w_2, \dots, w_n]$ . Then, the weighted normalized matrix  $X$  can be obtained, the elements of which are

$$X_{ij} = W_j D_{ij}. \quad (11)$$

**3.3. Dynamically Updating the Search Path Algorithm.** TOPSIS is an efficient and advanced MCDM methodology, which was first introduced by Hwang and Yoon to obtain the finest choice based on the compromise solution principle [27]. The acceptable solution can be seen as preferring the answer with the shortest route from the favorable ultimate limit and the longest route from the unfavorable ultimate limit [28]. The Technique for Order Preference by Similarity to Ideal Solution is used to determine the positive ideal solutions (PISs) and negative ideal solutions (NISs). The relative closeness of each solution to the ideal solution is calculated, and a static search scheme is given according to the relative closeness size [29, 30]. The PIS is the virtual best scheme where every attribute value is optimal; on the contrary, the NIS is the virtual worst scheme where each attribute value is the worst. Then, we can compare the distance between each scheme and the positive and negative ideal solutions to determine the priority of these schemes. The best scheme is near the PIS and away from NIS, and the worst scheme is inverse. The fault mode represented by the worst scheme has a high priority level, which needs to be prioritized and eliminated in time [31, 32]. The PIS and the NIS are defined as

$$S^+ = \left\{ \left( \max_i S_{ij} | j \in J \right) | i = 1, 2, \dots, n \right\}, \quad (12)$$

where  $J$  is the benefit attribute set.

$$S^- = \left\{ \left( \min_i S_{ij} | j \in J' \right) | i = 1, 2, \dots, n \right\}, \quad (13)$$

where  $J'$  is the cost attribute set.

The distance from each solution to the positive ideal solution and the negative ideal solution is

$$L_i^+ = \sqrt{\sum_{j=1}^m (S_{ij} - S_j^+)^2}, \quad i = 1, 2, \dots, n, \tag{14}$$

$$L_i^- = \sqrt{\sum_{j=1}^m (S_{ij} - S_j^-)^2}, \quad i = 1, 2, \dots, n.$$

The relative closeness of each solution to the positive ideal solution is

$$E_i^+ = \frac{L_i^-}{L_i^+ + L_i^-}, \quad 0 \leq E_i^+ \leq 1, \quad i = 1, 2, \dots, n. \tag{15}$$

The priority of static search solutions is as follows: arranged in the order of  $E_i^+$  from largest to smallest, the search plan ranked in the front should be searched first.

The dynamic update of the search path is obtained by fusing dynamic information acquired based on a static search scheme. Determine the dynamic search decision matrix according to the influence matrix of the dynamic information and the static search decision matrix, and then form the weighted normalization matrix. Finally, TOPSIS is used to calculate the dynamic update search path. In the search and investigation process, when dynamic information is affected, the search path must be updated. The flowchart of multiattribute troubleshooting with dynamic information is shown in Figure 4.

### 4. Discussion

Taking a certain type of escalator reversal failure with dynamic information about gearbox vibration and motor vibration as a column, a comparative study of multiattribute decision-making troubleshooting and fusion dynamic information multiattribute decision-making fault troubleshooting is carried out.

*4.1. Escalator Reverse Fault Diagnosis Based on Multiattribute Decision-Making.* The failure probability  $P$ , the search cost  $M$ , and the influence degree  $I$  of the escalator reversal bottom event are taken as decision attributes. First of all, the failure probability is the ratio of the number of failures to the number of all escalators in a certain period of time. Secondly, the search cost includes three parts: the time spent in troubleshooting, the cost of troubleshooting, and the level of maintenance personnel. The scores of each part are scored by elevator maintenance units and experts and then averaged. The value of the search cost is to weight the parts and add them up, a value of 0 to 100. The last attribute to be considered is the influence degree, which is the impact of the event's hazard on the system, the value of 0 to 10. The ranking of these three attributes is shown in Table 3.

The static search decision matrix established according to Table 4 and formula (1) is

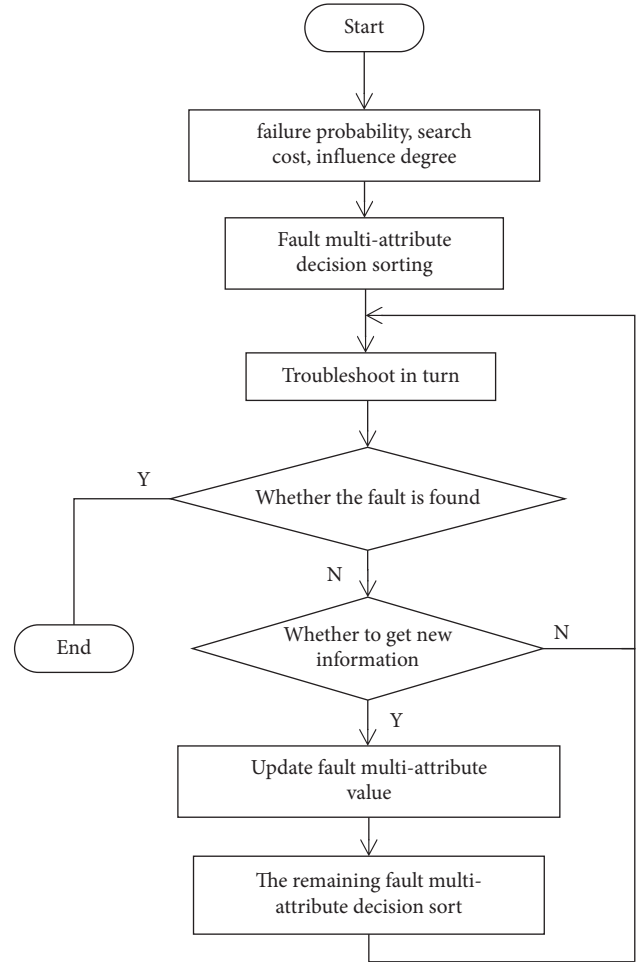


FIGURE 4: Multiattribute fault location fused with dynamic information.

$$A = \begin{matrix} & \begin{matrix} P & M & I \end{matrix} \\ \begin{bmatrix} 0.2 & 5 & 4 \\ 0.1 & 60 & 1 \\ 0.15 & 55 & 1 \\ 0.1 & 10 & 2 \\ 0.3 & 50 & 6 \\ 0.05 & 40 & 1 \\ 0.1 & 20 & 2 \\ 0.15 & 30 & 1 \\ 0.1 & 15 & 2 \\ 0.2 & 35 & 1 \end{bmatrix} & \end{matrix} . \tag{16}$$

Based on the structural characteristics of the escalator and the actual fault diagnosis, the experts give a matrix  $D$  for the pairwise comparison of the probability of failure, search cost, and influence degree.

TABLE 3: Ranking table of failure probability, search cost, and influence degree.

| Event symbol | Bottom event                          | Failure probability $P$ | Search cost $M$ | Influence degree $I$ |
|--------------|---------------------------------------|-------------------------|-----------------|----------------------|
| $X_1$        | Overload                              | 0.2                     | 5               | 4                    |
| $X_2$        | Damaged gearbox bearings              | 0.1                     | 60              | 1                    |
| $X_3$        | Gear meshing failure of gearbox       | 0.15                    | 55              | 1                    |
| $X_4$        | Loose host position                   | 0.1                     | 10              | 2                    |
| $X_5$        | The brake is not working properly     | 0.3                     | 50              | 6                    |
| $X_6$        | Damaged rung chain                    | 0.05                    | 40              | 1                    |
| $X_7$        | Deformation and damage of drive chain | 0.1                     | 20              | 2                    |
| $X_8$        | Reversal protection device fails      | 0.15                    | 30              | 1                    |
| $X_9$        | Insufficient grid voltage             | 0.1                     | 15              | 2                    |
| $X_{10}$     | Motor power is too small              | 0.2                     | 35              | 1                    |

TABLE 4: Gearbox vibration influence matrix  $N_1$ .

| Affected bottom event             | Impact on failure probability | Impact on search costs | Impact on influence degree |
|-----------------------------------|-------------------------------|------------------------|----------------------------|
| Damaged gearbox bearings          | 3                             | 0.9                    | 1                          |
| Gear meshing failure of gearbox   | 2                             | 0.8                    | 1                          |
| The brake is not working properly | 1.2                           | 1                      | 1                          |

$$D = \begin{bmatrix} 1 & 1/2 & 3 \\ 2 & 1 & 5 \\ 1/3 & 1/5 & 1 \end{bmatrix}. \tag{17}$$

The weight matrix is solved by the ordinary least square method, and we get  $W = [0.3015 \ 0.5859 \ 0.1126]$ .

According to formula (14), calculate the relative closeness of each solution  $E_i^+ = [0.81781979 \ 0.08788215 \ 0.18998842 \ 0.65570464 \ 0.43039158 \ 0.2951551 \ 0.5744929 \ 0.49053362 \ 0.6200986 \ 0.4672242 \ ]^T$ . Determine the static search scheme in the order of  $E_i^+$  from largest to smallest, and search and troubleshoot the first scheme first. According to the above calculation, the ranking of the static search sequence can be obtained:  $X_1, X_4, X_9, X_7, X_8, X_{10}, X_5, X_6, X_3, X_2$ .

4.2. Escalator Reversal Fault Diagnosis Based on Multi-attribute Decision-Making with Dynamic Information. When the maintenance worker checked the escalator reversal faults in turn according to the static search scheme, it was found that the escalator did not have an overload fault ( $X_1$ ), and according to the sorting scheme, he goes to the computer room to check whether the host is moving ( $X_4$ ). At this time, it was found that the gearbox vibration and the motor vibration were abnormal. According to the bottom events affected by the dynamic information in Figure 3, two dynamic information impact matrices  $N_1$  and  $N_2$  are constructed. The vibration influence matrix of the gearbox is shown in Table 4, and the motor vibration influence matrix is shown in Table 5.

Before determining the dynamic multiattribute decision matrix  $C$ , on the basis of the established static multiattribute decision matrix  $A$  and the static search scheme, remove the checked bottom events to form the remaining static multiattribute matrix  $A'$ .

$$A' = \begin{matrix} & P & M & I \\ \begin{bmatrix} 0.1 & 10 & 2 \\ 0.1 & 15 & 2 \\ 0.1 & 20 & 2 \\ 0.15 & 30 & 1 \\ 0.2 & 35 & 1 \\ 0.3 & 50 & 6 \\ 0.05 & 40 & 1 \\ 0.15 & 55 & 1 \\ 0.1 & 60 & 1 \end{bmatrix} & & & \end{matrix}. \tag{18}$$

The dynamic multiattribute decision matrix  $C$  is obtained by the dot product of the remaining static multiattribute matrix  $A'$ , the block matrix  $N_1$ , and the block matrix  $N_2$ .

$$C = A' \bullet N_1 \bullet N_2 = \begin{matrix} & \begin{bmatrix} 0.1 & 10 & 2 \\ 0.1 & 15 & 2 \\ 0.1 & 20 & 2 \\ 0.15 & 30 & 1 \\ 0.5 & 31.5 & 1 \\ 0.648 & 50 & 6 \\ 0.05 & 40 & 1 \\ 0.45 & 39.6 & 1 \\ 0.45 & 43.2 & 1 \end{bmatrix} & & \end{matrix}. \tag{19}$$

According to formula (14), the relative closeness  $E_i^+ = [0.58264259 \ 0.54647906 \ 0.49801184 \ 0.37603026 \ 0.52195369 \ 0.44488445 \ 0.18551129 \ 0.39504794 \ 0.35804312]^T$ . Determine the search scheme in the order of  $E_i^+$  from largest to smallest, and search and troubleshoot the first scheme first. According to



TABLE 5: Motor vibration influence matrix  $N_2$ .

| Affected bottom event             | Impact on failure probability | Impact on search costs | Impact on influence degree |
|-----------------------------------|-------------------------------|------------------------|----------------------------|
| Damaged gearbox bearings          | 1.5                           | 0.8                    | 1                          |
| Gear meshing failure of gearbox   | 1.5                           | 0.9                    | 1                          |
| The brake is not working properly | 1.8                           | 1                      | 1                          |
| Motor power is too small          | 2.5                           | 0.9                    | 1                          |

the above calculation, the ranking of the search sequence can be dynamically updated:  $X_4, X_9, X_{10}, X_7, X_5, X_3, X_8, X_2, X_6$ .

Follow the dynamic update search scheme to perform troubleshooting in turn. During this process, no dynamic information is encountered. Therefore, follow the updated order to perform troubleshooting. Finally, the fault is searched and the motor power is too small ( $X_{10}$ ). The fault location is better than the static search scheme, which improves the efficiency of fault diagnosis.

## 5. Conclusion

Based on the escalator reversal fault tree, this paper comprehensively considers the failure probability, search cost, and influence degree of the bottom event to construct a static decision matrix, then integrates the dynamic information impact matrix to establish a dynamic decision matrix and normalize the matrix with weights, and finally uses TOPSIS to troubleshoot the reversal accident and give the optimal troubleshooting sequence. Compared with the method of solving the importance of the fault bottom event and the method of multiattribute decision-making, this method takes into account the dynamic information that appears in the troubleshooting, which can provide a dynamic search path for the fault, improve the efficiency of the troubleshooting, and save the troubleshooting time. But, this method cannot effectively solve the problem of troubleshooting where the minimum cut set is not a single event, which shows its limitations. In the future troubleshooting study, we will solve the problem that the fault tree has complex logic gates and apply the solution to other special equipment troubleshooting work.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that there are no conflicts of interest.

## Acknowledgments

This work was supported by the National Key Research and Development Program of China (No. 2019YFF0302203).

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