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A Comprehensive Evaluation Method of Machining Center Components' Importance Based on Combined Variable Weight

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Abstract: The fault transitivity of machining center components causes their fault propagation indexes to demonstrate dynamic time variability, which affects their importance. The method proposed in this study overcomes the biases of existing methods of evaluating the importance of system components, as they are mostly based on single indexes; the fault propagation probability and fault propagation risk are selected to perform a comprehensive evaluation. This study first establishes a network hierarchical structure model for machining center components, and the degree of influence of fault propagation among the components is calculated. On this basis, the improved adjacent spreading paths (ASP) algorithm is used to calculate the fault propagation index of each component; from the two perspectives of fault propagation probability and fault propagation risk, an evaluation mechanism involving the combined variable weight is used to comprehensively evaluate components' importance. Taking a certain type of machining center as an example, through a comparison with ranking results from other node importance methods, it is verified that the proposed method can more effectively distinguish the differences in the importance of each component, thus illustrating the effectiveness and practical value of this method.

Keywords: machining center; fault propagation probability; fault propagation risk; combined variable weight; importance evaluation

MSC: 60E05; 05C20; 93-08

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1. Introduction

As the foundation and one of the most widely used types of equipment in the equipment manufacturing industry, with the development of artificial intelligence and system automation, the structure of machining center systems has gradually become complex, and the components have become more diverse [1]. The complex coupling relationships between components cause fault propagation to occur frequently, which increases investments in fault diagnosis and equipment maintenance [2–4]. Therefore, the comprehensive evaluation of the importance of machining center components at different moments allows the timely and accurate identification of the key components of a system, which is conducive to real-time maintenance and the management of equipment for enterprises, thus reducing the occurrence of cascade failures, improving the service life of the machining center, increasing the utilization and service life of manufacturing equipment, and laying the foundation for the development of predictive maintenance technology.

Research on node importance evaluations has mainly been focused on complex networks, and a variety of related techniques and methods for finding key nodes that affect the structure and function of the network have been proposed, which is the focus in the field of network science [5–9]. The characteristics of a network are extended to hardware systems. By abstracting a hardware system into a topological network, the complexity and statistical characteristics of the system can be described and analyzed, and an algorithm can be designed to identify the key nodes quickly and accurately. Since the ranking of node importance is based on different network models, many node-ranking methods have been derived, and they can be divided into three categories:

(1) Methods of node ranking based on complex network topology characteristics. These methods [10] use a network's characteristics to identify its key nodes, including the connections of a node itself and its connections with adjacent nodes, as well as degree centrality, semi-local centrality, eigenvector centrality, etc. Bonacich, P. [11] proposed "degree centrality" in 1972, arguing that the influence of a node on the whole network depends on the number of nodes with which it is connected. Chen et al. [12] proposed a method for ranking node importance based on "semi-local centrality" by using semi-local information to sort nodes. Martin et al. [13] improved the eigenvector centrality method by proposing a non-retrospective centrality method. This method was relatively simple and easy to understand, but it was only suitable for regular and less complex networks; it was not suitable for problems with high computational complexity, and the results were not accurate enough.

(2) Methods of key network node identification based on node operations. These methods [14] measure the importance of a node according to its impact on the whole network after processing the nodes, such as by shrinking nodes, deleting nodes, inserting nodes, etc. Berberler, Z. N. et al. [15] conducted a node importance analysis in wheel-related networks by using a method of evaluating node importance through node contraction based on network agglomeration in communication networks. Obeidat, A. et al. [16] presented a novel adaptive and dynamic network routing algorithm based on a regenerating genetic algorithm (RGA) with the analysis of network delays, the deletion of links or nodes from the network, and the assessment of the network volume (with numerous routes). Choi, W. Y. [17] proposed a node insertion algorithm for the real-time implementation of a connectivity-based multi-polling mechanism in the MAC protocol for Wi-Fi sensor networks. Although this type of method can be used to evaluate node importance in reverse, it may cause the disconnection of the network after its operation, and the measurement method does not consider the particularities of network topologies, resulting in inaccurate evaluation results.

(3) Methods of node importance evaluation based on iterative optimization algorithms. In an iterative calculation process, such methods [18] judge the importance of nodes according to the scoring values of their neighbors and themselves to ensure that the scoring values can converge quickly, such as in the PageRank algorithm, LeaderRank algorithm, HIT algorithm, etc. Liu, C. et al. proposed a novel algorithm for evaluating node contributions based on TOPSIS and PageRank [19], and Jiang, S. et al. defined an improved gravity centrality for identifying key nodes in multi-layer networks based on multi-PageRank centrality [20]. Jiang, S. et al. [21] used an improved weighted LeaderRank algorithm to measure the importance of components and obtain the sequence of critical components. Vinodha, R. et al. [22] recommended a hypertext induced topic search (HITS) based point of interest (POI) recommendation calculation that could take into account the effects of social connections when recommending POIs to individual users. This type of method takes the number of nodes connected to a node and the importance of adjacent nodes when evaluating the importance of a node into account, and this has a wide range of applications. However, most algorithms are not universal; the convergence speeds of various iterative algorithms are different and the evaluation indexes are singular, which is not conducive to their application and popularization.

In this study, based on a hierarchical structure model of a network of machining center components, a comprehensive method of evaluating component importance using the combined variable weight evaluation mechanism is proposed. Compared with the existing methods, the fault propagation impact degree model based on the characteristics of complex network topology established in this paper can demonstrate the relationship of fault propagation among system components more clearly. Moreover, previous studies have not considered the differences of each component at a different hierarchy, which will inevitably lead to deviation in the fault propagation impact results. Therefore, in this paper, it is more reasonable to evaluate the degree of fault propagation impact between components based on a complex network and an interpretive structure model (ISM). The structural characteristics of the model and fault mechanism of the machining center is considered synthetically, two key indexes of importance are proposed from the perspective of fault propagation, and the problem of bias in the evaluation of a single index is corrected. The fuzzy and dynamic problems in the comprehensive evaluation are solved by using the mechanism of combined variable weights, which makes the evaluation results more realistic and provides them with high use value.

2. Comprehensive Evaluation of the Importance of Machining Center Components Based on the Combined Variable Weight

Firstly, according to the mechanical structure and failure information of machining center components, a hierarchical network structure model based on a complex network and an ISM method was established, the characteristic parameters of the network structure of the components were calculated, and the degree of influence of fault propagation among the components was determined from the perspective of the components themselves and the levels of the associated components. Secondly, considering the correlation with failure time, the Johnson method was applied to correct the rankings of the fault data, and a failure probability model for the whole machine and each component was established. Considering the correlations between failure modes, the analytic hierarchy process (ANP) was used to calculate the degree of influence of the failure mode, and the failure risk of each component was calculated according to its failure mode frequency and failure rate. Integrating the degree of influence of fault propagation among the component units, the fault propagation probability and fault propagation risk of each component were calculated by using an improved ASP algorithm. Finally, from the two perspectives of fault propagation probability and fault propagation risk, the mechanism of the combined variable weight was used to comprehensively evaluate the importance of the components. The specific process of the comprehensive evaluation of the importance of machining center components is shown in Figure 1.

2.1. Construction of the Model of the Degree of Influence of Fault Propagation

The choice of the fault propagation path is influenced by the structural characteristics of the fault propagation model and the reliability level of the nodes in the network [23]. In combination with the historical fault information of the machining center, the correlation of the fault was analyzed, and the machining center was taken as a complex system. According to its structural characteristics and functional modules, the model of the influence of fault propagation was constructed based on the ISM of a complex network and an analysis of the fault mechanism.

2.1.1. Calculation of the Feature Parameters of the Topology Based on the Complex Network

The network model of a machining center is a simple abstract expression of the fault propagation relationships of the components of the machining center system through abstract concepts such as nodes and connecting edges in the network. Each node in the network shows an inequality due to the different physical locations. Therefore, it is possible to reflect the differences in the influence of each node on fault propagation by evaluating the network nodes' characteristic parameters [24]. Combined with the structural characteristics of the machining center and the relevant problems studied, the network topological characteristic parameters selected in this study were the node efficiency and edge betweenness.

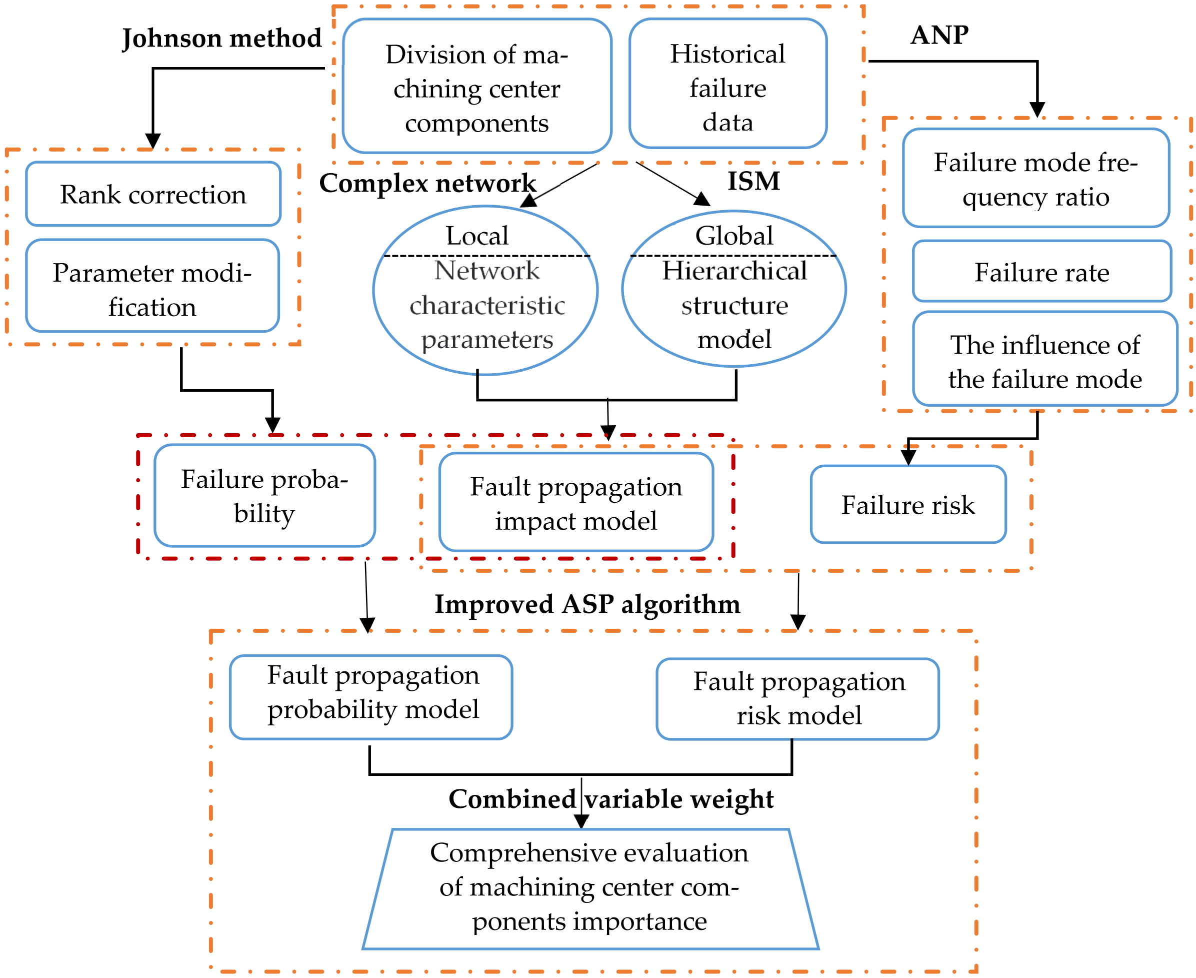

Figure 1. Flowchart of the comprehensive evaluation of the importance of the machining center.

Node efficiency is a metric that indicates the topological properties of a network. The efficiency of a node indicates its average degree of correlation with other nodes. The larger the efficiency value is, the greater the centrality of the node in the network will be. The calculation formula for the efficiency of machining center components I_i is as follows:

$$I_i = \frac{1}{N} \sum_{j=1, i \neq j}^{N} \frac{1}{d_{ij}}, \tag{1}$$

where d_{ij} is the distance between components i and j, and N is the number of machining center components.

Edge betweenness is a dynamic feature indicator of edges in a network diagram. The larger the edge betweenness is, the greater the load of the edge will be, the stronger the contact control effect of the edge on other components will be, the more likely it is to lead to the rapid propagation of faults. The calculation formula for the edge betweenness $L(v_i \to v_j)$ is as follows:

$$L(v_i \to v_j) = \sum_{\substack{v_i, v_j, v_e, v_f \\ (e,f) \neq (i,j)}} \frac{\kappa_{ef} E(v_i, v_j)}{\kappa_{ef}}, \tag{2}$$

where k_{ef} is the number of paths between any components e and f, and $k_{ef} E(v_i, v_j)$ is the number of edges $v(i,j)$ passing by the paths between any components e and f.

2.1.2. Calculation of the Network Hierarchical Weights Based on the ISM Method

The ISM method [25] hierarchically divides all of the elements affecting a system, identifies the interrelationships between the different elements, and forms a relationship matrix and hierarchical structure diagram. The network-level weight is an important index that reflects the differences in component importance between different hierarchies from a quantitative perspective. In this study, the ISM method was used to classify the hierarchy, and the network hierarchical weight of the component to be evaluated was comprehensively evaluated by using the network hierarchy in which the component itself was located and the network hierarchies in which other components connected to the component were located.

The formula for calculating the network hierarchical weight of a component is presented below:

$$H_i = \frac{1/i'}{\sum\limits_{i'=1}^{n} (1/i')}, \tag{3}$$

where H_i represents the network hierarchical weight of component i to be evaluated, and i' represents the network hierarchy in which component i is located.

T_i is used to indicate the degree of influence of the network hierarchical weights of component i to be evaluated; the calculation formula is shown in Equation (4).

$$T_i = Q\sum_k H_{k\to i} D_{k\to i} + O\sum_j H_{i\to j} D_{i\to j}, \tag{4}$$

where Q and O are, respectively, the in-degree node coefficient and out-degree node coefficient, and $Q + O = 1$. Because the importance of system components is considered from the perspective of fault propagation in this study, this means that the influence of a component's failure on other components is the main consideration. Therefore, the out-degree node of the component is more important than the in-degree node, so $O > Q$, and the weight values of the two indicators can be calculated with the method of weight determination. In this study, the analytic hierarchy process was chosen to calculate $Q = 0.25$ and $O = 0.75$. $H_{k\to i}$ denotes the network-level weights at which all in-degree nodes associated with component i are located; $H_{i\to j}$ denotes the network-level weights at which all out-degree nodes associated with component i are located; $D_{k\to i}$ denotes the number of in-degree nodes associated with component i; $D_{i\to j}$ denotes the number of out-degree nodes associated with component i.

2.1.3. Construction of the Model of the Degree of Influence of Fault Propagation

The contribution matrix of the influence of fault propagation represents the matrix form of the contribution values of all nodes in the network to the fault influences of other neighboring nodes [26]. It reflects the communication control effect between neighboring nodes in the network. That is, the stronger the communication control effect between interconnected nodes, the more likely it is to lead to a rapid propagation of faults. Combined with the edge betweenness that was calculated above, the contribution matrix of the components' influence on fault propagation H_C is defined as follows:

$$H_C = \begin{bmatrix} r_{ij} & \frac{r_{ij}L(v_1\to v_2)}{\sum L(v_i\to v_j)} & \cdots & \frac{r_{ij}L(v_1\to v_n)}{\sum L(v_i\to v_j)} \\ \frac{r_{ij}L(v_2\to v_1)}{\sum L(v_i\to v_j)} & r_{ij} & \cdots & \frac{r_{ij}L(v_2\to v_n)}{\sum L(v_i\to v_j)} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{r_{ij}L(v_n\to v_1)}{\sum L(v_i\to v_j)} & \frac{r_{ij}L(v_n\to v_2)}{\sum L(v_i\to v_j)} & \cdots & r_{ij} \end{bmatrix}, \tag{5}$$

where r_{ij} is the contribution assignment parameter; $r_{ij} = 1$ if the node i has an influence on the node j, otherwise $r_{ij} = 0$. $\sum L(v_i \to v_j)$ is the sum of all edge betweennesses.

In order to determine the position of a component in the whole network and its degree of influence on other components accurately, based on the contribution matrix of components' influence on fault propagation, a determination matrix of components' influence on fault propagation H_E is defined with the efficiency values of the components themselves and the comprehensive weights of their locations.

$$H_E = \begin{bmatrix} r_{11}T_1\frac{I_1}{\sum I_i} & r_{12}T_1\left(\frac{I_1}{\sum I_i} + \frac{L(v_1 \to v_2)}{\sum L(v_i \to v_j)}\right) & \cdots & r_{1n}T_1\left(\frac{I_1}{\sum I_i} + \frac{L(v_1 \to v_n)}{\sum L(v_i \to v_j)}\right) \\ r_{21}T_2\left(\frac{I_2}{\sum I_i} + \frac{L(v_2 \to v_1)}{\sum L(v_i \to v_j)}\right) & r_{22}T_2\frac{I_2}{\sum I_i} & \cdots & r_{2n}T_2\left(\frac{I_2}{\sum I_i} + \frac{L(v_2 \to v_n)}{\sum L(v_i \to v_j)}\right) \\ \vdots & \vdots & \cdots & \vdots \\ r_{n1}T_n\left(\frac{I_n}{\sum I_i} + \frac{L(v_n \to v_1)}{\sum L(v_i \to v_j)}\right) & r_{n2}T_n\left(\frac{I_n}{\sum I_i} + \frac{L(v_n \to v_2)}{\sum L(v_i \to v_j)}\right) & \cdots & r_{nn}T_n\frac{I_n}{\sum I_i} \end{bmatrix}, \tag{6}$$

where $\sum I_i$ is the sum of all component efficiencies.

2.2. Calculation of the Fault Propagation Index Based on an Improved ASP Algorithm

Considering the influence of fault propagation among machining center components, fault propagation probability and fault propagation risk were selected as important parameters for evaluating the influences of components in this study, and a specific process of solving this problem was introduced.

2.2.1. Fault Probability Modeling Based on Time Correlation

The traditional method of fault probability modeling for a machining center and its components does not consider the correlation with the failure time, which leads to some deviation in the model [27]. In order to obtain relatively accurate results, this study establishes a fault probability model of a machining center and its components based on time correlation. First of all, the hypothetical distribution is identified according to data on the operating failure intervals of the component units, and then the least-square method is used to estimate the parameters based on the correction of the rank of the fault data by using Johnson's method. When the number of samples is small, the estimated parameters should undergo an unbiased correction. Finally, a test of the hypothesis was carried out on the obtained probability model, and the fault probability functions of the whole machine and the components were obtained after passing the test. The specific solution process is shown in Figure 2.

2.2.2. Fault Risk Assessment Based on the ANP Method

The fault risk of a machining center component refers to the risk caused by a fault in the component itself, and the calculation formula is as follows:

$$RI_i(t) = \sum_{j=1}^{n} \alpha_{ij}(t)\lambda_i(t)\beta_{ij}, \tag{7}$$

where $RI_i(t)$ represents the fault risk value of component i at time t, n is the number of types of fault modes of component i, $\alpha_{ij}(t)$ represents the ratio of fault mode frequencies of the component unit i at time t due to failure mode j, $\lambda_i(t)$ is the fault rate of component unit i at time t, and β_{ij} represents the impact of the first failure mode j of component unit i.

In order to obtain the fault risk value of a machining center component, it is necessary to calculate its ratio of fault mode frequencies, fault rate, and degree of fault mode influence. The solutions for these three metrics will be highlighted below:

(1) Calculation of the fault mode frequency ratio

The fault modes and causes are analyzed for each component in the machining center, the kinds of fault modes that may occur in the parts or components are found, the fault mechanisms are identified or inferred, the impacts are studied, and then the fault mode frequency ratio of the machining center is obtained.

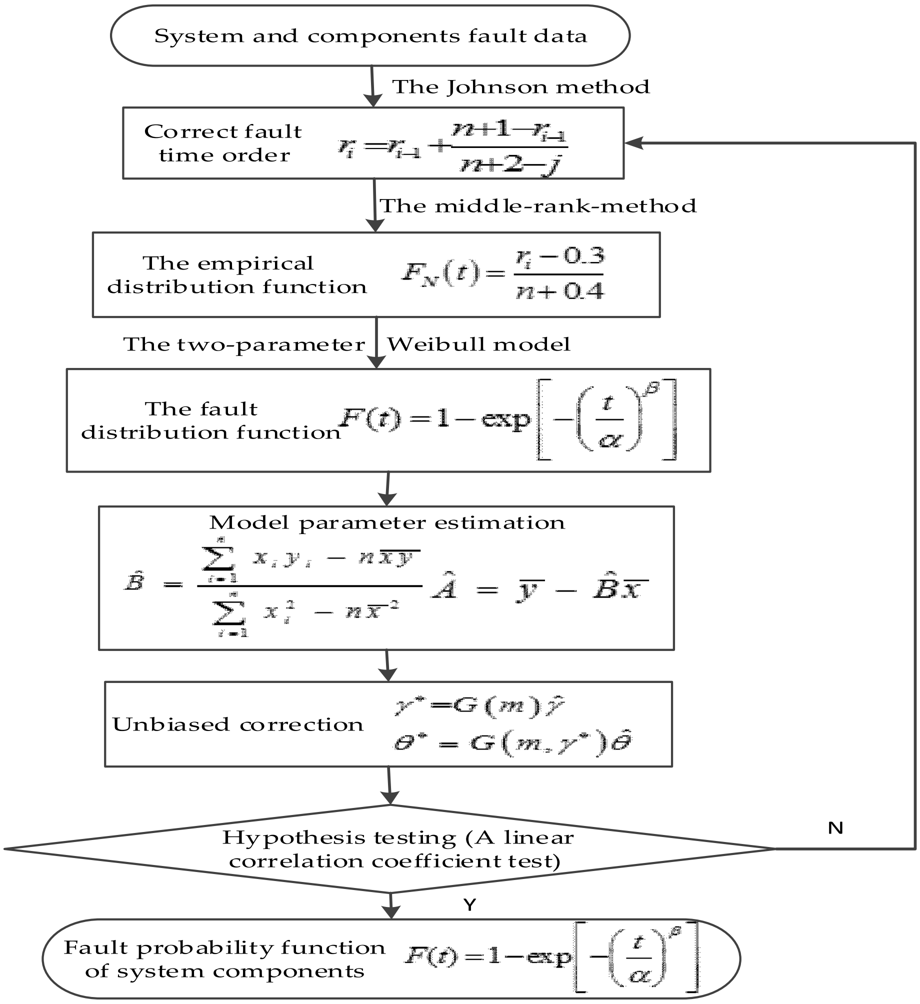

Figure 2. Flowchart of fault probability modeling for machining center components.

(2) Calculation of the fault rate

Since there is a relationship between the failure rate function and the failure probability function, the failure rate function of machining center components at any time can be obtained.

$$F(t) = 1 - \exp\left(-\int_0^t \lambda(t)dt\right). \tag{8}$$

Therefore, the calculation formula of the fault rate function of each component of the machining center is as follows:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\alpha^\beta} t^{\beta-1}. \tag{9}$$

(3) Calculation of the degree of influence of a fault mode

By analyzing the fault modes of each component of the machining center, it can be found that the fault modes of different components may be the same or different; the same fault mode may have different impacts on different components, and there are certain correlations and differences among the fault modes. Therefore, the ANP method [28] is introduced to calculate the impact of the fault mode of each component. The steps of the calculation are shown in Figure 3.

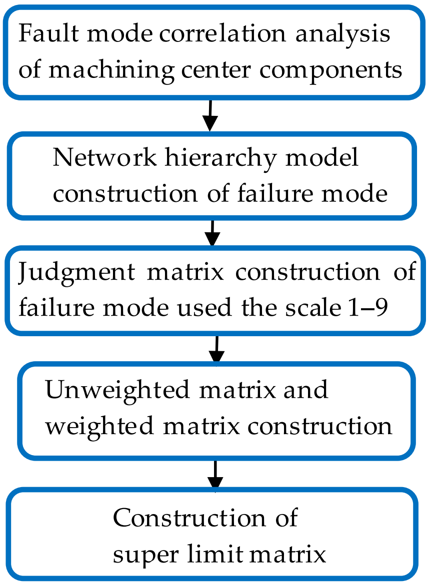

Figure 3. Flowchart of the assessment of fault modes' impacts on machining center components.

2.2.3. Evaluation of Fault Propagation Indexes Based on the Improved ASP Algorithm

In the actual fault propagation process, the fault information of a machining center component depends on its fault indicators and the impacts of upstream component faults. Therefore, in order to examine the fault propagation among components, fault probability and fault risk are combined with the determination matrix of fault propagation effect in a machining center in this study. It is known that a fault in a system component may cause faults in other components that are associated with it. The fault probability and fault risk of a component and the influences of faults among components are combined to represent the fault propagation probability and fault propagation risk among these components.

$$P\left(v_i, v_j\right)(t) = F_i(t) H_E\left(v_i, v_j\right), \quad (10)$$

$$RP\left(v_i, v_j\right)(t) = RI_i(t) H_E\left(v_i, v_j\right), \quad (11)$$

where $P\left(v_i, v_j\right)(t)$ is the probability of component i propagating a fault to component j at time t; $\mathrm{R}P\left(v_i, v_j\right)(t)$ is the risk of component i propagating a fault to component j at time t.

The different locations of machining center components cause the influences of propagation to be different. According to the principle of third-order influence [29], faults in machining center components will not only propagate to the adjacent components, but they may also have an impact on the components within the third order. Therefore, the fault propagation probability and the fault propagation risk are introduced into the improved ASP algorithm. By combining this with the structural model of fault propagation, the values of the probability of fault propagation and the risk of fault propagation can be calculated for each component. The specific calculation process and calculation formula are shown below:

$$fp^U{}_{ASP\_i}(t) = fp^U{}_{ASP\_ij}(t) + fp^U{}_{ASP\_in}(t) + fp^U{}_{ASP\_iq}(t), \quad (12)$$

where $fp^U{}_{ASP\_i}(t)$ is the Uth fault propagation index of component i at time t. In this study, we choose to use the fault propagation probability and the fault propagation risk as the fault propagation indexes, so $U = 1, 2$. $fp^U{}_{ASP\_ij}(t)$ is the success rate of component i in propagating fault information to the one-step-neighboring component j at time t; $fp^U{}_{ASP\_in}(t)$ is the success rate of component i in propagating fault information to the two-step neighboring component n at time t; $fp^U{}_{ASP\_iq}(t)$ is the success rate of the component i in propagating fault information to the three-step neighboring component q at time t.

The solution process for the fault propagation probability is similar to that for the fault propagation risk. Taking the solving process of fault propagation probability as an example, for the one-step-neighboring components of component i, $fp^1{}_{ASP\_ij}(t)$ is the success rate of component i in propagating fault probability to the one-step-neighboring component j at time t, and calculation formula is shown below:

$$fp^1{}_{ASP\_ij}(t) = \sum_{j \in A(i)} P(v_i, v_j)(t) + \sum_{m \in A(i)} P(v_i, v_m)(t)P(v_m, v_j)(t) + \sum_{r \in A(i)} P(v_i, v_m)(t)P(v_m, v_r)(t)P(v_r, v_j)(t), \quad (13)$$

where $A(i)$ is the set of all one-step-neighboring components of component i; $P(v_i, v_j)(t)$ is the fault propagation probability between components i and j at time t; $P(v_i, v_m)(t)P(v_m, v_j)(t)$ is the propagation probability at time t, where component i passes the fault to component j through component m; $P(v_i, v_m)(t)P(v_m, v_r)(t)P(v_r, v_j)(t)$ is the propagation probability for component i passing the fault to component j through components m and r.

For the two-step-neighboring components of component n,

$$fp^1{}_{ASP\_in}(t) = \sum_{m \in A(i), n \in A^2(i)} P(v_i, v_m)(t)P(v_m, v_n)(t) + \sum_{l \in A^2(i)} P(v_i, v_m)(t)P(v_m, v_l)(t)P(v_l, v_n)(t), \quad (14)$$

where $A^2(i)$ is the set of all two-step-neighboring components of component i; $P(v_i, v_m)(t)P(v_m, v_n)(t)$ is the propagation rate of component i passing the fault to component n through component m; $P(v_i, v_m)(t)P(v_m, v_l)(t)P(v_l, v_n)(t)$ is the propagation rate of component i passing the fault to component n through components m and l.

For the three-step-neighboring components of component q,

$$fp^1{}_{ASP\_iq}(t) = \sum_{m \in A(i), n \in A^2(i), q \in A^3(i)} P(v_i, v_m)(t)P(v_m, v_n)(t)P(v_n, v_q)(t), \quad (15)$$

where $A^3(i)$ is the set of all three-step-neighboring components of component i; $P(v_i, v_m)(t)P(v_m, v_n)(t)P(v_n, v_q)(t)$ is the propagation rate of component i passing the fault to component q through components m and n.

2.3. Mechanism for Evaluating Component Importance Based on the Combined Variable Weight

In order to avoid deviations in the evaluation of the importance of a single index, a comprehensive evaluation of the importance of machining center components was carried out from the two perspectives of fault propagation probability and fault propagation risk. In comprehensive evaluations, subjective weighting and objective weighting methods have advantages and disadvantages. Subjective weighting can better reflect the importance of an index itself, while objective weighting mainly reflects information on the laws of index data. Therefore, a combined weighting method is reasonable and effective.

In this study, the Delphi method was used to calculate the subjective weight, and the entropy weighting method was used to solve the objective weight. Both methods are relatively mature, and they will not be described again here. The subjective weight values for the m evaluation indicators were determined as $\omega_s = (\omega_1, \omega_2, \cdots, \omega_u)$, and the objective weight values were determined as $\omega_o = (\omega'_1, \omega'_2, \cdots, \omega'_u)$. It was assumed that the two weighting methods were of the same importance. After passing a consistency test, equal weights were combined to assign weights, and the constant weight coefficient of each index was obtained. The calculation formula is as follows:

$$\omega_c^U = \left(\omega_c^1, \omega_c^2, \cdots, \omega_c^u\right) = \frac{1}{2}(\omega_1 + \omega'_1, \omega_2 + \omega'_2, \cdots, \omega_u + \omega'_u). \quad (16)$$

Although the combined weighting method can be used to effectively evaluate the comprehensive importance of machining center components on both the subjective and objective levels, the weight coefficients obtained with this method cannot change with the change in the component fault propagation index value. When the value of a certain index is high, but the weight proportion is relatively small, the evaluation result still cannot accurately reflect the actual situation. Therefore, a variable weight formula is introduced to modify the combined variable weights in real time.

$$\omega_b^u\left(fp_{ASP\_i}^u(t)\right) = \frac{\omega_c^u}{fp_{ASP\_i}^u(t)_j\sum_{j=1}^{u}\left(\omega_c^u/fp_{ASP\_i}^u(t)\right)}, \tag{17}$$

where $\omega_b^u\left(fp_{ASP\_i}^u(t)\right)$ is the variable weighting coefficient of the uth fault propagation index value of component i at time t; ω_c^u is the constant weighting factor of the uth index, and U is the number of indexes.

The formula for calculating the comprehensive importance of machining center components $CI_i(t)$ is as follows:

$$CI_i(t) = \omega_b^1\left(fp_{ASP\_i}^1(t)\right)fp_{ASP\_i}^1(t) + \omega_b^2\left(fp_{ASP\_i}^2(t)\right)fp_{ASP\_i}^2(t). \tag{18}$$

The calculated results are sorted according to their size to determine the importance ranking of each component. Once a component in the top ranking fails, it has a great impact on other components; attention should be paid to this to provide a strong guarantee for the subsequent development of fault tracing and maintenance strategies.

3. Case Application

We took MDH series horizontal machining centers, which are mainly used to process rotary parts, as research objects. According to the working principle and the functional mapping relationships of the structures of such machining centers, they were divided into 11 components, namely, the spindle system (S), tool magazine (M), feed system (J), CNC system (NC), hydraulic system (D), electrical system (V), pneumatic system (G), lubrication system (L), cooling system (W), auxiliary system (K), and workbench (T). A total of 108 on-site fault details from 36 machining centers of this series were collected and analyzed over the course of one year. After a fault analysis, we determined whether each component fault was an independent fault or a related fault. If it was a related fault, the previous component that caused the component fault was determined through fault analysis, and a network diagram expressing the fault propagation relationship among the components of the machining centers was established as shown in Figure 4.

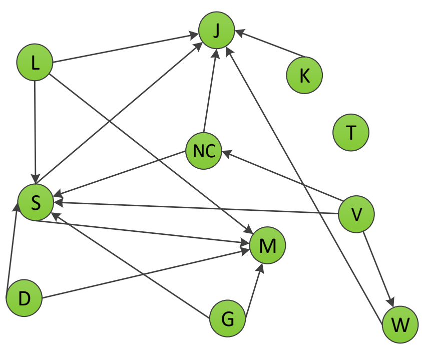

Figure 4. Diagram of the failure propagation network of machining center components. Note: Component T did not have any associations with other components, so subsequent operations did not consider this component.

In order to facilitate quantitative analysis, the failure propagation network diagram of machining center components in Figure 4 is represented by a matrix based on binary logic relationships. Matrix A is an n-order square matrix consisting of 0 and 1 as elements, if the failure of component i directly affects component j, $a_{ij} = 1$, else $a_{ij} = 0$. A corresponding direct correlation matrix was established for the fault correlations of the remaining 10 components:

$$A = \begin{array}{c} \\ S \\ M \\ J \\ NC \\ D \\ V \\ G \\ L \\ W \\ K \end{array} \begin{array}{c} \begin{array}{cccccccccc} S & M & J & NC & D & V & G & L & W & K \end{array} \\ \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{array}. \quad (19)$$

In order to facilitate path analysis and hierarchical processing, it is necessary to convert matrix A into matrix M. The Warshall algorithm was applied to transform the adjacency matrix A into a reachable matrix M:

$$M = \begin{array}{c} \\ S \\ M \\ J \\ NC \\ D \\ V \\ G \\ L \\ W \\ K \end{array} \begin{array}{c} \begin{array}{cccccccccc} S & M & J & NC & D & V & G & L & W & K \end{array} \\ \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \end{array}. \quad (20)$$

According to Formulas (1)–(4), the network topology parameters for each component of the machining center were calculated, as were the weight values of the influence of the network hierarchy, as shown in Tables 1 and 2.

Table 1. Statistics on the edge betweenness of machining center components.

$v(i,j)$	$L(v_i \to v_j)$	$v(i,j)$	$L(v_i \to v_j)$	$v(i,j)$	$L(v_i \to v_j)$	$v(i,j)$	$L(v_i \to v_j)$
S→M	3.5	V→W	0.25	V→S	0.75	D→S	1.5
S→J	3.5	G→S	1.5	V→NC	1.5	D→M	0
NC→S	2.75	G→M	0	W→J	0.25	L→M	0
NC→J	0.25	L→S	1	K→J	0	L→J	0

Table 2. Statistics on the efficiency and network hierarchical weight of components.

Code	I_i	T_i	Code	I_i	T_i
S	0.20	0.220183	V	0.40	0.128440
M	0	0.122324	G	0.20	0.064220
J	0	0.116208	L	0.30	0.091743
NC	0.25	0.100917	W	0.10	0.064220
D	0.20	0.064220	K	0.10	0.027523

The data were brought into Equations (5) and (6) to solve for the contribution matrix and the decision matrix for the influence of fault propagation.

$$H_c = \begin{bmatrix} 0 & 0.208955 & 0.208955 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.164179 & 0 & 0.014925 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.089552 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.044776 & 0 & 0 & 0.089552 & 0 & 0 & 0 & 0 & 0.014925 & 0 \\ 0.089552 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.059701 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.014925 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{21}$$

$$H_E = \begin{bmatrix} 0.025164 & 0.076057 & 0.076057 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.030102 & 0 & 0.015469 & 0.014417 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.011520 & 0.006459 & 0 & 0 & 0.007339 & 0 & 0 & 0 & 0 & 0 \\ 0.030897 & 0 & 0 & 0.035959 & 0 & 0.029358 & 0 & 0 & 0.027523 & 0 \\ 0.011520 & 0.006459 & 0 & 0 & 0 & 0 & 0.007339 & 0 & 0 & 0 \\ 0.018661 & 0.013841 & 0.013841 & 0 & 0 & 0 & 0 & 0.015727 & 0 & 0 \\ 0 & 0 & 0.004738 & 0 & 0 & 0 & 0 & 0 & 0.003670 & 0 \\ 0 & 0 & 0.001384 & 0 & 0 & 0 & 0 & 0 & 0 & 0.001573 \end{bmatrix}. \tag{22}$$

The model obtained for the degree of influence of fault propagation is shown in Figure 5.

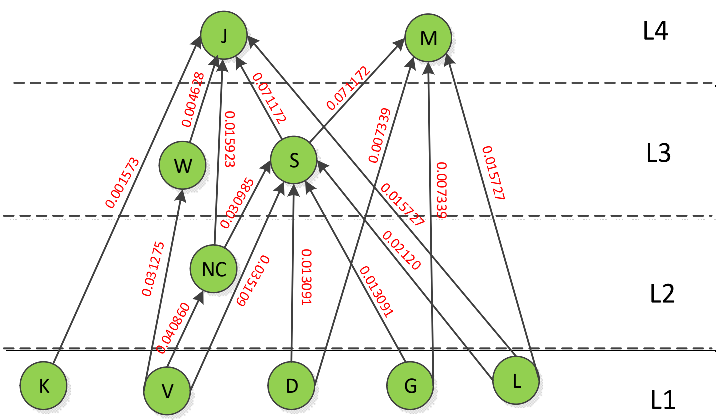

Figure 5. Degree of influence of failure propagation between machining center components.

The collected field failure data of the machining center were statistically analyzed to obtain the frequency diagram of the failure components of the machining centers as shown in Figure 6. The component element code and fault time of the machining centers are shown in Table 3.

Based on the modeling of the failure probability of machining center components shown in Figure 2 and the fault time of machining center components shown in Table 3, the failure probability function was determined for each component of the machining center and the statistical results are shown in Table 4.

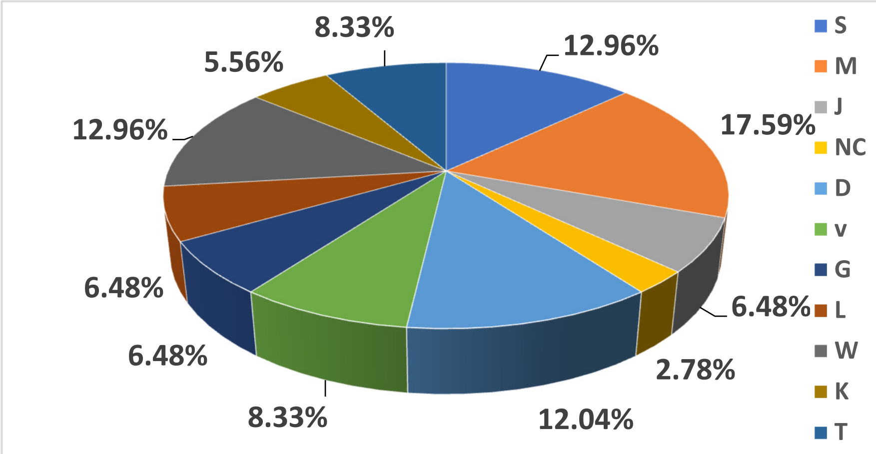

Figure 6. Frequency diagram of failure parts of the machining centers.

Table 3. System component code and failure time statistics table.

Element Code	Fault Time (h)						
D	9.53	19.07	57.21	182.15	200.22	266.96	362.30
	400.44	429.04	896.22	1849.64	2507.51		
S	19.07	28.60	104.88	152.55	209.75	247.89	371.84
	533.92	600.66	610.19	696.00	743.67	781.81	1029.70
M	104.88	143.01	190.68	276.49	343.23	400.44	514.85
	524.38	638.79	657.86	676.93	962.96	1010.63	1239.45
	1411.07	1420.60	2059.40	2269.40	3422.79		
J	123.95	305.10	419.51	448.11	486.25	648.33	686.47
NC	219.29	486.25	1353.87				
V	57.21	85.81	95.34	266.96	362.30	724.60	791.34
	1296.66	1821.04					
G	9.53	128.71	181.15	247.89	419.51	1191.78	1372.93
L	57.21	114.41	705.53	1277.59	1649.42	1792.44	1925.92
W	38.14	104.88	114.41	133.48	162.08	266.96	276.49
	476.71	543.45	791.34	943.89	1058.30		
K	114.41	448.11	505.32	514.85	982.03	1859.18	
T	47.67	57.21	152.55	228.82	247.89	400.44	429.04
	1678.03	2088.00					

Table 4. The fault probability functions of system components in the machining center.

Code	Fault Probability	Code	Fault Probability
S	$F_S(t) = 1 - \exp\left[-\left(\frac{t}{7832.7}\right)^{0.6414}\right]$	V	$F_V(t) = 1 - \exp\left[-\left(\frac{t}{7935.7}\right)^{0.7712}\right]$
M	$F_M(t) = 1 - \exp\left[-\left(\frac{t}{2458.1}\right)^{1.3117}\right]$	G	$F_G(t) = 1 - \exp\left[-\left(\frac{t}{27503.4}\right)^{0.5243}\right]$
J	$F_J(t) = 1 - \exp\left[-\left(\frac{t}{2606.4}\right)^{1.2949}\right]$	L	$F_L(t) = 1 - \exp\left[-\left(\frac{t}{8161.5}\right)^{0.7910}\right]$
NC	$F_{NC}(t) = 1 - \exp\left[-\left(\frac{t}{7912.4}\right)^{0.5422}\right]$	W	$F_W(t) = 1 - \exp\left[-\left(\frac{t}{4145.7}\right)^{0.9101}\right]$
D	$F_D(t) = 1 - \exp\left[-\left(\frac{t}{8905.1}\right)^{0.6556}\right]$	K	$F_K(t) = 1 - \exp\left[-\left(\frac{t}{5960.8}\right)^{0.9314}\right]$

The ANP method was applied to solve the influence of the failure mode of each component, and according to the process of assessing the impacts of the failure modes of machining center components shown in Figure 3. The results are summarized in Table 5.

Table 5. Statistics on the influence of the failure modes of machining center components.

Code	Mode	$\alpha_{ij}(t)$	β_{ij}	Code	Mode	$\alpha_{ij}(t)$	β_{ij}
S	0101	0.142857	0.07288	V	0103	0.777778	0.28312
	0202	0.142857	0.02272		0108	0.111111	0.20851
	0203	0.071429	0.01607		0409	0.111111	0.50837
	0410	0.214286	0.45179	G	0103	0.142857	0.30574
	0503	0.071429	0.10450		0301	0.714286	0.20805
	0603	0.071429	0.03647		0404	0.142857	0.48621
	0605	0.142857	0.03157	L	0101	0.142857	0.41025
	0606	0.071429	0.17020		0103	0.571429	0.35443
	0609	0.071429	0.09381		0301	0.285714	0.23532
M	0101	0.315789	0.23085	W	0101	0.285714	0.21368
	0201	0.052632	0.02538		0103	0.071429	0.27109
	0202	0.105263	0.04964		0301	0.214286	0.08792
	0205	0.105263	0.21235		0302	0.142857	0.06050
	0501	0.052632	0.08795		0601	0.071429	0.14315
	0503	0.157895	0.12623		0610	0.071429	0.18355
	0506	0.052632	0.07042		0805	0.142857	0.04010
	0605	0.105263	0.04268	K	0101	0.500000	0.50000
	0616	0.052632	0.13226		0501	0.500000	0.50000
J	0101	0.285714	0.20472	D	0101	0.153846	0.28747
	0103	0.142857	0.28898		0103	0.153846	0.17769
	0502	0.142857	0.13812		0104	0.076923	0.36466
	0603	0.142857	0.12362		0105	0.076923	0.03580
	0607	0.142857	0.20530		0301	0.461538	0.03171
	0803	0.142857	0.03925		0607	0.076923	0.10267
NC	0102	0.666667	0.50000				
	0501	0.333333	0.50000				

The relationship between the failure probability function and the failure rate function in Formulas (8) and (9) was used to solve the probability of failure and the failure rate of each component of the machining center at any time, and the failure rate value was brought into formula (7) to obtain the failure risk value of each component. In this study, 500 h and 2000 h were used as examples, and the results obtained are shown in Table 6.

Table 6. Statistics on the failure probability and failure risk of machining center components.

Code	F_i(500)	F_i(2000)	$RI_i(500) \times 10^{-4}$	$RI_i(2000) \times 10^{-4}$
S	0.157533	0.340882	0.031861	0.193801
M	0.160189	0.509823	0.048254	0.743361
J	0.107180	0.563434	0.052543	0.790793
NC	0.174242	0.377515	0.121305	0.643066
D	0.155207	0.298884	0.024791	0.153796
V	0.172201	0.292742	0.054853	0.399435
G	0.115266	0.223705	0.033573	0.173614
L	0.182400	0.312183	0.057049	0.426991
W	0.135228	0.406857	0.036364	0.321034
K	0.147985	0.296352	0.092606	0.842048

By using the improved ASP algorithm, the data in Table 6 were brought into Formulas (12)–(15) to find the value of the fault propagation index of each component, and at the same time, through the solution process of combining the variable weights, the variable weight for each fault propagation index of each component at different moments was obtained. Again, 500 h and 2000 h were used as examples, and the results after normalization are shown in Tables 7 and 8.

Table 7. Statistics of the failure propagation probability and combined variable weight.

Code	$fp^1{}_{ASP\_i}(500)$	$\omega_b^1(fp^1_{ASP\_i}(500))$	$fp^1{}_{ASP\_i}(2000)$	$\omega_b^1(fp^1_{ASP\_i}(2000))$
S	0.342023	0.411216	0.168593	0.375533
M	0	0.520614	0	0.520614
J	0	0.520614	0	0.520614
NC	0.126512	0.703178	0.217187	0.635815
D	0.049059	0.352237	0.026581	0.345499
V	0.284106	0.521667	0.385911	0.586170
G	0.037379	0.491478	0.071993	0.432069
L	0.147825	0.517005	0.110365	0.586613
W	0.009546	0.481495	0.005994	0.454933
K	0.003550	0.683642	0.013376	0.750343

Table 8. Statistics of the failure propagation risk and combined variable weight.

Code	$fp^2{}_{ASP\_i}(500)$	$\omega_b^2(fp^2_{ASP\_i}(500))$	$fp^2{}_{ASP\_i}(2000)$	$\omega_b^2(fp^2_{ASP\_i}(2000))$
S	0.219957	0.588784	0.208086	0.624467
M	0	0.479386	0	0.479386
J	0	0.479386	0	0.479386
NC	0.275976	0.296822	0.227537	0.364185
D	0.024564	0.647763	0.023701	0.654501
V	0.285307	0.478333	0.323120	0.413830
G	0.033266	0.508522	0.026755	0.567931
L	0.145703	0.482995	0.169606	0.413387
W	0.008163	0.518505	0.011208	0.545067
K	0.007064	0.316358	0.009989	0.249657

The results in Tables 7 and 8 were brought into Equation (18) to evaluate the comprehensive importance of each component at 500 h and 200 h and then rank them accordingly. The results are shown in Table 9.

Table 9. Comprehensive importance values and the ranking of machining center components.

Code	$CI_i(500)$	Rank	$CI_i(2000)$	Rank
S	0.270152	2	0.271060	2
NC	0.170876	3	0.172858	3
D	0.033192	6	0.032358	5
V	0.284681	1	0.278933	1
G	0.035287	5	0.031696	6
L	0.146800	4	0.146255	4
W	0.008829	7	0.012743	7
K	0.004662	8	0.005202	8
M	0	9	0	9
J	0	10	0	10

The ranking results in Table 4 showed that at 500 h and 2000 h, the electrical system (V) was ranked first in terms of importance, followed by the spindle system (S), which should be taken into account in fault diagnosis and health maintenance.

Since the values of the fault propagation indexes for each component of the machining center dynamically changed at different moments, the fault propagation probability and the fault propagation risk of the system components could be determined at any time by using Formulas (7)–(15). Then, the comprehensive importance values at any time could be determined when different time values were inputted into Formulas (16)–(18). So, the trends of the comprehensive importance of each component are shown in Figure 7.

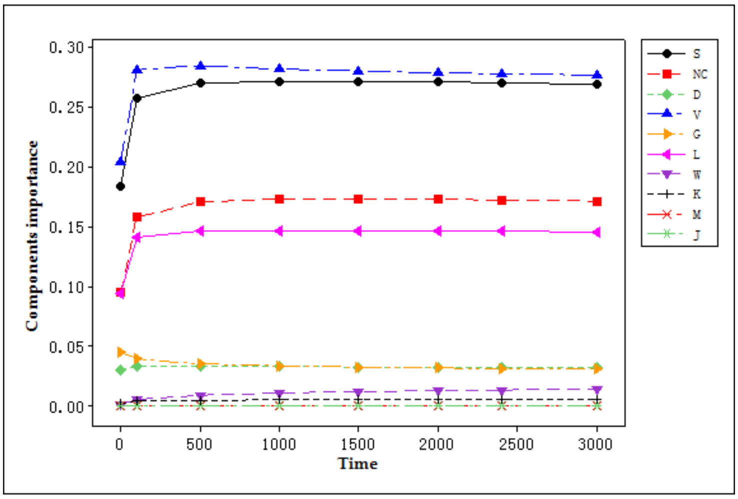

Figure 7. Diagram of the comprehensive importance of machining center components.

4. Comparative Analysis

The method proposed in this study was compared with a method of evaluating the importance of machining center components based on the PageRank algorithm [30]. Referring to the process of calculating the PR value of web nodes with the PageRank algorithm, the system components were regarded as web nodes, and the fault propagation relationships between components were used to replace link relationships between web pages. Unlike in the calculation of web nodes, the degree of influence of component faults was calculated based on the out-degree. According to the above case, based on fault information, MATLAB programming was used to achieve the iterative calculation of the importance of each component of the machining center. The calculation results were compared with the comprehensive importance values at 2000 h, and the statistical values are shown in the following table.

From the ranking results in Table 10, it can be seen that the components with the highest importance values according to the two methods were the electrical system (V) and the spindle system (S), and the ranking results were basically consistent, which verified the correctness and reliability of the method in this study. However, the importance values of the CNC system (NC) and hydraulic system (D) according to the PageRank algorithm were equal, and the values of the cooling system (W) and auxiliary system (K) were also equal, so the differences in the importance of the components were not reflected well. The calculation results verified that the method proposed in this study was more effective than the PageRank method in distinguishing the differences in the importance of each component.

Table 10. Comparison of the importance values of machining center components.

Code	CI_i	Rank	Pr_i	Rank
S	0.229485	2	0.105196	2
M	0	9	0.091134	9
J	0	10	0.091134	10
NC	0.163382	3	0.097193	4
D	0.045910	6	0.097193	5
V	0.423358	1	0.129771	1
G	0.079020	5	0.097193	6
L	0.122867	4	0.103252	3
W	0.009634	8	0.093847	8
K	0.012700	7	0.093847	7

In this study, the comprehensive importance values obtained with the proposed method were compared with the importance evaluation results obtained with a single index. Taking the results calculated for 500 h as an example, Figure 8 was drawn.

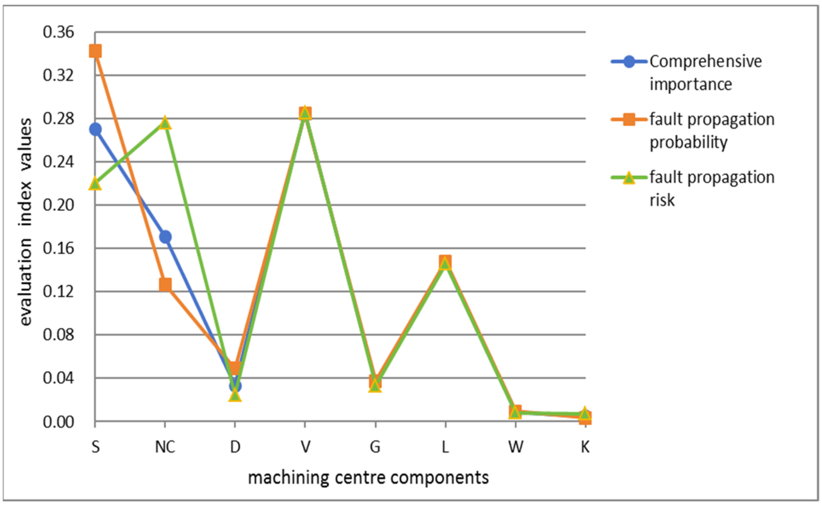

Figure 8. Comparison of the evaluation indicator values of machining center components.

The graph shows that the component with the highest fault propagation probability at 500 h was the spindle system (S), and the spindle system (S) was considered to be the most important component in the importance evaluation using the fault propagation probability. In the graph, we can also see that the component with the highest fault propagation risk was the electrical system (V) at 500 h, and the electrical system (V) was considered to be the most important component in the importance evaluation using the fault propagation risk. The results of evaluating the importance with a single indicator were highly biased. Therefore, the method in this study effectively avoided the one-sidedness and bias of evaluating node importance from a single perspective, and it improved the accuracy of the importance evaluation.

5. Conclusions

In this study, a method of comprehensively assessing importance was proposed, and the main results and conclusions were as follows:

(1) A model of the degree of influence of fault propagation was constructed. The calculation results showed that the spindle system had the greatest fault propagation influence on the tool magazine and feed system components, followed by that of the electrical system on the CNC system, thus clarifying the position of each component in the propagation structure and the influences on other components. The topological structure-based fault propagation impact model of the machining center laid the structural foundation for a comprehensive evaluation of importance.

(2) A comprehensive importance evaluation method was established. The comprehensive importance value of the machining center at 2000 h was obtained, and the ranking result was V > S > NC > L > G > D > K > W > M = J. The component with the highest comprehensive importance was the electrical system, followed by the spindle system, and the two components with the lowest importance were the tool magazine and feed system. The tool magazine and feed system were at the end of the propagation in the fault propagation structure model and did not propagate faults to other components; hence, they had the least importance. The evaluation results for the importance are significant for the identification and maintenance of critical components.

(3) A solution method for combined variable weights was established. The weight value of the first evaluation index of the spindle system at 500 h was 0.411216, the weight value of the first evaluation index of the CNC system was 0.703178, and the weight

value of the spindle system at 2000 h was 0.375533. Through calculation, it was found that the weight values of the importance indexes of different components in different machining centers changed at different times. This effectively solved the problem of a constant weight coefficient not accurately reflecting the variations in index values, and this is conducive to accurately evaluating the importance of each index at different times.

This study presented a comprehensive method of evaluating the importance of components of a machining center, and this can be used to identify the key components of a center at any time. On this basis, fault warning and preventive maintenance can be conducted in a targeted manner, thereby reducing the economic losses and safety hazards of manufacturing enterprises due to equipment faults. However, there are some shortcomings of this study that need to be improved. For example, the mathematical model for evaluating the importance of machining center components was established only from the point of view of fault propagation, without considering other reliability factors of the components themselves, causing certain limitations. Future studies will involve importance evaluations from multiple angles and with multiple indicators, as well as the establishment of a more comprehensive importance evaluation mechanism.

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