Hindawi
Complexity
Volume 2019, Article ID 3237254, 11 pages
https://doi.org/10.1155/2019/3237254

Research Article

Risk Analysis of Coupling Fault Propagation Based on Meta-Action for Computerized Numerical Control (CNC) Machine Tool

Yifan Chen,[1] **Genbao Zhang**,[1,2] **and Yan Ran**[1]

[1] *College of Mechanical Engineering and State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400044, China*
[2] *College of Mechanical Engineering, Chongqing University of Arts and Sciences, Chongqing 402160, China*

Correspondence should be addressed to Yan Ran; ranyan@cqu.edu.cn

Received 7 March 2019; Accepted 4 July 2019; Published 25 July 2019

Academic Editor: Dan Selişteanu

A comprehensive fault analysis of CNC machine tool is conducive to improving its reliability. Due to the highly complex structure of CNC machine tool, there are different degrees of coupling relationship between faults. However, the traditional fault analysis methods (FMEA, FTA, etc.) for CNC machine tool do not solve this problem perfectly. Therefore, we propose a coupling fault propagation model based on meta-action. First, in order to simplify the structural complexity of CNC machine tool, the "Function-Motion-Action (FMA)" decomposition structure is used to decompose the product function into simple meta-action, and the numerical matrix is used to quantify the coupling relationship between the meta-actions. Then, based on the fault transfer characteristics of meta-action, the fault propagation model is established, and the global risk effect (GRE) is combined to realize the comprehensive evaluation of the risk criticality of meta-actions. Finally, the rationality and validity of the method are verified by the case analysis of the automatic pallet changer (APC) of computerized numerical control (CNC) machining center.

1. Introduction

Coupling fault analysis of CNC machine tool plays an important role in the early design phase of product. In recent decades, in order to meet people's needs, the product has been continuously improved in terms of function, which means that the function of product will become more powerful and the structure becomes more complicated than before. Meanwhile, there is an indeterminate coupling relationship between subsystems and subsystems, or between units and units, thus forming a complex coupling propagation process, which brings certain difficulties to product design engineers. Commonly used reliability analysis methods include FMEA [1–3], FTA [4, 5], Bayesian [6, 7], Markov [8, 9], and Petri net [10, 11]. These methods mainly judge fault behavior based on single index such as failure rate, risk value, and fault propagation probability, and they analyze each event as an independent event. However, in actual engineering problems, most of the occurrence of a fault has an interaction [12]. Therefore, the traditional methods cannot identify the interaction between faults, so that correct corrective measures cannot be taken, resulting in repeated faults in the use of products, thus reducing the reliability of product.

For CNC machine tool, coupling refers to a phenomenon in which two or more forms of motion interact with each other [13]. The research of coupling analysis originated from project management and planning in 1950 [14]. Coupling analysis includes direct coupling and indirect coupling. Simply put, direct coupling means that there is no contact between two motion units; the interaction between two motion units is directly affected by each other, for example, worm gear and worm. On the contrary, indirect coupling is the contact of one or more units between two units, thus forming a coupling propagation network diagram.

CNC machine tool is one of the typical products of complex electromechanical products. In fact, the fault of CNC machine tool is caused by the joint influence of multiple components. Most of the faults in engineering have interactions, even intricate. Furthermore, coupling fault strength is also inconsistent, since the coupling strength directly reflects the priority of fault, which brings trouble to the engineering designer in the decision-making of product design improvement. At present, the coupling fault propagation analysis of complex electromechanical product has become a focus of academic research [15–17]. For example, Lin et al. [18] established a fault propagation model based on the historical data of high-speed train bogie system and analyzed all possible fault propagation paths and the probability of occurrence of each path after propagating each fault node. Zhang et al. [19] established the fault propagation directed graph model of CNC lathe subsystem and calculated the fault propagation strength of each subsystem and determined the fault source of CNC lathe. Long et al. [20] established the fault transfer directed graph of system by combining the relevant fault mechanism analysis with graph theory and evaluated the fault correlation degree of each subsystem of machining center by PageRank algorithm. Li et al. [21] established a fault propagation model based on small world clustering characteristics and analyzed the fault propagation path and key nodes of complex electromechanical system. The above literature has contributed to the analysis of coupling fault propagation of complex electromechanical product. However, the current research still has the following problems: (1) they all only conduct propagation analysis based on the coupling relationship between subsystems and subsystems or components and components; for the current complex electromechanical products coupling fault propagation analysis, it does not combine its own structural characteristics; (2) it is incomplete to locate the fault simply by using the probability index of fault propagation; the reason is that the actual engineering is not just to judge the risk priority from the perspective of probability, such as severity and detection; and (3) due to the complex coupling relationship between faults, it is necessary to further reasonably express and quantify the coupling relationship and degree between faults.

However, the design structure matrix (DSM) was developed by Steward in 1981 [22]. It is an n-order square matrix and is used to display the interaction of elements in the matrix, which is conducive to visual analysis of complex product. Therefore, it is an effective tool to deal with the coupling problem of engineering [23, 24]. Later, in order to quantify the coupling relationship in the matrix, some scholars effectively solved the coupling degree between the coupling factors [25–27]. In order to solve the complexity in the coupling analysis, matrix can be widely used by virtue of its own expression and operation [28, 29].

To solve the above problems, based on the DSM and expert knowledge, this paper proposes a risk analysis framework for CNC machine tool coupling fault propagation based on meta-action. Firstly, the author's lab team put forward a concept of meta-action, which divides product function into motion units by structural decomposition of "Function-Motion-Action (FMA)". Then, the coupling fault relationship of meta-actions is identified and propagated to determine the specific weak motion unit. Secondly, in the process of fault propagation, AHP is a good choice to rationally quantify uncertainty. Finally, in order to solve the risk priority evaluation of traditional single index, on the basis of Fang [27], the fault characteristics of CNC machine tool are fully combined, and the global risk effect (GRE) is introduced on the basis of the criticality after propagation, so as to achieve a more comprehensive risk priority analysis.

The main contents of this paper are organized as follows. In Section 2, the relevant research methods are introduced, such as meta-action, fault network model, and fault propagation model. In Section 3, the flow chart of the proposed method is introduced. In Section 4, a case analysis of the automatic pallet changer (APC) of CNC machining center (THM6380) is given, and the numerical results are compared with the traditional method. Section 5 gives the conclusion.

2. Related Work

2.1. Meta-Action. The most basic form of motion that conveys power in a mechanical product is called meta-action [30, 31].

2.1.1. FMA Structural Decomposition. A commonly used method of mechanical product decomposition is based on functional decomposition (FBS) [32, 33]. The FBS method is for the part at the last node of the decomposition. Although the analysis of the system structure is simplified, the decomposition process has subjective randomness. In addition, since the single part itself is static, most of faults are caused by motion and power transfer between the parts when performing fault analysis on the machine system. Hence, the traditional static attributes of parts are not conducive to the dynamic analysis of fault.

However, The FMA structural decomposition method is a function-to-motion mapping and a motion-to-action mapping based on the transmission path of the machining motion. The advantage of this method is that the motion units of product can be reasonably divided based on the controllable and analyzable minimum granularity of "meta-action", so that the fault analysis of product can be carried out quickly and accurately. The decomposition process is shown in Figure 1.

2.1.2. Meta-Action Fault Characteristics. To some extent, due to the intricate structure of the CNC machine tool, the indirect influence caused by a meta-action fault forms a complex fault effect network diagram. It is worth noting that if there are multiple effects on the same meta-action, then the failure probability of this meta-action is even greater. In general, meta-action fault generally have the following basic characteristics:

(1) Hierarchy: as can be seen from the decomposition tree of Figure 1, the meta-action is the lowest component units, and each layer is composed of meta-actions, so the occurrence of fault will inevitably affect the normal operation of other layers.

(2) Propagation: since the meta-action can only run by relying on the interaction of each unit, as long as a certain meta-action fails, the contact units must be affected, which may be multilayer, as shown in Figure 2.

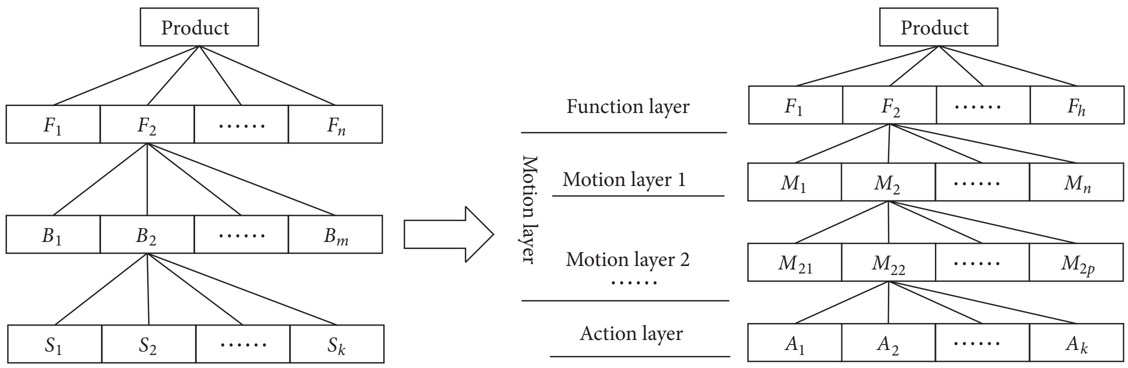

Figure 1: Converting FBS to FMA structural decomposition.

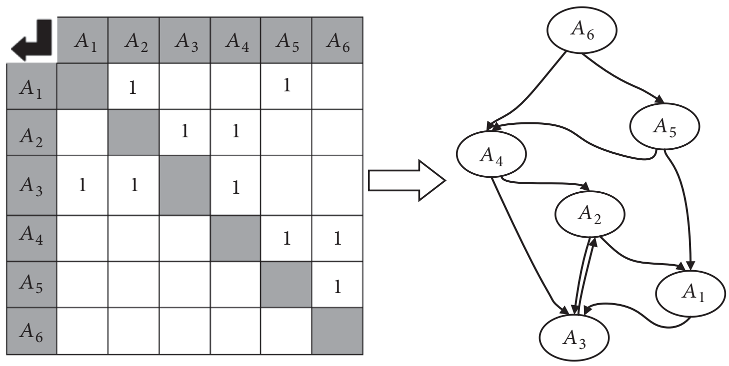

Figure 2: Coupling fault identification between meta-actions.

Table 1: Qualitative classification of meta-action failure mode level [34].

Level	S	O	D
1	No	Almost never	Almost certain
2	Very slight	Remote	Very high
3	Slight	Very slight	High
4	Minor	Slight	Moderate high
5	Moderate	Low	Medium
6	Significant	Medium	Low
7	Major	Moderately high	Slight
8	Extreme	High	Very slight
9	Serious	Very high	Remote
10	Hazardous	Almost certain	Almost impossible

(3) Uncertainty: the coupling strength between each meta-action cannot be completely quantified, and it needs to be judged by expert experience.

Qualitative classification of failure mode grades for meta-action is shown in Table 1.

2.1.3. Global Risk Effect (GRE). Generally, the traditional fault propagation methods for CNC machine tool are mostly based on the occurrence probability of fault and locate the cause of fault according to the occurrence probability of fault. However, only considering the occurrence probability of fault cannot fully reflect the comprehensive information of fault. For example, the occurrence probability of meta-action A1 fault is larger than that of meta-action A2 fault, but the effect of meta-action A1 fault is much smaller than that of meta-action A2 fault. Obviously, it is unreasonable that meta-action A1 has a higher risk level than meta-action A2. Therefore, combined with the characteristics of CNC machine tool fault diagnosis, the weight factor is added on the basis of the traditional FMEA method and the GRE is proposed. Compared with the traditional FMEA method, the GRE can not only identify the most vulnerable components in the system by analyzing various data of fault, but also consider the effect of three variables on the whole, as shown in formula (1).

$$GRE(A_i) = \sum_{i=1}^{n}\left(\frac{R_{S_i}}{\sum_{i=1}^{n} R_{S_i}}\omega_{S_i} + \frac{R_{O_i}}{\sum_{i=1}^{n} R_{O_i}}\omega_{O_i} + \frac{R_{D_i}}{\sum_{i=1}^{n} R_{D_i}}\omega_{D_i}\right) \quad (i = 1, \cdots, n) \qquad (1)$$

where $\omega_{S_i}, \omega_{O_i}$, and ω_{D_i} are the weights of S, O, and D, respectively, and R_{S_i}, R_{O_i}, and R_{D_i} are S, O, and D scores of the ith meta-action, respectively.

2.2. Meta-Action Fault Network Model

2.2.1. Meta-Action Coupling Fault Identification. Identification is the primary task of coupling fault analysis. The

Table 2: Numerical scale [35].

Indicator A_i is compared with indicator A_j	A_{ij}
Equally important	1
Relatively important	3
Obviously important	5
Strongly important	7
Extremely important	9
Intermediate value between the above two adjacent judgments	2, 4, 6, 8
Factor exchange comparison result	Reciprocals

DSM method proposed by Steward is widely recognized for identifying the coupling relationship between units [36]. The relationship between faults is represented by a binary DSM. When $DSM_{ij} = 1(i, j = 1, \cdots, n; i \neq j)$, it means that there is an interaction between two meta-actions. In the matrix, the rows represent the input of information and the columns represent the output of information. The matrix diagram can be converted into a directed graph, and the direction arrow means the relationship of each meta-action fault, as shown in Figure 2.

2.2.2. Quantification of Fault Intensity. Fault Numeric Matrix (FNM) is a qualitative to quantitative evaluation process. This process is conducive to evaluating and measuring the strength of the connection between faults, so as to provide more detailed fault network information. The Analytic Hierarchy Process (AHP) was proposed by Saaty [37] in 1980. It constructs a judging matrix by comparing the factors in pairs, and assigns the relative importance of the judgment matrix on a scale of 1 to 9. The quantization scale is shown in Table 2. The method can effectively quantify the fault interaction and obtain the correlation matrix. Then, according to the coupling fault of meta-actions, the FNM is divided into column (output) matrices and row (input) matrices, and their eigenvectors are calculated, respectively, so that the numerical effect matrix (NEM) and numerical cause matrix (NCM) are composed of eigenvectors [25]. The FNM is expressed by formula (2).

$$FNM(i, j) = \sqrt{NCM(i, j) \times NEM(i, j)}; \quad \forall (i, j), \ 0 \leq FNM(i, j) \leq 1 \tag{2}$$

In addition to calculating the coupling strength of fault (i.e., the transition probability), there are two parts in the evaluation stage, namely, the spontaneous probability of fault and the effect of fault. Spontaneous probability of fault (S) refers to the probability that a motion unit can fail itself without being affected by other units. As shown in Figure 2, the occurrence of A_6 fault is only related to its own spontaneous probability. However, A_4 fault may come from its own spontaneous probability and the transition probability between A_5 fault and A_6 fault. Fault effect (E) refers to the degree of influence on the system caused by the fault of a certain meta-action, including severity (S), occurrence (O), and detection (D). Their mathematical product is equal to E, as shown in formula (3).

$$E = S \times O \times D \tag{3}$$

where O is the frequency index, S is the severity index, and D is the detection index.

In the E calculation, the score of each parameter is 1 to 10, as shown in Table 1. In general, the higher the E of a meta-action fault, the higher the fault level.

2.3. Fault Propagation Model. In this study, the effect of coupling fault between meta-actions is fully considered. Moreover, the propagation of meta-action in fault network is evaluated. In order to calculate risk propagation in fault network, the following assumptions are given:

(1) If the number of interaction between a meta-action and other meta-actions reaches two or more, it means that it is more susceptible to other causes. Hence, the frequency of fault is cumulative under the condition that the fault is subject to different influences [12].

(2) In the process of analysis, the transition probability in FNM matrix will not change; that is, other fault factors are not considered except the interaction in the fault network diagram.

Matrix representation can not only visualize the coupling relationship, but also deal with multidimensional data problems through matrix operation. As shown in Figure 2, A_6 fault can trigger A_1 fault through three paths, namely, $A_6 \longrightarrow A_5 \longrightarrow A_1$, $A_6 \longrightarrow A_4 \longrightarrow A_2 \longrightarrow A_1$ and $A_6 \longrightarrow A_5 \longrightarrow A_4 \longrightarrow A_2 \longrightarrow A_1$. It can be found that the propagating steps corresponding to these three paths are 2, 3 and 4, respectively. The risk propagation of the initial state probability vector is equal to $B^i \cdot S$ after the propagation in stage i. If only i propagation steps are considered, and the fault probability vector $P(A_i)$ is obtained by combining the assumption of the fault cumulative frequency, as shown in formula (4).

$$P(A_i) = S + \sum_{i=1}^{m} B^i \cdot S = \left(I + \sum_{i=1}^{m} B^i\right) \cdot S = \left(\sum_{i=0}^{m} B^i\right) \cdot S \tag{4}$$

where B denotes the transition probability matrix, S means the spontaneous probability vector of fault, $P(A_i)$ represents the fault probability vector, and I is the identity matrix.

In the infinite propagation steps of fault, it can be defined as

$$P(A_i) = \lim_{m \longrightarrow \infty} \left(\sum_{i=0}^{m} B^i\right) \cdot S \tag{5}$$

Multiply both sides by (I-B)

$$(I - B) \cdot P(A_i) = (I - B) \cdot \left(\sum_{i=0}^{m} B^i\right) \cdot S = \left(I - B^{m+1}\right) \cdot S \tag{6}$$

Usually it satisfies

$$\lim_{m \longrightarrow \infty} B^{m+1} = 0 \tag{7}$$

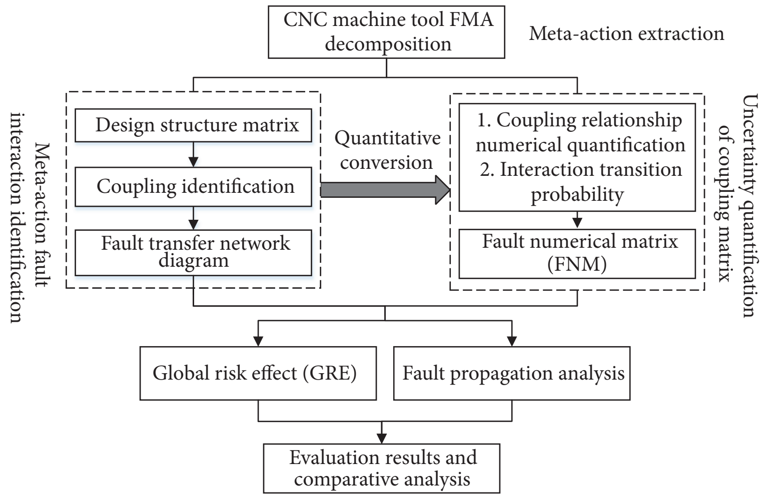

Figure 3: Flow chart of coupled fault propagation analysis of meta-action.

Consequently, the evaluation formula of fault probability is as follows:

$$P\left(A_i\right) = (I - B)^{-1} \cdot S \tag{8}$$

Besides, after calculating the fault probability vector, it is necessary to further evaluate the risk criticality. Considering all the potential consequences of each fault in the fault network diagram, the risk criticality is equal to the sum of the product of fault probability and effect.

$$C\left(A_i\right) = \sum_{j=1}^{n} E\left(A_j\right) \cdot P_{A_i}\left(A_j\right) \tag{9}$$

Subsequently, in order to evaluate the effect of meta-action $A_i(i = 1, 2, \cdots, n)$ fault on other units in the whole fault network diagram, the spontaneous probability of $A_i(i = 1, 2, \cdots, n)$ fault is assigned to 100%, while the initial probability of other meta-actions is assigned to 0%, that is, the initial vector $S = I^i$. Formula (10) gives the evaluation of risk criticality.

$$C\left(A_i\right) = E^T \cdot (I - B)^{-1} \cdot \left(I^i \cdot P\left(A_i\right)\right) \tag{10}$$

where I^i is the ith column in the identity matrix and $C(A_i)$ is the risk criticality vector of meta-action fault

2.4. Meta-Action Comprehensive Risk Criticality (CRC). Since the criticality after fault propagation only expresses the result of a faulty node under the joint influence of multiple other nodes, as can be seen from Section 2.3 of Section 2, according to the actual situation of engineering, the risk effect of each meta-action is different. Hence, the mathematical product of global risk effect $GRE(A_i)$ and criticality after propagation $C(A_i)$ is defined as meta-action comprehensive risk criticality $CRC(A_i)$.

$$CRC\left(A_i\right) = GRE\left(A_i\right) \times C\left(A_i\right) \tag{11}$$

3. A Framework for Risk Analysis of Coupling Fault Propagation Based on Meta-Action

In order to solve the problems in the literature, this paper presents a meta-action-based risk analysis method for coupling fault propagation. According to the form of motion, it can simplify the CNC machine tool to the most basic motion unit (i.e., meta-action). Meanwhile, the interaction of meta-action fault is identified, quantified, propagated, and evaluated. Figure 3 gives an overview of the method. The main differences between the special attributes of each method are shown in Table 3. It can be found that the proposed method makes up for the shortcomings of the traditional method and effectively performs a more accurate risk ranking for CNC machine tool, so as to provide reference for managers in fault management and maintenance.

The proposed method can be divided into the following steps.

Step 1. Since the function of the mechanical product is realized by the relative motion between the components, the product is decomposed into meta-actions in the form of "function-motion-action".

Step 2. The DSM is used to identify the coupling relationship between meta-actions, and the directed graph of fault network is obtained.

Step 3. The AHP is used to transform the DSM into a FNM to quantify the interaction of meta-actions fault.

Step 4. Calculate the global risk effect (GRE) of meta-actions.

Step 5. Establish a mathematical model of fault propagation and calculate the risk criticality of meta-actions fault after propagation.

Step 6. Combine the criticality after propagation with the GRE to realize a comprehensive analysis of the risk priority of meta-actions.

Table 3: Attribute comparison of fault analysis methods.

Method	Structural characteristic analysis	Analysis with propagation	Analysis with hierarchy	Analysis with uncertainty	Comprehensive consideration of analysis indicators
FTA	×	×	√	×	×
FMEA	×	×	√	√	×
Petri net	×	√	√	×	×
The proposed method	√	√	√	√	√

Figure 4: THM6380 machining center.

4. Case Analysis

As shown in Figure 4, it is a THM6380 machining center. It features high speed, high efficiency, and high precision. The advantages in processing are obvious, especially in the fields of automobile, aviation, and ship industry. In order to reduce downtime caused by fault, improve production efficiency and provide guidelines for maintenance decision-making. Therefore, this paper analyzes the coupling fault propagation of its automatic pallet changer (APC) to verify the feasibility and effectiveness of the method.

4.1. FMA Decomposition of APC. The APC is a typical function of the whole machine. The APC is decomposed into 12 meta-actions by FMA, as shown in Figure 5. Each meta-action is the most basic motion unit to ensure the normal operation of the APC. The normal exchange of workpieces depends on the specified motion between the meta-actions.

According to the historical fault data, the failure mode of the meta-actions is obtained, as shown in Table 4. The failure mode can be used as the basis for evaluating the effect of the meta-actions fault. In general, the higher the failure mode level, the more serious the meta-action fault and the wider the fault propagation range.

4.2. Meta-Action Interaction Identification. In order to further analyze the coupling characteristics of the meta-actions of APC, the coupling relationship between the 12 meta-actions is identified by the experience of experienced designers and experts, and the correlation matrix which characterizes the coupling relationship of the meta-actions is constructed. The correlation matrix is transformed into a fault network directed digraph to visualize the propagation paths and steps of meta-actions fault, as shown in Figure 6.

Table 4: Meta-actions and corresponding failure modes.

Code	Failure mode
A_1	No action
A_2	Rising instability
A_3	(1) The exchange noise is large (2) Inappropriate motion
A_4	No action
A_5	Rotary Instability
A_6	Abnormal sound
A_7	Abnormal sound
A_8	(1) the exchange noise is large (2) Inappropriate rotation
A_9	No action
A_{10}	Slow motion
A_{11}	Insufficient contractility
A_{12}	(1) Exchange is not in place (2) jamming

4.3. Uncertainty Quantification of Coupling Matrix. Firstly, a pairwise comparison matrix is established for each row in Figure 6, and the comparison index is the coupling unit of the corresponding row. Then, the eigenvectors corresponding to the maximum eigenvalue are calculated by AHP. Besides, the consistency test is performed for each eigenvector calculation, namely, $CR < 0.1$. Finally, NEM composed of eigenvectors of all rows is obtained. Similarly, NCM can also be calculated. As a result, the FNM is calculated by substituting NEM and NCM into (2), which is represented by matrix B.

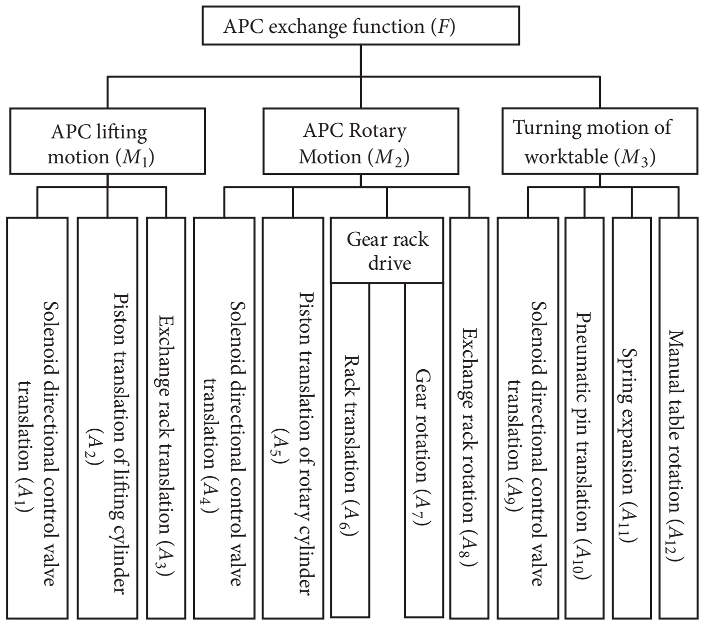

Figure 5: "FMA" decomposition tree for APC.

$$B = \begin{array}{cc} & \begin{array}{cccccccccccc} A_1 & A_2 & A_3 & A_4 & A_5 & A_6 & A_7 & A_8 & A_9 & A_{10} & A_{11} & A_{12} \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \\ A_7 \\ A_8 \\ A_9 \\ A_{10} \\ A_{11} \\ A_{12} \end{array} & \begin{bmatrix} & 0.9354 & & & & & & & & & & \\ & & 0.8018 & & & & & & & & & 0.2777 \\ & 0.2856 & & & & & & 0.2491 & & & & 0.082 \\ & & & & 0.3780 & & & & & & & \\ & & & & & 0.4319 & & 0.691 & & & & 0.1695 \\ & & & & 0.8571 & & 0.1543 & & & & & \\ & & & & & 0.1543 & & 0.280 & & & & \\ & & 0.4330 & & & & 0.4564 & & & & & \\ & & & & & & & & & 0.5 & & \\ & & & & & & & & & & 0.5 & 0.1684 \\ & & & & & & & & & & & \\ & & & & & & & & & & & \end{bmatrix} \end{array} \quad (12)$$

4.4. Calculate Global Risk Effect of Meta-Action. By establishing a pairwise comparison matrix for the indicator [38], the weights of S, O, and D are calculated by AHP, and the consistency test is performed. The results are shown in Table 5.

The fault scores of the meta-actions are obtained by combining historical fault data and expert experience, as shown by formulas (13), (14), and (15).

$$R_{S_i} = [4, 8, 6, 4, 8, 5, 5, 6, 4, 3, 2, 2] \quad (13)$$

$$R_{O_i} = [2, 5, 5, 2, 4, 4, 6, 6, 2, 7, 3, 2] \quad (14)$$

$$R_{D_i} = [3, 7, 4, 3, 7, 5, 5, 4, 3, 4, 2, 3] \quad (15)$$

Substituting formulas (13), (14), and (15) into formula (1), thereby obtaining the global risk effect vector $GRE(A_i)$ of the meta-actions.

$$GRE(A_i) = [0.061, 0.134, 0.096, 0.061, 0.13, 0.092, 0.099, 0.099, 0.061, 0.08, 0.042, 0.046] \quad (16)$$

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}
A_1		1										
A_2			1									1
A_3		1						1				1
A_4					1							
A_5						1		1				1
A_6					1		1					
A_7						1		1				
A_8			1				1					
A_9										1		
A_{10}											1	1
A_{11}										1		
A_{12}												

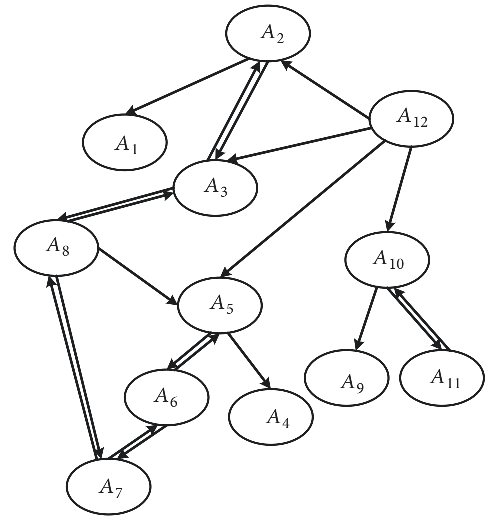

Figure 6: Meta-actions fault network directed graph.

4.5. Meta-Action Fault Propagation Analysis. S is obtained by calculating the fault data. Meanwhile, according to the expert experience and Table 1, the E is obtained.

$$S = [0.083, 0.208, 0.208, 0.083, 0.167, 0.167, 0.250, 0.250, 0.083, 0.292, 0.125, 0.083]^T \tag{17}$$

$$E = [24, 280, 120, 24, 224, 100, 150, 144, 24, 84, 12, 12]^T \tag{18}$$

Here, the score of E represents the potential effect of each meta-action fault. By substituting S and B into formula (8), the probability vector of each meta-action fault can be calculated.

$$P(A_i) = [0.7797, 0.7448, 0.6408, 0.6188, 1.4175, 1.4930, 0.7201, 0.8561, 0.2672, 0.3685, 0.1250.0830]^T \tag{19}$$

Then, the risk criticality after propagation of the meta-actions fault is calculated by formula (10).

$$C(A_i) = [18.713, 452.066, 683.235, 14.851, 928.92, 735.527, 511.567, 908.612, 6.413, 35.376, 7.5, 32.804]^T \tag{20}$$

4.6. Discussion and Comparison. Substituting $GRE(A_i)$ and $C(A_i)$ into formula (11), the comprehensive risk criticality vector $CRC(A_j)$ of each meta-action is calculated.

$$CRC(A_i) = [1.141, 60.577, 65.591, 0.906, 120.760, 67.668, 50.645, 89.953, 0.391, 2.830, 0.315, 1.509]^T \tag{21}$$

Each meta-action is prioritized and compared with the traditional fault analysis results, as shown in Table 6.

Compared with the traditional method, the risk priority ranking of each meta-action after propagation has changed.

Table 5: Weight distribution of S, O, and D.

	S	O	D	ω_i
S	1	3	1	0.444
O	1/3	1	1/2	0.169
D	1	2	1	0.387
Consistency test			$CR = 0.016 < 0.1$	

The reason is that in the fault network of Figure 6, A_2, A_3, A_5, A_6, A_7, A_8, and A_{10} are all used as a coupling node; that is, the coupling nodes will be affected to varying degrees when other meta-actions fail, and this effect depends on the degree of coupling between them. Therefore, their priority ranking is relatively high, and the meta-actions corresponding to these coupling nodes can be regarded as weak links. In addition, A_1, A_4, A_9, A_{11}, and A_{12} have fewer interaction paths in the fault network graph, so their priority ranking is lower. In addition, the ranking of A_2 and A_7, A_9, and A_{11} has changed compared with the method in reference [27], that is, $A_2 > A_7$, $A_9 > A_{11}$. The reason is that the factors of global risk effect (GRE) are fully considered. According to the weights distribution of the three indicators (i.e., S, O, and D) of each fault, the impact of each fault on the overall ranking is comprehensively obtained.

In order to control the fault caused by the coupled fault node, the meta-actions of the more complex coupled nodes should be selected as the key control objects of the fault, namely, A_5, A_8, A_6, and the regular maintenance should be strengthened. That is to say, when they do not fail, the failure frequency of other meta-actions is counted. Then, intercept the same time operation fault data, and the maintenance data before and after control are compared and analyzed, as shown in Figure 7.

As can be seen from Figure 7, the failure frequency of meta-actions has been significantly improved except for A_9, A_{10}, and A_{11} when A_5, A_8, and A_6 are taken as the key control objects of coupling fault. The reason is that the coupling relationship between the three control objects and A_9, A_{10}, A_{11} is very weak, and their failure frequency does not depend on the coupling relationship. On the contrary, as can be seen from Figure 6, the failure of other meta-actions is likely to be caused by their interrelationship. Therefore, it is proved that the risk ranking obtained by this method is reasonable, and the analysis result in Table 6 is beneficial to fault maintenance.

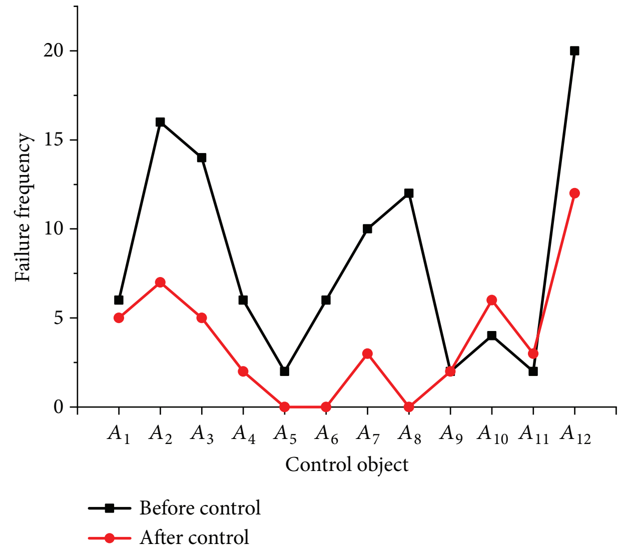

Figure 7: Comparative analysis of failure frequencies before and after critical coupling fault node control.

5. Conclusion and Prospects

For the fault analysis of CNC machine tool, the traditional methods (FTA, FMEA, etc.) cannot measure the fault effectively and accurately. Therefore, this paper proposes a new method based on meta-action for risk analysis of coupling fault propagation of CNC machine tool. Firstly, the AHP is used to quantify the coupling degree of meta-actions, and the coupling degree is expressed by transferring probability, which makes up for the deficiency of traditional fault analysis. Secondly, in order to accurately evaluate the fault propagation result with different propagation steps and paths, a coupling fault propagation model is established. Finally, combined with the GRE and the criticality after propagation, the comprehensive risk ranking of the criticality of meta-actions is realized. The research result shows that the method can reasonably evaluate the risk criticality of meta-action fault under the condition of coupling relationship.

By applying the fault propagation model to the APC of the machining center, we can find some conclusions based on the results of the fault propagation analysis: (1) due to the interaction and propagation of meta-actions fault, the fault level of meta-actions has changed, and the range of change depends on the coupling strength and the number of propagation paths, (2) since the fault propagation is cumulative, this results in different ranking gaps between meta-actions, (3) the GRE makes minor adjustments to certain fault ranking, but it does not affect critical fault ranking. Therefore, according to the criticality analysis result of the meta-actions, it is necessary to strengthen the maintenance and regular replacement of meta-actions with higher criticality to avoid the occurrence of fault.

It is well known that coupling fault is a critical and complex problem in mechanical product, and there are a large number of uncertainties in the coupling relationship. Therefore, the construction of experimental platform is the focus of future research.

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 regarding the publication of this paper.

Table 6: Comparison of meta-action risk analysis results.

Code	Traditional risk criticality analysis $S\times E$	Ranking	Risk criticality after propagation $C(A_i)$ [27]	Ranking	The proposed method $CRC(A_i)$	Ranking
A_1	1.992	8	18.713	9	1.141	9
A_2	58.24	1	452.066	6	60.577	5
A_3	24.96	5	683.235	4	65.591	4
A_4	1.992	8	14.851	10	0.906	10
A_5	37.408	3	928.92	1	120.760	1
A_6	16.7	7	735.527	3	67.668	3
A_7	37.5	2	511.567	5	50.645	6
A_8	36	4	908.612	2	89.953	2
A_9	1.992	8	6.413	12	0.391	11
A_{10}	24.528	6	35.376	7	2.830	7
A_{11}	1.5	9	7.5	11	0.315	12
A_{12}	0.996	10	32.804	8	1.509	8

Acknowledgments

This work was financially supported by the National Natural Science Foundation, China (nos. 51705048; 51835001; 51575070); the National Major Scientific and Technological Special Project for "High-grade CNC and Basic Manufacturing Equipment", China (2018ZX04032-001; 2016ZX04004-005).

References

[1] X. Yu, W. Liang, L. Zhang, G. Reniers, and L. Lu, "Risk assessment of the maintenance process for onshore oil and gas transmission pipelines under uncertainty," *Reliability Engineering and System Safety*, vol. 177, pp. 50–67, 2018.

[2] K. Chang, "Generalized multi-attribute failure mode analysis," *Neurocomputing*, vol. 175, pp. 90–100, 2016.

[3] A. Certa, F. Hopps, R. Inghilleri, and C. M. La Fata, "A dempster-shafer theory-based approach to the failure mode, effects and criticality analysis (FMECA) under epistemic uncertainty: application to the propulsion system of a fishing vessel," *Reliability Engineering & System Safety*, vol. 159, pp. 69–79, 2017.

[4] K.-C. Hyun, S. Min, H. Choi, J. Park, and I. Lee, "Risk analysis using fault-tree analysis (FTA) and analytic hierarchy process (AHP) applicable to shield TBM tunnels," *Tunnelling and Underground Space Technology*, vol. 49, pp. 121–129, 2015.

[5] J. F. W. Peeters, R. J. I. Basten, and T. Tinga, "Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner," *Reliability Engineering & System Safety*, vol. 172, pp. 36–44, 2018.

[6] S. Dindar, S. Kaewunruen, M. An, and J. M. Sussman, "Bayesian Network-based probability analysis of train derailments caused by various extreme weather patterns on railway turnouts," *Safety Science*, vol. 110, pp. 20–30, 2018.

[7] Z. Chiremsel, R. Nait Said, and R. Chiremsel, "Probabilistic fault diagnosis of safety instrumented systems based on fault tree analysis and bayesian network," *Journal of Failure Analysis and Prevention (JFAP)*, vol. 16, no. 5, pp. 747–760, 2016.

[8] A. Brun and M. M. Savino, "Assessing risk through composite FMEA with pairwise matrix and Markov chains," *International Journal of Quality & Reliability Management*, vol. 35, no. 9, pp. 1709–1733, 2018.

[9] Y. Zhou, C. Lin, Y. Liu, and H. Xu, "Analytical study on the reliability of redundancy architecture for flight control computer based on homogeneous markov process," *IEEE Access*, vol. 6, pp. 18290–18298, 2018.

[10] L.-L. Song, T.-Y. Wang, X.-W. Song, L. Xu, and D.-G. Song, "Research and application of FTA and petri nets in fault diagnosis in the pantograph-type current collector on CRH EMU trains," *Mathematical Problems in Engineering*, vol. 2015, 12 pages, 2015.

[11] D. Wu and W. Zheng, "Formal model-based quantitative safety analysis using timed Coloured Petri Nets," *Reliability Engineering & System Safety*, vol. 176, pp. 62–79, 2018.

[12] Y. Sun, L. Ma, J. Mathew, and S. Zhang, "An analytical model for interactive failures," *Reliability Engineering System Safety*, vol. 91, no. 5, pp. 495–504, 2006.

[13] Y. Chen and H. Teng, "Advances of coupling analysis for product design," *Computer Integrated Manufacturing Systems*, vol. 17, no. 8, pp. 1729–1736, Aug 2017.

[14] J. D. Weist and F. K. Levy, *A Management Guide to pert/cpm*, Prentice-Hall, New Jersy, NJ, USA, 1977.

[15] A. Mosleh, "Dependent failure analysis," *Reliability Engineering & System Safety*, vol. 34, no. 3, pp. 243–248, 1991.

[16] S. Yang, J. Qiu, and G. Liu, "Hierarchical model-based approach to testability modeling and analysis for PHM of aerospace systems," *Journal of Aerospace Engineering*, vol. 27, no. 1, pp. 131–139, 2014.

[17] M. Kokawa, S. Miyazaki, and S. Shingai, "Fault location using digraph and inverse direction search with application," *Automatica*, vol. 19, no. 6, pp. 729–735, 1983.

[18] S. Lin, Y. Wang, and L. Jia, "System reliability assessment based on failure propagation processes," *Complexity*, vol. 2018, 12 pages, 2018.

[19] Y. Zhang, J. Liu, and G. Shen, "Failure propagation mechanism analysis of CNC lathe," *Journal of Harbin Institute of Technology*, vol. 50, no. 7, pp. 131–136, 2018.

[20] Z. Long, G. Shen, Y. Zhang, W. Zeng, and F. Rong, "Evaluation of the fault correlation of machining center components," *Journal of Harbin Institute of Technology*, vol. 49, no. 1, Jan 2017.

[21] G. Li, J. Gao, Z. Gao, and H. Jiang, "Failure propagation model of complex system based on small world net," *Journal of Xi'an Jiaotong University*, vol. 41, no. 3, pp. 334–338, 2007.

[22] D. V. Steward, "The design structure system: a method for managing the design of complex system ," *IEEE Transactions on Engineering Management*, vol. 28, no. 3, pp. 71–74, 1981.

[23] R. P. Smith and S. D. Eppinger, "Identifying controlling features of engineering design iteration," *Management Science*, vol. 43, no. 3, pp. 276–293, 1997.

[24] M. Danilovic and T. R. Browning, "Managing complex product development projects with design structure matrices and domain mapping matrices," *International Journal of Project Management*, vol. 25, no. 3, pp. 300–314, 2007.

[25] S. J. Chen and L. Li, "Decomposition of interdependent task group for concurrent engineering," *Computers & Industrial Engineering*, vol. 44, no. 3, pp. 435–459, 2003.

[26] F. Marle and L.-A. Vidal, "Potential applications of DSM principles in project risk management," in *Proceedings of the 10th International Design Structure Matrix Conference, DSM'08*, pp. 157–168, Sweden, November 2008.

[27] C. Fang and F. Marle, "Dealing with project complexity by matrix-based propagation modelling for project risk analysis," *Journal of Engineering Design*, vol. 24, no. 4, pp. 239–256, 2013.

[28] B. Sheng, C. Deng, Y. Xiong, Y. Wang, and Z. Luo, "Fault diagnosis for CNC machine tool based on graph theory," *Computer Integrated Manufacturing Systems, CIMS*, vol. 21, no. 6, pp. 1559–1570, 2015.

[29] X. Zhou, F. Zhang, K. Li, X. Hui, and H. Wu, "Finding vital node by node importance evaluation matrix in complex networks," *Acta Physica Sinica*, vol. 61, no. 5, pp. 1–7, 2012.

[30] Y. Ran, G. Zhang, and L. Zhang, "Quality characteristic association analysis of computer numerical control machine tool based on meta-action assembly unit," *Advances in Mechanical Engineering*, vol. 8, no. 1, pp. 1–10, 2016.

[31] D. Li, M. Li, G. Zhang, Y. Wang, and Y. Ran, "Mechanism analysis of deviation sourcing and propagation for meta-action assembly unit," *Journal of Mechanical Engineering*, vol. 51, no. 17, pp. 146–155, 2015.

[32] Y. Umeda, M. Ishii, M. Yoshioka, Y. Shimomura, and T. Tomiyama, "Supporting conceptual design based on the function-behavior-state modeler," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol. 10, no. 4, pp. 275–288, 1996.

[33] X. Hu and S. Yang, "Research on model of information mapping in product conceptual design," *China Mechanical Engineering*, vol. 16, no. 15, pp. 1366–1368, 2005.

[34] K. Chang, Y. Chang, and I. Tsai, "Enhancing FMEA assessment by integrating grey relational analysis and the decision making trial and evaluation laboratory approach," *Engineering Failure Analysis*, vol. 31, pp. 211–224, 2013.

[35] T. L. Saaty, "Axiomatic foundation of the analytic hierarchy process," *Management Science*, vol. 32, no. 7, pp. 841–855, 1986.

[36] T. R. Browning, "Applying the design structure matrix to system decomposition and integration problems: a review and new directions," *IEEE Transactions on Engineering Management*, vol. 48, no. 3, pp. 292–306, 2001.

[37] T. L. Saaty, *The Analytic Hierarchy Process*, McGraw-Hill, New York, NY, USA, 1980.

[38] M. Braglia, "MAFMA: multi-attribute failure mode analysis," *International Journal of Quality & Reliability Management*, vol. 17, no. 9, pp. 1017–1033, 2000.