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Spare Parts Forecast Analysis based on Important Calculation of Element Fault Tree

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Abstract

Spare parts are an important material basis for the use and maintenance of machine tools, and they are an important factor affecting equipment life cycle costs. In this paper, the element movements and the element action failure modes of equipment operation are found for the machine function unit. The reason of the failure of the unit base element is identified by using the element action fault tree to determine the reason of the fault of the unit base element. The calculation of the importance degree of the machine unit is carried out, and the importance degree is analyzed for rational distribution, thus ensuring the reduction of maintenance costs and the normal operation of the system. It is proven that the method based on the importance of the fault tree of the element action plays a guiding role in the analysis of spare parts.

Keywords: spare parts forecast; element action fault tree; reliability; CNC machine tools

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1. Introduction

Spare parts are the foundation of the maintenance support of CNC machine tool systems and an important part of their function as "mother machines". If the number of spare parts in stock is less than the number of spare parts needed in the maintenance cycle, the system to be repaired will experience unnecessary downtime before obtaining the missing spare parts. However, if the number of spare parts in stock is more than the number of spare parts needed in the maintenance cycle, it will lead to unnecessary spare parts inventory costs. The purpose of spare parts demand forecasting is to meet the need of timely maintenance without causing the overstock of spare parts. The expenditure of spare parts accounts for a considerable proportion in the whole life cycle cost of equipment, and existing research data indicate the following: in the decomposition structure that affects the equipment life cycle cost, the use guarantee cost accounts for more than 55%, among which the spare parts cost accounts for about 23%-28% [1]. The performance of parts is sensitive to the production environmental conditions, but this point is ignored in the existing spare parts demand forecasting process. In the actual production process, the performance of parts is affected not only by the inherent damage, but also by the operation and environmental conditions, resulting in a prediction accuracy error of more than 20% [2].

The determination of spare parts demand is the premise of spare parts inventory management. Spare parts demand is affected by many factors, such as the reliability of spare parts, use of spare parts, maintenance methods, and maintenance strategies. These complex factors play a very important role in the calculation of spare parts demand. Careful analysis of these complex factors is an important link in spare parts supply planning, as well as the basic work of spare parts management. As the occurrence of spare parts demand is usually highly random, the influencing factors are complex and the data collection is difficult, which increases the difficulty of demand analysis and prediction. Therefore, researchers need to continuously seek demand analysis methods that can more effectively deal with the randomness characteristics and consider environmental factors [3].

For spare parts demand analysis, the empirical method is a very basic method that mainly depends on the machine line

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operation data. It involves observing and analyzing the usage of components and forecast spare parts for each component. Compared with this method, there are two analysis methods with higher prediction accuracy: one is the method of time series data, which mainly includes exponential smoothing (SES), the Croston method, and the Bootstrap method. The method of the traditional prediction model is simple and fixed. It cannot follow changing trends of data effectively, so it has limitations [4-5]. Feng et al. [6] proposed spare parts prediction based on SES, which could better solve the large amount of data without historical data or samples. Croston [7] considered the factors of historical demand and demand time intervals and innovatively proposed to divide the demand sequence of uncommon spare parts into demand continuous sequences and demand interval continuous sequences for prediction. Franco-villoria et al. [8] used Bootstrap to process data to allow for the evaluation of the uncertainty spatial correlation function of the prediction curve as well as the evaluation of the uncertainty of the prediction curve. The second is based on the calculation method of the reliability model, which is based on the equipment reliability model. Compared with the traditional time series method, the calculation method of spare parts demand based on the reliability model adopts the reliability function and maintenance model to calculate spare parts demand. The above two methods are dependent on data and models for calculation, so they cannot analyze and store spare parts according to the actual movement of machine tools and the distribution of parts' importance. For this reason, this paper first proposes the use of the element action fault tree significance method to analyze the spare parts of machine tool units. This analysis method starts from the actual use of machine tools and from the decomposition action of the bottom layer, which is more convincing and authentic for component prediction.

This paper analyzes the concrete structure of numerical control machine using the element action fault tree decomposition method. This method mainly starts from the bottom of the movement unit to analyze the probability of top event, decomposes the numerical control machine from motion to the lowest level of element action, and, based on element action fault tree analysis to find out the root cause of the abnormal action, calculates the importance of the corresponding machine tool parts in the system run for reasonable distribution of parts. The results for the prediction of machine spare parts and stores play a guiding role. Compared with other analyses and prediction methods, this analysis method of the importance of the element action fault tree starts from the reality of the bottom layer and tracks down the minimum movement according to the analysis of the movement mode of the machine tool. The results obtained by this method are more convincing and instructive for the analysis of spare parts.

2. Description and Analysis of Element Action

2.1. Element Action

CNC machine tools can complete many actions, such as milling, drilling, expanding, stranding, cutting, and other actions. During the cutting process, the worker uses the machine tool numerical control device to issue instructions to the machine tool itself, and then the machine tool system begins to run. The tool will act in accordance with the numerical control instructions and the designated position to cut. The series of actions can be broken down into tool clamping and moving and changing the tool. The components of these actions, which are the most basic parts, are called the element actions [9].

According to the numerical control machine tool function, actions such as drilling, expanding, cutting are called pedigree; when cutting the main motion of the spindle, the workpiece feed motion can be called function; the transmission of spindle motion, such as the gear and screw drive, is called motion; finally, the basic units of motion, such as shaft rotation and moving of common parts, are called actions. The spectrum at the top of the function of the spectrum is decomposition. According to its concept, find the operation of the nc machine tool to process the functions that must be implemented. Then, give priority to these functions and decompose them into different parts. Finally, according to the transfer principle of each movement, the situation can be decomposed into element actions. By analyzing these basic elements, we can achieve the goal from "complex to simple". The fault tree diagram of element action is shown in Figure 1.

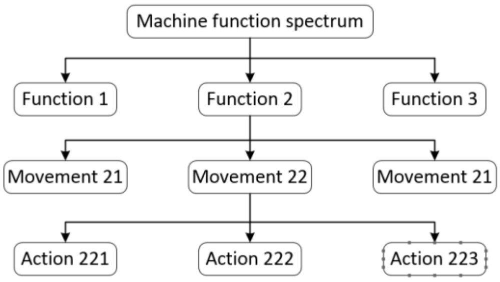

Figure 1. Fault tree diagram of element action

2.2. Element Action Fault Model

The movement modes of CNC machine tools can be divided into movement and rotation, and there are many kinds of element action faults according to their movement modes. For the whole CNC machine tool, there are more failure modes. When analyzing element action faults, we can classify element action faults, element action motion faults, and element action accuracy. The diversification of fault models cannot be described in detail. The main failure modes are listed in Table 1.

Table 1. Numerical control machine tool element action fault performance

Type	Failure mode	Common examples
Element action fault representation	System leakage, percolation coolant	Spindle system into the cooling fluid, cylinder leakage, etc
	Related parts are not assembled well	Locknut is not tight, in combination with surface can't stick close
	Action in the process of sound and noise	Abnormal sound of grinding wheel spindle and lathe spindle rotation, etc
Element action fault performance	element action error action	Wheel frame fast forward and rewind the contrary, the hydraulic pump reversal
	Action does not reach the designated position	The feed is not in place and the workpiece is not moved in place on the worktable
	Overaction	Feeding too much
	Action process is not flexible	Ball screw rotation is not flexible, the movement of the sliding block is not flexible
Precision representation of element action	Poor linear speed accuracy	Ball screw angular velocity difference, punch workpiece linear velocity difference
	Poor linear displacement accuracy	Lead screw nut line displacement and indexing disc angular displacement difference
	Poor geometric accuracy of motion	The axial runout and radial runout of the spindle are not standard, and the parallelism between the slider and the guide rail is poor
	The track error is too large	Motion path trajectory error exceeds allowable value

The failure mode of element action is a kind of failure form or failure of components with specific function in the process of element action movement. As shown in Table 1, it is mainly manifested in the faults occurring during the operation of the machine tool and in the accuracy problems arising from the installation. Some of the local characteristics of the fault manifestations are shown in Table 1. At the same time, from the classification of failure modes in Table 1, we can see that element action fault is the error process between its performance and design requirements. The larger the error, the more serious the fault will be. The analysis of element action fault model can trace the cause of machine tool failure. When machine tool failure occurs, the structure of unit components involved in the failure can be obtained from the bottom analysis, and the cause of the failure can be found from bottom to top, which shortens the time of finding the fault and reduces the cost of maintenance. Similarly, such a solution is still applicable to the fault treatment of components in other units, so it is more pertinent to diagnose and analyze the failure of components.

3. Analysis of Element Action Fault Tree

3.1. The Relation Between Meta-Action Fault Tree and Fault Tree

The analysis process of the meta-action fault tree has many similarities with fault tree (FTA) in structure. Both the meta-action fault tree and FTA adopt the logical analysis method in the specific analysis process and carry out fault analysis visually, which has the characteristics of simplicity, clarity of thinking, and strong logic. At the same time, the specific qualitative and quantitative analysis can be calculated.

Fault trees are generally used to improve the quality of machine tool parts. They are built for the faults of machine tools in use. The fault mode of the element action fault tree is deduced according to the design requirements. It may or may not occur in the actual process. Therefore, the analysis of the element action fault tree should not only use the idea of fault tree analysis, but also embody the characteristics of the element action fault mode in the process, such as:

A. The number of element action fault trees is known. The top event of the element action fault tree assumes that the element action of a component is invalid, that is to say, a fault tree can be established by a unit action. For example, the number of element actions obtained by functional structural decomposition of a machine tool system is n, as is the number of fault trees that can be established by the system.

B. The fault cause of the first layer of the element action fault tree is known. The fault reasons of the first layer of element action fault are transformed from the design requirements of element action, that is to say, if a certain element action has N design requirements, then the fault reasons of the first layer have N. In addition, the cause of failure is opposite to the design requirement. If the design requirement is event D, it is assumed that the cause of failure is the failure of the design requirement, as is its opposite event $\overline{D}$.

The construction process of element action fault tree is shown in Figure 2.

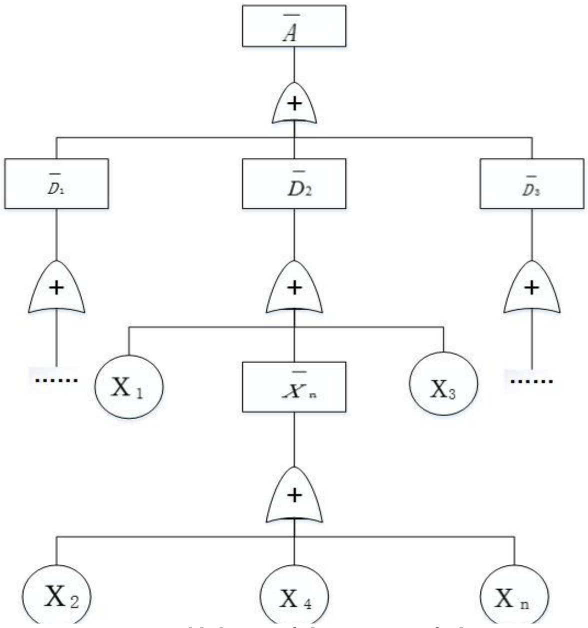

Figure 2. Establishment of element action fault tree

In the element action fault tree, it is assumed that a mechanism will fail. The failure causes of the first layer can be determined according to the connection between the top event of or-door connection and the first layer fault and its design requirements. At the same time, the failure reasons of each design requirement can be obtained by continuing to analyze the bottom layer.

3.2. Quantitative Analysis of Element Action Fault Tree

The main aspect of quantitative analysis of meta-action fault trees is to decompose the total probability of the top event and calculate the importance of the bottom event after decomposition. In order to accurately measure the impact relationship of the bottom event, the relative probability importance is introduced to calculate and analyze it.

3.2.1. Calculation of Top Event Probability

When the fault tree is built, all the minimum cut sets can be found by qualitative analysis, and then the structure functions of the fault tree expressed by the minimum cut sets can be written.

$$\phi(x) = \bigcup_{j=1}^{K} M_j \,,\quad M_j = \bigcap_{j \in M_j} x_i \tag{1}$$

The probability of top event occurrence is

$$P\left[\phi(x)\right] = P(\bigcup_{j=1}^{K} M_j) = P(M_1 \cup M_2 \cup \cdots \cup M_K) \tag{2}$$

In this equation, X_i represents the state variable of the bottom event, $\phi(x)$ is the structural function of the element action fault tree, and M represents the minimum cut set.

Generally, the minimum cut sets are not mutually exclusive, and the bottom events can be repeated in several minimum cut sets. In order to calculate the probability of the top events, the exclusion formula must be used. The above equation can be changed as follows:

$$P\left[\phi(x)\right]=\sum_{i=1}^{n}P(M_j)-\sum_{i\prec j=2}^{K}P(M_iM_j)+\sum_{i\prec j\prec l}^{K}P(M_iM_jM_l)-\cdots+(-1)^{K-1}P(M_1\cdots M_K) \tag{3}$$

There are 2^k-1 items in the above equation. When K is large enough, the calculation is very heavy and the problem of "combination explosion" will occur. Therefore, in order to achieve accurate calculation, it is necessary to disjoint the fault tree structure functions. At the same time, in the actual application process, if the probability of events is less than 0.005, it can be neglected and the approximate calculation value of events can be obtained:

$$P\left[\phi(x)\right]=\sum_{i=1}^{n}P(M_j)-\sum_{i\prec j=2}^{K}P(M_iM_j) \tag{4}$$

3.2.2. Calculation of Probability Importance

In order to analyze the impact of bottom events on the system, the top events are decomposed by full probability from the bottom of the fault tree. System unreliability is always a function of component unreliability, so

$$P\left[\phi(x)=1\right]\triangleq g(Q) \tag{5}$$

In this equation, $Q=\left(Q_1,Q_2,\cdots,Q_n\right)$.

Starting from a bottom event of the fault tree, the top event is decomposed in full probability.

$$P\left[\phi(x)\right]=P(x_i=1)P\left[\phi(x=1)\mid x_i=1\right]+P(x_i=0)P\left[\phi(x)=1\mid x_i=0\right] \tag{6}$$

In this equation,

$$P\left[\phi(x)=1\mid x_i=1\right]\triangleq g(1_i,Q)$$
$$P\left[\phi(x)=1\mid x_i=0\right]\triangleq g(0_i,Q)$$

Therefore, the above equation can be rewritten as follows:

$$g(Q)=Q_i g(1_i,Q)+(1-Q_i)g(0_i,Q) \tag{7}$$

Both sides take the partial derivative:

$$\frac{\partial g(Q)}{\partial Q_i}=g(1_i,Q)-g(0_i,Q)$$

The above equation shows that the unreliability variation of the i^{th} component causes system unreliability variation, which is the probability that the system is in a state of failure and the system will fail only if the component I fails. In other words, it is the probability that the system is in the state where component *I* is the key component. It represents the importance of component (bottom event) *I* to the system (top event), and the probability significance is defined as

$$I_p(i)=\frac{\partial g(Q)}{\partial Q_i} \tag{8}$$

In the actual analysis and processing, it is found that the probability of some bottom events is small, but the change in probability has a greater impact on the system failure. Meanwhile, the probability of some bottom events is larger, but the change in probability has a smaller impact on the system failure. Therefore, in order to measure this relationship more accurately, the relative probability importance is introduced:

$$I_C(i) = \lim_{\Delta Q_i \to 0} \frac{\Delta g(Q) / g(Q)}{\Delta Q_i / Q_i} = \frac{Q_i}{g(Q)} \frac{\partial g(Q)}{\partial Q_i} = \frac{Q_i}{g(Q)} I_p(i) \tag{9}$$

It is known that $I_C(i) = \frac{Q_i}{g(Q)} I_p(i)$. Since the probability of top event $g(Q)$ is a fixed value, in order to simplify the calculation, the equation is adjusted and the approximate relative importance is defined.

$$I'_C(i) = g(Q) I_c = Q_i I_p(i) \tag{10}$$

The impact of bottom events on top events in the fault tree is not equally important. Generally speaking, the contribution of the bottom event to the top event is called the importance degree. If the order is based on the importance degree of the parts to the system, the weak links can be found and the parts can be replaced in time. At the same time, the demand situation of spare parts can be obtained through the calculation of the importance degree, which is very important for predicting and reserving spare parts.

4. Analysis of Ball Screw based on Element Action Fault Tree

The ball screw drive mechanism can be used in various different fields of work. Among them, the most widely used area is the traditional machinery manufacturing industry. In the CNC of mechanical processing equipment, it is usually used as a transmission component, converting rotational motion into linear motion or linear motion into rotational motion. The ball screw drive is widely used in various high precision machine tools because of its smooth movement, high precision, high durability, high synchronization, and other advantages. The feed shaft of the screw grinding wheel controls the feed of each grinding [10-11]. The feed rate has an impact on the quality of grinding wheel and workpiece. A small feed rate increases grinding time, and a large feed rate easily causes serious wear of the grinding wheel, thus affecting the quality of workpiece processing. The reliability of the lead screw directly affects the feed rate. The source of the failure of the lead screw is shown in Figure 3.

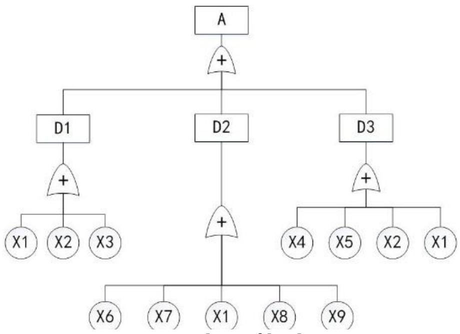

Figure 3. Failure of lead screw

The failure analysis table of the ball screw drive in the element action fault tree is shown in Table 2.

Table 2. Lead screw rotation fault analysis

Code name	Definition
A	Rotation failure of ball screw
D1	There is abnormal noise and noise when the lead screw rod rotates
D2	Inflexible rotation of lead screw rod
D3	Poor rotation accuracy of lead screw rod
X1	Failure of a bearing at both ends of lead screw
X2	Bad assembly of bearings at both ends
X3	The lead screw rod has high friction and serious wear
X4	Improper preload of bearing at both ends
X5	Bearing's own poor accuracy
X6	Inappropriate clearance adjustment of bearings at both ends
X7	Bending Deformation of Lead Screw
X8	Improper bearing end cover assembly, no tightening
X9	Lead screw lubrication does not meet the requirements

The definition of failure events can be seen by analyzing the element action fault tree based on the reliability fault tree graph. According to the specific formula of quantitative analysis of the element action fault tree, the importance of components can be calculated. For the bottom event, the probability Q*i* of the bottom event is calculated according to the statistics of after-sale failure records. The probability importance and relative probability importance are calculated according to the calculation equations in the previous section. The calculation results are shown in Table 3. By calculation, the order of probability importance Ip(*i*) and approximate relative importance *Ic*(*i*) of the bottom event is from large to small, which are: X1, X2, X6, X5, X9, X7, X3, X4, X8.

Table 3. Event probability and importance

Importance degree / Event	Q_i	$I_p(i)$	$I_c(i)/10$
X1	0.041	0.86	3.5096
X2	0.024	0.839	2.0136
X3	0.015	0.83	1.245
X4	0.013	0.828	1.0764
X5	0.021	0.836	1.7556
X6	0.022	0.837	1.8414
X7	0.017	0.832	1.4144
X8	0.012	0.827	0.9924
X9	0.02	0.835	1.67

Queuing according to the importance of components to the system can be obtained from Table 3. X1 means that the probability importance and relative importance of bearing failure are the highest in the structure of the ball screw drive. Other problems, such as the bending of the lead screw rod and the rotation system, account for different degrees of importance. The data of importance degree indicates the influence degree of component failure or state change on system reliability, which is a function of component reliability parameters and system structure, and also indicates the direction of reasonable allocation of maintenance resources, so as to ensure the reduction of maintenance cost and the normal operation and use of the system.

5. Conclusions

Through the calculations and analysis of this paper, the following results are obtained.

1) The innovation of this paper is that it is the first to put forward the method of machine tool spare parts analysis based on the importance of the element action fault tree. Using the method of element action fault tree analysis, starting from the bottom with the basic unit of mechanism motion, the failure can be traced back to its origin, and the failure area and the cause of component failure can be locked in time.

2) Through the establishment and analysis of the element action fault tree and by taking the motion mechanism of the rolling screw drive of machine tool as the test point, the importance of the components and mechanism functions is analyzed and calculated. It is concluded that the bearing of the rolling screw drive plays an important role in the process of machine tool operation, and its importance is much higher than that of other parts. When spare parts of rolling screw drive parts of machine tools are reserved, relative probability importance data should be used to reserve spare parts, which can ensure the normal operation of machine tools.

3) When using the element action fault tree analysis method to predict machine tool components, the main advantages of this method are that it does not rely heavily on data and can achieve correct prediction and analysis. When making more detailed analyses, the structure of the element action fault tree can be further decomposed, so that the analysis results will be more directive and accurate.

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