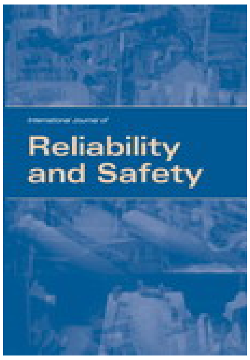


International Journal of Reliability and Safety

ISSN online: 1479-3903 - ISSN print: 1479-389X
https://www.inderscience.com/ijrs

Reliability assignment of a heavy-duty CNC machine tool spindle system based on fault tree analysis

Hongxia Chen, Junfeng Zhang, Chenguang Li, Jihua Wang, Chuncheng Guo

DOI: 10.1504/IJRS.2022.10053782

Article History:

Received:	31 March 2022
Last revised:	02 August 2022
Accepted:	20 September 2022
Published online:	30 January 2023

Reliability assignment of a heavy-duty CNC machine tool spindle system based on fault tree analysis

Hongxia Chen, Junfeng Zhang*,
Chenguang Li, Jihua Wang and
Chuncheng Guo

College of Mechanical Engineering,
Inner Mongolia University of Technology,
Huhhot, Inner Mongolia, China
and
Key Laboratory of Advanced Manufacturing Technology of Inner Mongolia Autonomous Region,
Inner Mongolia University of Technology,
Huhhot, Inner Mongolia, China
Email: chenhongxia@imut.edu.cn
Email: 1297335663@qq.com
Email: 570857577@qq.com
Email: 1553288171@qq.com
Email: 2291331381@qq.com
*Corresponding author

Abstract: Research on the distribution of machine tool reliability indexes is of great significance to improve the reliability of machine tools in the design and manufacture stages. Owing to the complex structure of heavy-duty CNC machine tools, multi-source and heterogeneous failure causes, etc., the traditional single method cannot get accurate results. In this paper, based on the FTA method, a three-level machine tool fault tree model is established to carry out research on reliability index assignment. Then, as the levels progress, the distribution of reliability indicators is based on probability importance analysis, reliability redistribution method, and AHP respectively. Finally, the top-down reliability assignment results are obtained. After analysis, the structure obtained by combining multiple reliability allocation methods is more in line with the actual situation. According to the results, the weak parts of the machine tool are designed and improved, thereby improving the reliability of the machine tool.

Keywords: heavy-duty CNC machine tool spindle system; FTA; reliability assignment; reliability index.

Reference to this paper should be made as follows: Chen, H., Zhang, J., Li, C., Wang, J. and Guo, C. (2022) 'Reliability assignment of a heavy-duty CNC machine tool spindle system based on fault tree analysis', *Int. J. Reliability and Safety*, Vol. 16, Nos. 1/2, pp.87–109.

Biographical notes: Hongxia Chen is a Professor in the College of Mechanical Engineering at Inner Mongolia University of Technology, China. She holds her BS degree in Mechanical Design and Manufacturing from Inner Mongolia University of Technology in 1992. She obtained her Master's degree in Mechanical Engineering from Inner Mongolia University of Technology in 2008. Her research interests include focused on quality and reliability engineering. She has published papers in several international journals.

Junfeng Zhang is a post-graduate student in the College of Mechanical Engineering at Inner Mongolia University of Technology, China. He holds his BS degree in Mechanical Design manufacture and Automation Major from North University of China at 2020. His research interests include reliability engineering.

Chenguang Li is a post-graduate student in the College of Mechanical Engineering at Inner Mongolia University of Technology, China. He holds his BS degree in Mechatronic Engineering from East University of Heilongjiang at 2019. His research interests include mechanical structure reliability analysis.

Jihua Wang is a post-graduate student in the College of Mechanical Engineering at Inner Mongolia University of Technology, China. He holds his BS degree in Mechanical Design Manufacture and Automation Major from Hengxing University in 2020. His research interests include reliability analysis of heavy CNC machine tool.

Chuncheng Guo is a post-graduate student in the College of Mechanical Engineering at Inner Mongolia University of Technology, China. He holds his BS degree in Mechanical Design Manufacture and Automation Major from Shenyang Ligong University in 2021. His research interests include reliability analysis of heavy CNC machine tool.

1 Introduction

As an ‘industrial mother machine’, heavy-duty CNC machine tools are of great significance to the development of the manufacturing industry. Improving the reliability of this type of machine tool is particularly important for promoting the development of aerospace, military, and navigation industries (Catelani et al., 2016, 2017; Wu et al., 2018). Spindle system is one of the subsystems of heavy CNC machine tools with relatively high frequency of failures. Therefore, it is necessary to analyse the reliability of the spindle system of machine tools (Kim and Kim, 2021; Liu et al., 2021; Yalaoui et al., 2005). In the field of reliability research, the reliability distribution is directly related to the reliability of the machine tool design stage. The research on reliability distribution based on the fault data of the machine tool in the use stage has important reference significance for its design and remanufacturing to improve the reliability of the machine tool (Eldosouky et al., 2021; Gao et al., 2020; Liu et al., 2020). Owing to the complex structure of heavy-duty CNC machine tools, few fault samples, difficulty in fault tracing and fuzzy causes of failures, it is impossible to use a single method to ensure effective reliability assignment for heavy-duty CNC machine tools. The assignment of reliability indicators is a step-by-step iterative process, so it is necessary to select different methods for reliability assignment at different stages according to the actual situation.

Reliability assignment refers to assigning weights to each system and component according to a certain algorithm based on the reliability index specified by the product. A large number of scholars have made corresponding contributions to the research on reliability distribution theory. At present, the widely used methods include AGREE distribution method, score distribution method, proportional combination method and so on. Among them, although the AGREE assignment method considers the complexity and importance of each component system, this method is often used in the analysis of the reliability of electronic systems, and it is not considered enough when analysing other situations (Hongbin et al., 2009; Li et al., 2018). The scoring distribution method makes up for the information defects caused by insufficient fault data by introducing subjective information, but the distribution results are greatly affected by the personal judgment and cognitive level of experts, and the distribution efficiency is low. The proportional distribution method needs to find similar systems for reference and is not universal. In order to solve the incompleteness of a single method, different methods are used comprehensively for the reliability distribution. The distribution hierarchy model is established based on the fault tree, and the Bayesian network is used to quantify the distribution weight. Based on Edgeworth series method and data envelopment analysis method, the assignment results can be made more accurate. When assigning reliability to systems with fuzzy data, the introduction of AHP based on fault tree can be supplemented by subjective information. In the face of complex heavy-duty CNC machine tools, it is necessary to integrate a variety of methods to allocate reliability for different situations (Wei et al., 2012; Zhang et al., 2019).

In this paper, based on fault tree analysis and synthesising a variety of reliability distribution methods, the reliability distribution of machine tools is carried out (Ding et al., 2021; Nair et al., 2020; Xu et al., 2020). First, analyse the fault tree of the spindle system of the heavy CNC machine tool, establish three-layer structure events, calculate the probability importance of the events and then obtain the weight of the events to be assigned, and obtain the reliability assignment result of the certain events, that is, the reliability of the intermediate events index. Secondly, use the reliability redistribution method to distribute the reliability of the intermediate events of the fault tree. Finally, the reliability index is further assigned to the bottom event by using the AHP, and the assignment result is further refined. The reliability assignment index can be mapped to the parts of the machine tool according to the fault information of the bottom event. The results of the comprehensive reliability assignment method based on the fault tree are more in line with the actual situation, which is conducive to improving the maintenance strategy of the machine tool, providing a reference for the reliability design of the machine tool and is of great significance for improving the reliability of the machine tool.

2 The fault tree-based reliability distribution model for spindle systems

2.1 Determine system reliability assignment metrics

When assigning reliability indexes, the Mean Time Between Failures (MTBF) of the system is usually selected as the reliability index of reliability assignment and this method can visually show the advantages and disadvantages of the assigned system reliability (Wu and Sun, 2021). In this paper, when assigning reliability to the spindle system of a heavy-duty CNC machine tool, a fault tree model needs to be established first, and a quantitative analysis is performed based on the probability importance to obtain the distribution weight of the reliability index. When calculating the probability importance of a fault event, the failure probability needs to be used (Kalantari et al., 2020; Parihar and Chakraborty, 2020; Ryu and Jae, 2021). So the collected fault data is processed to obtain the fault probability of the fault event, which is used as the reliability assignment index in this paper, and is transformed by:

$$\lambda = \frac{1}{\text{MTBF}} = \frac{c}{N \cdot \Delta t} \tag{1}$$

Among them, c is the number of faulty components within the considered time range Δt; N is the number of all components; Δt is the considered time range.

$$q_i = 1 - e^{-\lambda_i t}, (i = 1, 2, 3, ..., n) \tag{2}$$

The obtained failure probability is replaced by the reliability assignment index, which is expressed as:

$$P_S^* \left(P_1, P_2, L, P_i, L, P_n\right) \le P_S \tag{3}$$

In the formula, P_S is the fault probability of the fault tree top event before assignment; P_S^* is the fault probability of the fault tree top event after assignment; P_i is the *i*-th event fault probability.

The fault probability of the fault tree top event after assignment is lower than the fault probability before assignment, otherwise recalculate until it meets the requirements.

2.2 Reliability assignment method of top event based on probability importance

Reliability assignment of fault tree top events based on probability importance analysis method. Probabilistic importance is often used in the quantitative analysis of fault trees, and the value of this value can reflect the impact of fault tree events on the overall fault probability. Therefore, the probability importance is introduced into the reliability assignment method, and the reliability of the fault tree top event is allocated according to the probability importance.

The process of calculating the probability importance of each event is as follows:

1) Assuming that there are *n* fault events in the system fault tree, the probability importance of the *j*-th event is as follows:

$$I_j = \frac{\partial P_s}{\partial P_j}, 1 \le i \le j \le n \tag{4}$$

When the logic gate is an 'OR' gate, the probability importance formula can be simplified as:

$$I_j = \frac{\partial P_s}{\partial P_j} = \prod_{j=1, i \ne j}^{n} \left(1 - P_i\right) \tag{5}$$

When the logic gate is an 'AND' gate, the probability importance formula can be simplified as:

$$I_j = \frac{\partial P_s}{\partial P_j} = \prod_{j=1, i \ne j}^{n} P_i \tag{6}$$

The calculation method of the failure probability P_S of the fault tree top event is as:

If the logic gate is an 'OR' gate:

$$P_S = \bigcup_{i=1}^{n} P_i = 1 - \prod_{i=1}^{r} (1 - P_i) \tag{7}$$

If the logic gate is an AND gate:

$$P_S = \bigcap_{i=1}^{n} P_i = \prod_{i=1}^{n} P_i \tag{8}$$

2) Reliability assignment of top events based on probability importance (Burdyshev and Tyurin, 2021; Umma et al., 2021)

Substitute the calculated fault tree event probability importance into the following formula (9) to obtain the difference Δq that needs to be adjusted after assignment, and then the specific fault probability after assignment can be obtained, as shown in formula (10).

$$\Delta q_1 : \Delta q_2 : \cdots : \Delta q_i = I_1 : I_2 : \cdots : I_i \tag{9}$$

Reliability assignment to event *i*:

$$P_i^* = P_i + \Delta q_i \tag{10}$$

where P_i is the probability of failure of event *i* before assignment; I_i is the probability importance of event *i*; Δq assigns the difference between the probability of failure before and after event i that needs to be adjusted.

The total fault probability P_S^* after distribution is as:

$$P_S^* = 1 - \prod_{i=1}^{n} \left(1 - (P_i + \Delta q_i)\right) \tag{11}$$

Complete the reliability assignment of fault tree top events through the above content. And get the fault probability value after the intermediate events of the fault tree are assigned.

2.3 *Reliability assignment of fault tree intermediate events based on reliability reassignment method*

The reliability redistribution method is often used in the series system. The intermediate event of the fault tree is the bridge connecting the previous and the next, and it is also the key of the series system in the fault tree. Therefore, the reliability redistribution method is adopted here. First, determine the relationship between each component unit and the system on the reliability index, and then sort the reliability index of each component unit in descending order. Units with high reliability indexes will improve the reliability level, while those with low reliability indexes. The unit of the index will keep the reliability level unchanged, so that the reliability of the system can meet the expected requirements. Using reliability redistribution method for intermediate events can not only ensure accurate distribution but also improve distribution efficiency.

The specific steps of the reliability reassignment method are as follows:

1) Sort events in descending order of failure probability as:

$$P_1 > P_2 > \cdots > P_{k_0} > P_{k_0+1} > \cdots > P_n \tag{12}$$

2) Principles of Reassignment; According to Reliability, Reduce the relatively high failure probabilities $P_1, P_2, \ldots, P_k$ in the event to a fixed value of P_0, the original lower failure probability, $P_{k0}, P_{k0+1}, \ldots, P_n$ will remain unchanged. P_S can be obtained by equation (13).

$$P_S = \phi\left(P_1, P_2, \ldots, P_n\right) = 1 - \left(1 - P_0\right)^{k_0} / \prod_{i=k_0+1}^{n}\left(1 - P_i\right) \tag{13}$$

The total failure probability P_S should be greater than the expected failure probability index P_S^*, then equation (1) can be rewritten as:

$$P_S^* \le P_S = 1 - \left(1 - P_0\right)^{k_0} / \prod_{i=k_0+1}^{n}\left(1 - P_i\right) \tag{14}$$

Determine k_0 and fixed value P_0, and make it satisfy the equation (15).

$$P_0 = 1 - \left(1 - P_S^* / \prod_{i=j+1}^{n+1}\left(1 - P_j\right)\right)^{1/k_0} \tag{15}$$

2.4 Reliability assignment results of bottom events based on AHP

Since basic events are the most fundamental cause of failures and involve various influencing factors in the spindle system of heavy-duty CNC machine tools, it is difficult to obtain reasonable assignment results using traditional assignment methods. Therefore, this layer adopts the reliability assignment method combined with the analytic hierarchy process, and its purpose is to divide the target layer, the criterion layer, and the scheme layer into the relevant factors of the main shaft system through the hierarchical structure. The reliability index is the target level, the influencing factor is the criterion level and the assignment object is the scheme level. Then, the experts judge the degree of influence of the criterion level on the scheme level, and obtain the assignment relationship of the assignment object reliability index and finally obtain the reliability of the assignment object Sexual index (Li et al., 2021a).

The steps of the reliability assignment method based on the AHP are as follows:

1) Establish the hierarchy required for analytic hierarchy process: First divide the hierarchy, as shown in Figure 1.

In Figure 1, the connection between each unit of the target layer, the criterion layer and the solution layer represents the connection between the units, and the factors or indicators between the same layer are independent of each other.

2) *Construct the judgment matrix of the criterion layer*: According to Figure 1, the affiliation between each unit can be clarified, and the influence factor 1 of the criterion layer is taken as an example to illustrate. The influence factor 1 is the upper layer of the indicators of each subsystem in the scheme layer. Weight assignment, when the weight can be obtained by quantitative calculation, the corresponding

weight value can be directly determined. Pairwise comparisons of risk factors representing the relative importance among risk factors are performed using Saaty's method that is designed to evaluate the degree to which a factor is important than comparing one, see Table 1(Li et al., 2021b).

Figure 1 Hierarchical model

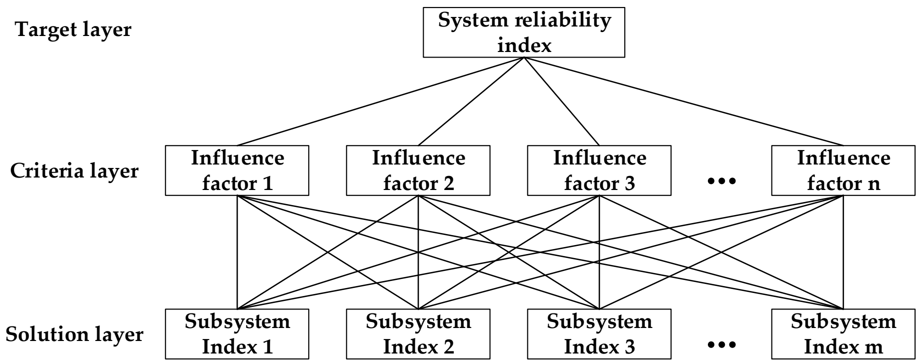


Table 1 Pairwise comparisons of Saaty's method

u_i'/u_j'	*Equally important*	*Weakly important*	*Fairly important*	*Strongly important*	*Absolutely important*
a_{ij}	1	3	5	7	9
u_i'/u_j'	*Equally unimportant*	*Weakly unimportant*	*Fairly unimportant*	*Strongly unimportant*	*Absolutely unimportant*
a_{ij}	1	1/3	1/5	1/7	1/9

From the same to the absolute strong, every two levels can be quantified by 2, 4, 6 and 8 in turn.

3) *Calculate the weight vector of the criterion layer and check the consistency*: The weight of each factor to the criterion layer can be obtained through the judgment matrix. Consistency test is to ensure the rationality of constructing judgment matrix. The specific method is as follows:

The consistency indicator is used to quantify the degree of inconsistency of the judgment matrix, denoted as C, which can arranged by:

$$C = (\lambda_{max} - n)/(n-1) \tag{16}$$

When $C = 0$, the judgment matrix is consistent, the larger the value of C, the more serious the inconsistency of the judgment matrix.

Whether the weight of the random consistency test is reasonable, expressed by C_k C_R, show as:

$$C_R = C/R \tag{17}$$

Among them, R is obtained through a reliable check table, as shown in Table 2.

Table 2 Random consistency index value

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*
R	0	0	0.58	0.90	1.12	1.24	1.32

4) *Calculate the weight vector*: If the relative weight of the target layer relative to the criterion layer is $w = (w_1, w_2, ..., w_n)$. The relative weight of a certain influencing factor at the criterion level to the scheme level is $v_i = \left(v^i{}_1, v^i{}_2, ..., v^i{}_m\right)^T$. Then, the combined weight vector of the scheme layer to the target layer is w_i, and that can be rewritten by equation (18).

$$w_i = wv_i^T \tag{18}$$

5) *Allocate reliability index*: The importance of system failure events to the system is the combination weight vector, and the assignment of indicators is completed based on the importance of the assignment. The fault probability P_i of the *i*-th unit consisting of *m* units in the scheme layer is as follows:

$$P_i = P\frac{1}{w_i} \Big/ \sum_{i=1}^{m} \frac{1}{w_i} \tag{19}$$

where *P* is the failure probability allowed by the top event.

3 Case study

Heavy-duty CNC machine tool is one of the most typical representatives of complex electromechanical products. It is especially important in the manufacturing and processing fields, such as the aviation industry and national defence and military industries. Especially in the development stage, it is very important to reasonably allocate the reliability indicators of the whole machine or system to each system or part. Reasonable reliability assignment can improve the reliability of the whole machine or system, and at the same time improve the quality of processed products (Baladeh and Zio, 2021). Given that the spindle system is one of the core functional systems of heavy-duty CNC machine tools (Zhou and Li, 2011; Zhang and Wu, 2012). Therefore, this research uses the spindle system of the THP6513 heavy-duty CNC horizontal milling and boring machine as a practical application to verify the feasibility and effectiveness of the proposed method. Figure 2 is a schematic diagram of the structure of the spindle system. The fault tree of the spindle system is established through the faults that have occurred, as shown in Figure 3, and the intermediate events and basic event descriptions are shown in Tables 3 and 4.

Figure 2 Spindle structure diagram. 1-Cone clamping device, 2-Link, 3-The front cover, 4-Front-end bearing, 5-Case, 6-Spindle, 7-Disc spring, 8-Rear bearing, 9-Piston, 10-Broachcylinder

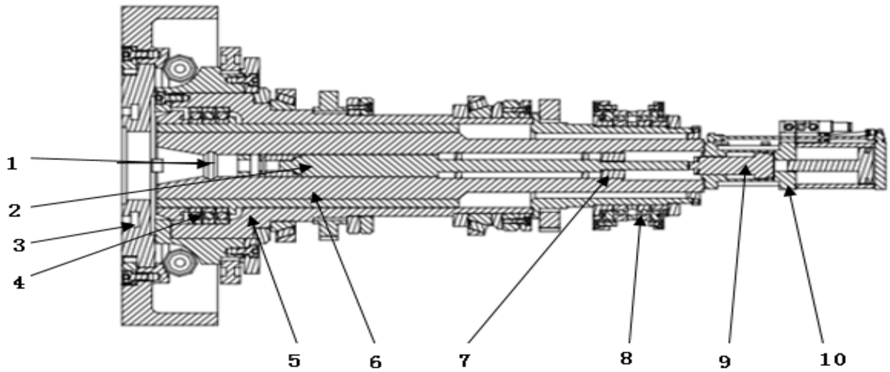
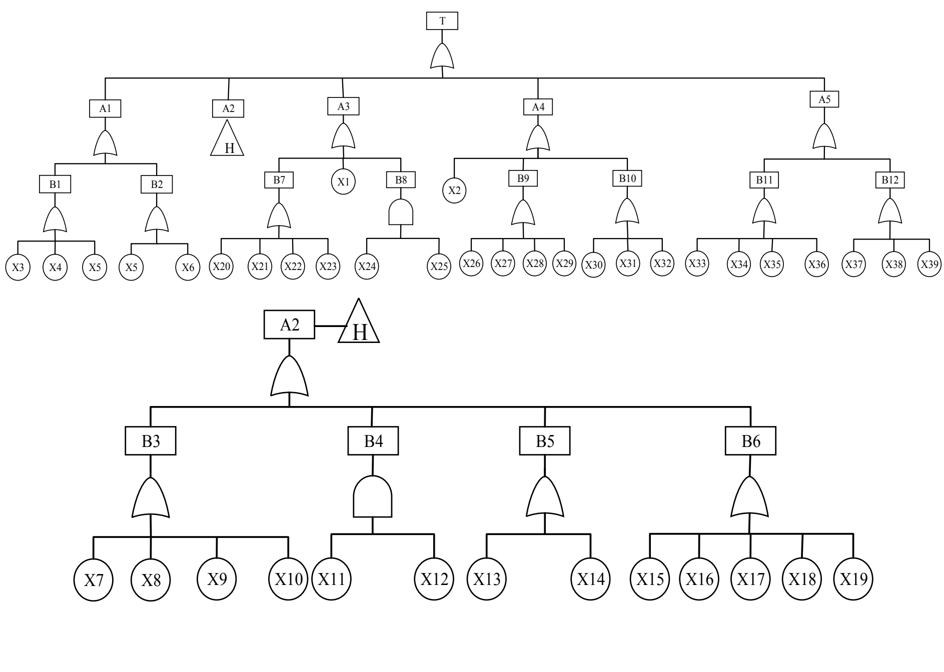


Figure 3 Spindle system fault tree



3.1 *Reliability assignment of top events in spindle system based on fault tree*

For the fault tree of the spindle system, the minimum cut set of the fault tree is obtained by the descending method. Using the fault maintenance data of an enterprise in the past 3 years, the fault interval time data is obtained through data processing, and it is substituted into equations (1) and (2) to obtain after processing. Event failure probability in the fault tree. Then, the probability importance of each basic event can be obtained by combining equations (7) and (8). The failure probability and probability importance of basic events are obtained as shown in Table 5.

Table 3 Intermediate event description table of fault tree

Mode number	*Failure mode*	*Mode number*	*Failure mode*
A1	Clamping device failure	B5	Solenoid valve failure
A2	Hydraulic system failure	B6	The oil pump cannot supply oil
A3	Abnormal noise from the spindle	B7	Vibration is big
A4	Spindle system alarm	B8	Encoder overcurrent
A5	Spindle speed is failure	B9	overcurrent
B1	Fixture component failure	B10	Temperature is too high
B2	Fixture operation failure	B11	Spindle does not rotate
B3	Piston is unstable	B12	Spindle speed is unstable
B4	Overflow valve blocked		

Table 4 Fault tree basic event description table

Mode number	*Failure mode*	*Mode number*	*Failure mode*
X1	The main motor coupling is loose	X21	Bearing sleeve wear
X2	Temperature switch circuit virtual connection	X22	Preload is too large
X3	Broken claw	X23	Insufficient of lubricating oil
X4	Butterfly spring crack	X24	Circuit current is too large
X5	Loose nut of the pull claw	X25	The fuse is not disconnected
X6	The connecting rod thread is defective	X26	Motor short circuit
X7	Piston ring damaged	X27	Poor power connection
X8	hydro-cylinder Internal leakage	X28	Coding line is disconnected
X9	hydro-cylinder crawl	X29	Inverter acceleration and deceleration time is too short
X10	hydro-cylinder External leakage	X30	Insufficient coolant
X11	No pressure in upper chamber of main valve	X31	Front bearing heating
X12	Spring force is too small	X32	Large cutting volume
X13	Burnt coil	X33	Spindle stuck
X14	Slow response	X34	Poor connection between control unit and motor
X15	Oil viscosity is too high	X35	The printed circuit board is dirty
X16	Blocked suction pipe	X36	Broach not in place
X17	Insufficient oil	X37	Override switch circuit is loose
X18	The adjustment screw is loose	X38	The grating is too dirty
X19	Oil pump speed is too low	X39	Aging of electronic components
X20	Pre-tightening force is too small		

Table 5 Basic event failure probability and probability importance table

Mode number	*Failure probability P_i*	*Probability importance I_i*	*Mode number*	*Failure probability P_i*	*Probability importance I_i*
X1	2.3335×10^{-5}	0.9990422	X21	3.0662×10^{-5}	0.9990495
X2	3.4775×10^{-5}	0.9990536	X22	2.3335×10^{-5}	0.9990422
X3	3.4856×10^{-5}	0.9990537	X23	3.4775×10^{-5}	0.9990536
X4	2.3335×10^{-5}	0.9990422	X24	3.0662×10^{-5}	0.9989956
X5	3.0662×10^{-5}	0.9990495	X25	2.3335×10^{-5}	0.9989882
X6	2.3335×10^{-5}	0.9990422	X26	3.4775×10^{-5}	0.9990536
X7	2.3335×10^{-5}	0.9990422	X27	3.0662×10^{-5}	0.9990495
X8	3.4775×10^{-5}	0.9990536	X28	2.3335×10^{-5}	0.9990422
X9	3.4775×10^{-5}	0.9990536	X29	2.3335×10^{-5}	0.9990422
X10	3.4855×10^{-5}	0.9990537	X30	3.4775×10^{-5}	0.9990536
X11	2.3335×10^{-5}	0.9989956	X31	3.4855×10^{-5}	0.9990537
X12	2.3335×10^{-5}	0.9989956	X32	3.0662×10^{-5}	0.9990495
X13	3.4775×10^{-5}	0.9990536	X33	2.3335×10^{-5}	0.9990422
X14	3.0662×10^{-5}	0.9990495	X34	3.0662×10^{-5}	0.9990495
X15	2.3335×10^{-5}	0.9990422	X35	2.3335×10^{-5}	0.9990422
X16	3.4775×10^{-5}	0.9990536	X36	2.3335×10^{-5}	0.9990422
X17	2.3335×10^{-5}	0.9990422	X37	2.3335×10^{-5}	0.9990422
X18	2.3335×10^{-5}	0.9990422	X38	2.3335×10^{-5}	0.9990422
X19	2.3335×10^{-5}	0.9990422	X39	2.3335×10^{-5}	0.9990422
X20	3.4775×10^{-5}	0.9990536			

Taking the fault probability P_i of the basic event of the fault tree in Table 1, the fault probability of the intermediate event can be obtained according to equations (4) and (5), and substituting it into equation (7) to obtain the probability importance of the intermediate event in the second layer of the fault tree. The calculation results are shown in Table 6.

Table 6 Probabilistic importance and failure probability of second-level events

Mode number	*Failure probability*	*Probability importance I_i*
A1	1.1218×10^{-4}	0.999130991
A2	3.2122×10^{-4}	0.999327484
A3	1.4686×10^{-4}	0.999161508
A4	2.4713×10^{-4}	0.999265857
A5	1.7066×10^{-4}	0.999189432

According to equations (5) and (6), the probability of occurrence of the fault tree top event is 9.8109×10^{-4}. It is now required that the fault probability can be reduced to 5.0×10^{-4} in the newly designed spindle system. Redistribute the fault probabilities of events A1, A2, A3, A4 and A5, and establish a system of equations from equations (9) to (11).

$$\begin{cases} \Delta q_1 : \Delta q_2 : \cdots : \Delta q_i = I_1 : I_2 : \cdots : I_i \\ P_i^* = P_i + \Delta q_i \\ P_S^* = 1 - \prod_{i=1}^{n} \left(1 - \left(P_i + \Delta q_i\right)\right) \end{cases} \tag{20}$$

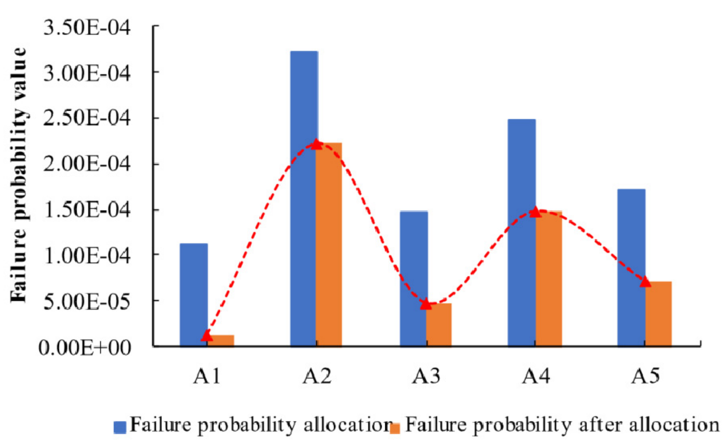
The MATLAB software can be used to calculate the result of the top event assignment, as shown in Table 7.

Table 7 Top event assignment results comparison

Mode number	*Failure probability before assignment*	*Failure probability after assignment*
A1	1.1218×10^{-4}	1.2596×10^{-5}
A2	3.2122×10^{-4}	2.2162×10^{-4}
A3	1.4686×10^{-4}	4.7273×10^{-5}
A4	2.4713×10^{-4}	1.4753×10^{-4}
A5	1.7066×10^{-4}	7.1070×10^{-5}

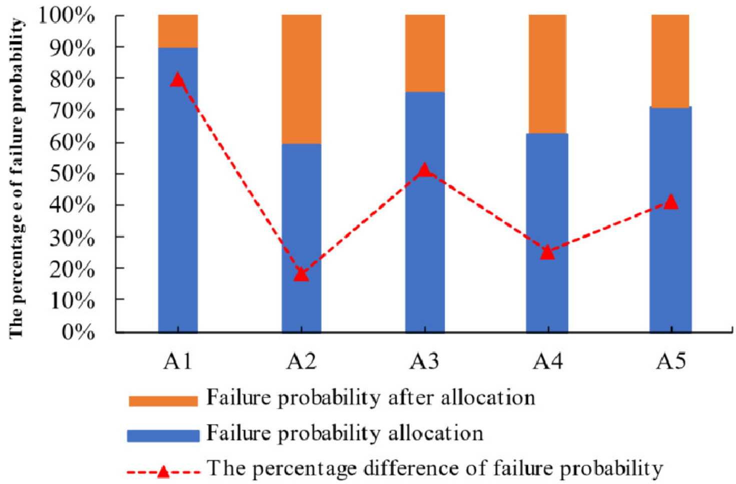
In order to have a clearer and more intuitive understanding of the comparison results after top event assignment, as shown in Figure 4.

Figure 4 Top event assignment result comparison chart (a) top event assignment results graph (b) Analysis chart of the proportion of top event assignment results



(a)

Figure 4 Top event assignment result comparison chart (a) top event assignment results graph (b) Analysis chart of the proportion of top event assignment results (continued)



(b)

It can be seen from Table 7 and Figure 4 that the failure probability of events A2, A4 and A5 is still very high. According to the principle of reliability assignment, it is known that for high failure probability events, the parts with higher allocated reliability index are more difficult to be improved. Therefore, when the conditions are met, the events with high failure probability should be allocated to a lower reliability index. The comparison of the assignment results proves that the reliability index allocated to each event is reasonable.

3.2 *Reliability assignment of intermediate events in spindle system based on fault tree*

After the assignment of the reliability index of the top event is completed, the failure probability of the first-level intermediate event has changed. The reliability redistribution method needs to be used for the first-level intermediate events. The event 'A1 fixture loosening and clamping device failure' is taken as an example for illustration. The specific steps are as follows:

1) *First, sort the events in descending order of failure probability*: The failure probability of events B1 and B2 at the next level of the A1 event in the fault tree is:

$$P_{B1} = 8.8844 \times 10^{-5},\ P_{B2} = 5.3996 \times 10^{-5} \text{ so } P_{B2} < P_{B1} \tag{21}$$

Reduce the failure probability of events with a higher failure probability P_{B1} to P_0 and keep the failure probability of P_{B2} unchanged. From Table 5, it can be seen that the failure probability of A1 after assignment is $P_S^* = 1.2596 \times 10^{-5}$, and the relationship between the failure probability of A1 and the failure probability of events B1 and B2 is expressed by equation (13).

Use trial and error method to determine k_o and P_o.

When $k_o = 1$,

$$P_{B2} = 5.3996 \times 10^{-5}$$

$$P_0 = 1 - \frac{\left(1 - P_S^*\right)}{\left(1 - P_{B2}\right)} = -4.1402 \times 10^{-5} < 0 \tag{22}$$

When $k_o = 2$,

$$P_S^* = 1 - \left(1 - P_0\right)^2$$

$$P_0 = 1 - \left(1 - P_S^*\right)^{\frac{1}{2}} = 6.2980 \times 10^{-6} \tag{23}$$

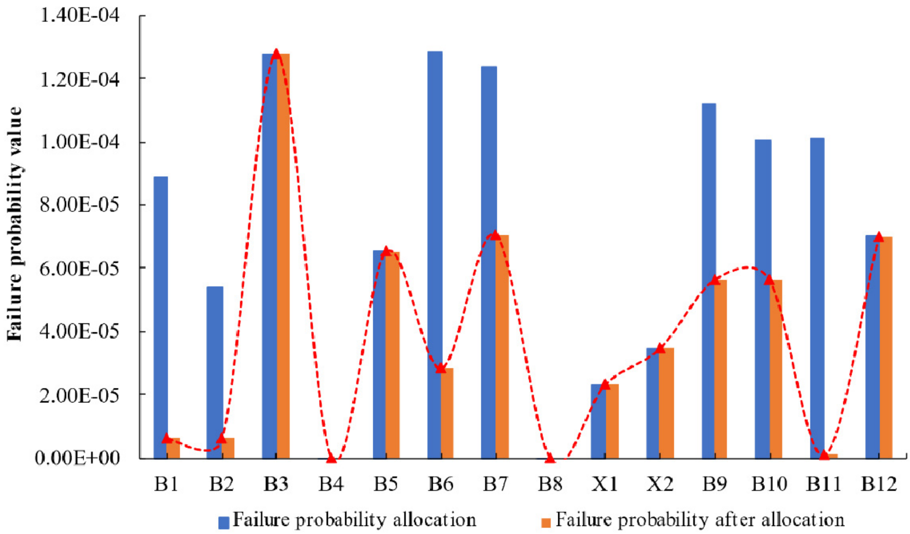
Since there are B1 and B2 in the next layer of event A1, it can be known from equation (13) that when the failure probability of events B1 and B2 are adjusted, the failure probability after the assignment of event A1 can be met. At this time, the failure probability of events B1 and B2 is 6.2980×10^{-6}.

Similarly, events A2, A3, A4 and A5 can be filtered through equation (13) to screen out the secondary events that need to adjust the failure probability. The results are shown in Table 8 and Figure 5.

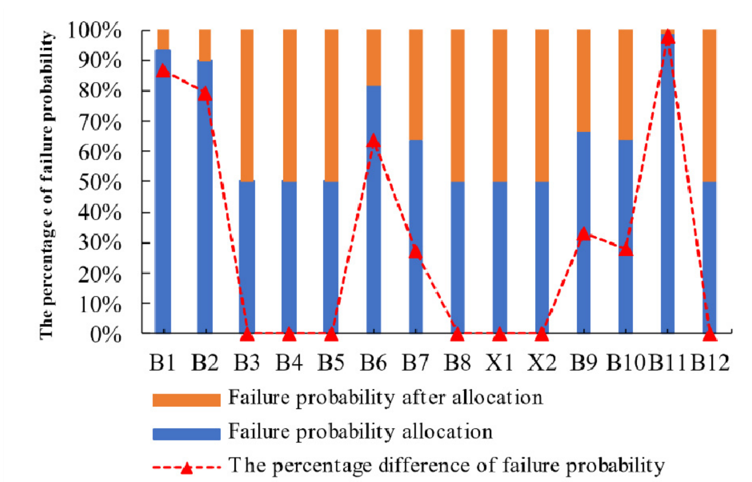
Table 8 Comparison of reliability assignment results of fault tree secondary intermediate events

Mode number	*Failure probability before assignment*	*Failure probability after assignment*	*Mode number*	*Failure probability before assignment*	*Failure probability after assignment*
B1	8.8844×10^{-5}	6.2980×10^{-6}	B8	7.1550×10^{-10}	7.1550×10^{-10}
B2	5.3996×10^{-5}	6.2980×10^{-6}	X1	2.3335×10^{-5}	2.3335×10^{-5}
B3	1.2772×10^{-4}	1.2772×10^{-4}	X2	3.4770×10^{-5}	3.4770×10^{-5}
B4	5.4452×10^{-10}	5.4452×10^{-10}	B9	1.1210×10^{-4}	5.6384×10^{-5}
B5	6.5431×10^{-5}	6.5431×10^{-5}	B10	1.0028×10^{-4}	5.6384×10^{-5}
B6	1.2810×10^{-4}	2.8482×10^{-5}	B11	1.0066×10^{-4}	1.0671×10^{-6}
B7	1.2353×10^{-4}	7.0606×10^{-5}	B12	7.0003×10^{-5}	7.0003×10^{-5}

Figure 5 Comparison chart of first-level event assignment results (a) Intermediate event assignment result graph (b) Analysis chart of the proportion of intermediate event assignment results



(a)



(b)

From Table 8 and Figure 5, it can be seen that after the assignment of the first-level intermediate events is completed, the new failure probability of the second-level event is obtained. Among them, B1, B2, B6, B7, B9, B10, B11 events need to be adjusted to the next layer of events to meet the new failure probability requirements. Secondary events that require a change in fault probability are shown in Table 9.

Table 9 Secondary intermediate events that need to change the probability of failure

Mode number	*Failure probability before assignment*	*Failure probability after assignment*	*Mode number*	*Failure probability before assignment*	*Failure probability after assignment*
B1	8.8844×10^{-5}	6.2980×10^{-6}	B9	1.1210×10^{-4}	5.6384×10^{-5}
B2	5.3996×10^{-5}	6.2980×10^{-6}	B10	1.0028×10^{-4}	5.6384×10^{-5}
B6	1.2810×10^{-4}	2.8482×10^{-5}	B11	1.0066×10^{-4}	1.0671×10^{-6}
B7	1.2353×10^{-4}	7.0606×10^{-5}			

3.3 Calculation of reliability assignment for secondary intermediate events in fault trees

After the reliability assignment of the first-level intermediate events is completed, this paper assigns the reliability indicators to the second-level intermediate events that need to be adjusted based on the AHP. The specific steps are as follows:

1) *Establish a hierarchy of basic events*: Establishing the hierarchy of basic events requires consideration of influencing factors such as event frequency M1, event importance M2, maintenance difficulty M3 and cost M4. Therefore, the basic event hierarchy is established with M1, M2, M3 and M4 as the criterion level, as shown in Figure 6.

Figure 6 Basic event hierarchy diagram

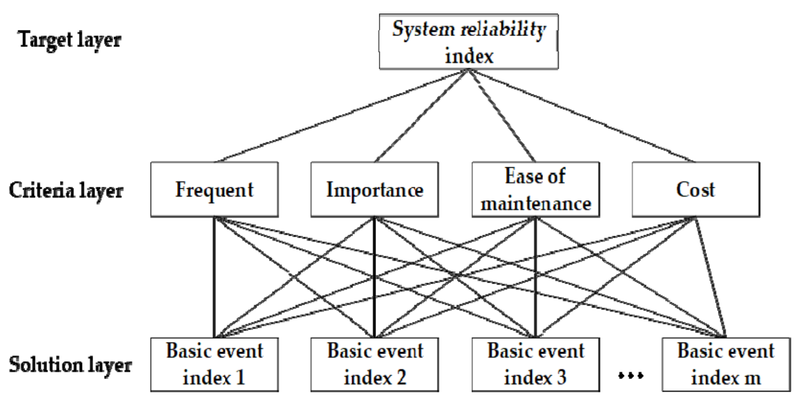


Table 10 Criterion-level judgment matrix

E	*M1*	*M2*	*M3*	*M4*
M1	1	3	2	3
M2	1/3	1	2	1
M3	1/2	1/2	1	1/2
M4	1/3	1	2	1

2) The calculation scheme layer checks the weight vector of the criterion layer and conducts the consistency check. Input the matrix into the MATLAB software to obtain the maximum eigenvalue $\lambda_{\max} = 4.1545$, and the consistency index can be obtained by equation (14).

$$C = \left(\lambda_{\max} - n\right) / \left(n - 1\right) = \left(4.1545 - 4\right) / 3 = 0.0515 \tag{24}$$

According to Table 2 and equation (17), we can get the value of C_R.

$$C_R = C / R = 0.0572 < 0.1 \tag{25}$$

Using the eigenvalue method, the weight of the scheme layer to the criterion layer can be obtained as: (0.6326, 0.1343, 0.0988, 0.1343).

3) *Calculate the weight of the scheme layer to the criterion layer*: The M1 and M2 of the basic event are calculated based on the failure probability and probability importance of each basic event, so the M1 and M2 judgment matrix of each basic event can be directly calculated. The judgment matrix of M3 and M4 is judged by experts according to Table 1.

This article takes the event B1 as an example for the calculation of the tool claw failure. The calculation process of other events is the same as that of the event B1, so the calculation results are directly given.

The judgment matrix of event B1 under 'event frequency M1' is shown in Table 11.

Table 11 Judgment matrix for frequent events

M1	*X3*	*X4*	*X5*
X3	1	1.4935	1.1366
X4	0.6696	1	0.7610
X5	0.8798	1.3140	1

Use MATLAB software to find the maximum eigenvalue of 3, test consistency index $C_R = 0 < 0.1$ and pass the test, the judgment matrix is reasonable. The weight is (0.2967, 0.3670, 0.3363).

The judgment matrix of event B1 under 'event frequency M2' is shown in Table 12.

Table 12 Judgment matrix of event importance.

M1	*X3*	*X4*	*X5*
X3	1	1.000011511	1.000004204
X4	0.999988489	1	0.999992693
X5	0.999995796	1.000007307	1

Use MATLAB software to find the maximum eigenvalue of 3, test consistency index $C_R = 0 < 0.1$ and pass the test, the judgment matrix is reasonable. The weight is (0.3561, 0.3386, 0.3053).

The judgment matrix of event B1 under 'difficulty of maintenance M3' is shown in Table 13.

Table 13 Judgement matrix of maintenance difficulty

M3	*X3*	*X4*	*X5*
X3	1	1	2
X4	1	1	2
X5	1/2	1/2	1

Use MATLAB software to find the maximum eigenvalue of 3, test consistency index $C_R = 0 < 0.1$ and pass the test, the judgment matrix is reasonable. The weight is (0.3238, 0.4508, 0.2254).

The judgment matrix of event B1 under 'cost M4' is shown in Table 14.

Table 14 Cost judgment matrix

M4	*X3*	*X4*	*X5*
X3	1	1	3
X4	1	1	3
X5	1/3	1/3	1

Use MATLAB software to find the maximum eigenvalue of 3, test consistency index $C_R = 0 < 0.1$ and pass the test, the judgment matrix is reasonable. The weight is (0.3892, 0.4466, 0.1643).

4) According to equation (16), the weights of events X3, X4 and X5 relative to the target layer can be expressed by the following equation:

$$\begin{aligned} w_{X3} &= (0.6326, 0.1343, 0.0988, 0.1343)(0.2967, 0.3561, 0.3238, 0.3892)^T = 0.3198 \\ w_{X3} &= (0.6326, 0.1343, 0.0988, 0.1343)(0.3670, 0.3386, 0.4508, 0.4466)^T = 0.3822 \\ w_{X3} &= (0.6326, 0.1343, 0.0988, 0.1343)(0.3363, 0.3053, 0.2254, 0.1643)^T = 0.2981 \end{aligned} \tag{26}$$

Therefore, the weight of event B1 is (0.3198, 0.3822, 0.2981).

The same can be obtained, the weights of events B2, B6, B7, B9, B10 and B11 relative to the target layer can be expressed by the following equation:

$$\begin{aligned} w_{B2} &= (0.4629, 0.5017) \\ w_{B6} &= (0.2081, 0.1526, 0.1869, 0.1984, 0.2369) \\ w_{B7} &= (0.2106, 0.3932, 0.2386, 0.1576) \\ w_{B9} &= (0.2799, 0.2330, 0.22960.2575) \\ w_{B10} &= (0.2767, 0.3235, 0.3998) \\ w_{B11} &= (0.2333, 0.1864, 0.3189, 0.2614) \end{aligned} \tag{27}$$

5) The reliability index is allocated according to the vector. Use equation (19). Obtain the failure probability of each basic event. Take event B1 as an example.

$$P_{X3} = \left(6.2980\times10^{-6}\right)\times\frac{\left(\frac{1}{0.3198}\right)}{\left(\frac{1}{0.3198}+\frac{1}{0.3822}+\frac{1}{0.2981}\right)} = 2.16\times10^{-6}$$

$$P_{X4} = \left(6.2980\times10^{-6}\right)\times\frac{\left(\frac{1}{0.3822}\right)}{\left(\frac{1}{0.3198}+\frac{1}{0.3822}+\frac{1}{0.2981}\right)} = 1.81\times10^{-6} \tag{28}$$

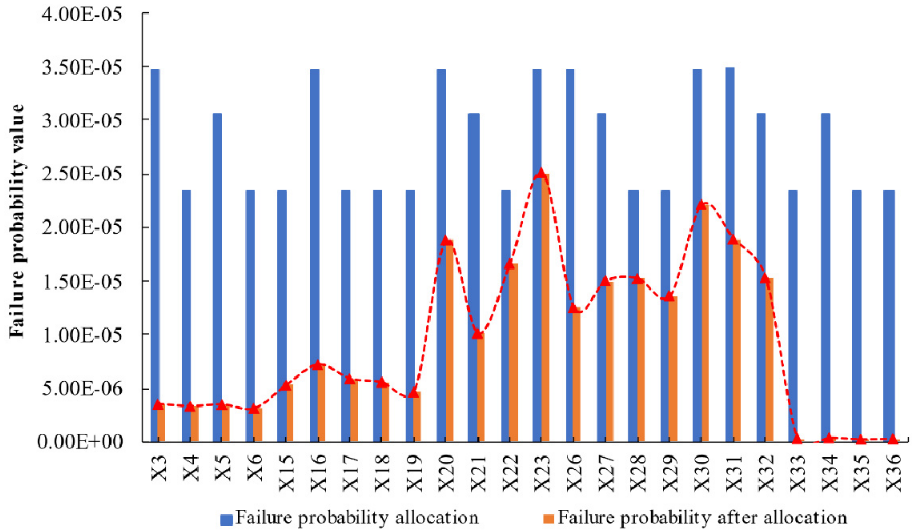
$$P_{X5} = \left(6.2980\times10^{-6}\right)\times\frac{\left(\frac{1}{0.2981}\right)}{\left(\frac{1}{0.3198}+\frac{1}{0.3822}+\frac{1}{0.2981}\right)} = 2.32\times10^{-6}$$

In the same way, the failure probability of the basic events of events B2, B6, B7, B9, B10 and B11 can be obtained. Since there are repeated basic events in the event, in order to improve the reliability level, the failure probability value of the basic event with a lower failure probability is selected and the result is as follows Table 15, as shown in Figure 7.

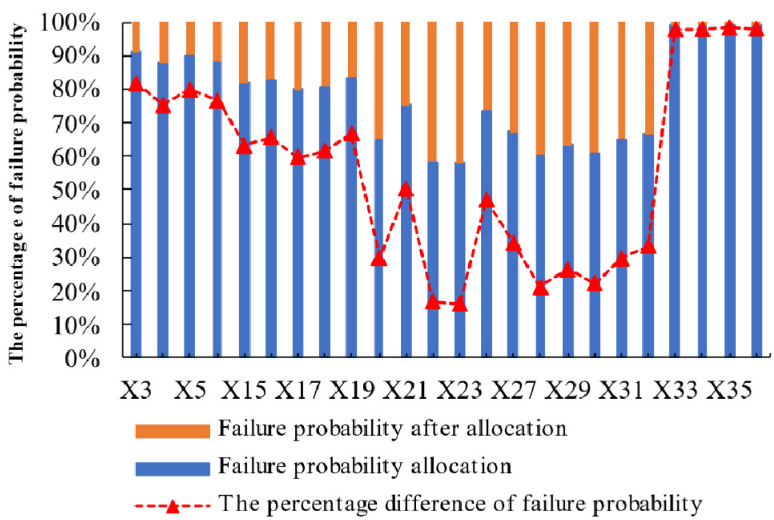
Table 15 Comparison of failure probability assignment results for secondary events

Mode number	*Failure probability before assignment*	*Failure probability after assignment*	*Mode number*	*Failure probability before assignment*	*Failure probability after assignment*
X3	3.4775×10^{-5}	3.56×10^{-7}	X23	3.4775×10^{-5}	2.51×10^{-5}
X4	2.3335×10^{-5}	3.32×10^{-7}	X26	3.4775×10^{-5}	1.25×10^{-5}
X5	3.0662×10^{-5}	3.45×10^{-7}	X27	3.0662×10^{-5}	1.50×10^{-5}
X6	2.3335×10^{-5}	3.10×10^{-6}	X28	2.3335×10^{-5}	1.52×10^{-5}
X15	2.3335×10^{-5}	5.27×10^{-6}	X29	2.3335×10^{-5}	1.36×10^{-5}
X16	3.4775×10^{-5}	7.19×10^{-6}	X30	3.4775×10^{-5}	2.21×10^{-5}
X17	2.3335×10^{-5}	5.87×10^{-6}	X31	3.4855×10^{-5}	1.89×10^{-5}
X18	2.3335×10^{-5}	5.53×10^{-6}	X32	3.0662×10^{-5}	1.53×10^{-5}
X19	2.3335×10^{-5}	4.63×10^{-6}	X33	2.3335×10^{-5}	2.75×10^{-7}
X20	3.4775×10^{-5}	1.88×10^{-5}	X34	3.0662×10^{-5}	3.45×10^{-7}
X21	3.0662×10^{-5}	1.01×10^{-5}	X35	2.3335×10^{-5}	2.01×10^{-7}
X22	2.3335×10^{-5}	1.66×10^{-5}	X36	2.3335×10^{-5}	2.46×10^{-7}

Figure 7 Comparison chart of secondary event assignment results (a) Bottom event assignment result graph (b) Analysis chart of the proportion of bottom event assignment results



(a)



(b)

Through calculation, the reliability assignment of the CNC machine tool spindle system is finally completed. From Table 15 and Figure 7, it can be seen that the tool claw is damaged X3, the butterfly spring is cracked X4, and the connecting rod and the tool claw nut are loosened X5, Defects in connecting rod thread processing X6, excessive oil viscosity X15, impurity blockage in the suction pipe X16, insufficient oil volume X17, loose pressure adjustment screw X18, oil pump speed too low X19, small preload X20, bearing sleeve wear X21, preload large force X22, insufficient lubricating oil X23, partial motor short circuit X26, poor power connection X27, spindle code line disconnection X28, inverter acceleration and deceleration time is too short X29, insufficient coolant X30, large cutting amount X31, front bearing heating X32, Spindle stuck X33, poor connection between spindle control unit and motor X34, printed circuit board dirty X35, broach not in place X36 are all key considerations for redesigning the spindle system.

4 Conclusion

Use the fault tree structure to carry out reliability assignment, and the fault events to indicate the failure of machine tool subsystems and parts, so that the assignment task of reliability assignment is clear and the reliability index can be distributed down layer by layer, and finally reliability indexes are allocated to the parts of the system. Owing to the different content of events between different layers in the fault tree, the influencing factors and the number of events included, the methods suitable for each layer are used to allocate methods: use probability importance for top events, reliability reassignment method for intermediate events and analytic hierarchy process for bottom event. This method makes the assignment process clearer and makes the assignment result more accurate. At the same time, this method effectively solves the problems of incomplete considerations and low assignment efficiency that are common in current assignment methods, and the assignment results are useful for system optimisation and design. All have a certain reference value.

Acknowledgement

This work was supported by the National Natural Science Foundation of China [Grant No. 51965051].

References

Baladeh, A.E. and Zio, E. (2021) ‘A two-stage stochastic programming model of component test plan and redundancy assignment for system reliability optimization’, *IEEE Transactions on Reliability*, Vol. 70, pp.99–109. Available online at: Doi: 10.1109/tr.2020.2974284.

Burdyshev, I.V. and Tyurin, S.F. (2021) ‘Increasing reliability by reallocating the failure probabilitys’, *Proceedings of the IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus)*, Saint Petersburg Electrotechnical University, RUSSIA, pp.256–259.

Catelani, M., Ciani, L., Patrizi, G. and Venzi, M. (2016) ‘Reliability assignment assessment using MEOWA method in complex redundant systems’, *Proceedings of the IEEE International Symposium on Systems Engineering (ISSE)*, Edinburgh, UK, pp.1–5.

Catelani, M., Ciani, L., Patrizi, G. and Venzi, M. (2017) ‘Reliability assignment procedures in complex redundant systems’, *IEEE Systems Journal*, pp.1182–1192.

Ding, R., Liu, Z.H., Xu, J.T., Meng, F.P., Sui, Y. and Men, X.H. (2021) ‘A novel approach for reliability assessment of residual heat removal system for HPR1000 based on failure mode and effect analysis, fault tree analysis, and fuzzy Bayesian network methods’, *Reliability Engineering and System Safety*, Vol. 216. Doi: 10.1016/j.ress.2021.107911.

Eldosouky, A., Saad, W. and Mandayam, N. (2021) 'Resilient critical infrastructure: Bayesian network analysis and contract-based optimization', *Reliability Engineering and System Safety*, Vol. 205. Doi: 10.1016/j.ress.2020.107243.

Gao, S., Zhang, W., He, X., Zou, Y.M., Li, W. (2020) 'Spacecraft fault diagnosis based on improved A* algorithm', *Proceedings of the 39th Chinese Control Conference (CCC)*, Shenyang, China, pp.4097–4100.

Hongbin, Z., Zhixin, J.I.A. and Anmin, X.I. (2009) 'Fuzzy decision method in NC machine reliability assignment', *Manufacturing Technology and Machine Tool*, Vol. 30, pp.60–63. Doi: 10.1109/MILCOM.2009.5379889.

Kalantari, K.R., Ebrahimnejad, A. and Motameni, H. (2020) 'Efficient improved ant colony optimisation algorithm for dynamic software rejuvenation in web services', *IET Software*, Vol. 14, pp.369–376. Doi: 10.1049/iet-sen.2019.0018.

Kim, D. and Kim, K.O. (2021) 'Optimal assignment of reliability improvement target under dependent component failures', *Proceedings of the Institution of Mechanical Engineers Part O-Journal of Risk and Reliability*. Doi: 0.1177/1748006x211035635.

Li, H., Díaz, H. and Guedes Soares, C. (2021b) 'A failure analysis of floating offshore wind turbines using AHP-FMEA methodology', *Ocean Engineering*, Vol. 234. Doi: 10.1016/j.oceaneng.2021.109261.

Li, H., Xie, L., Song, J. and Zhao, Z. (2018) 'Reliability assignment optimization of aero engine based on grey prediction theory', *Proceedings of the 12th International Conference on Reliability, Maintainability, and Safety (ICRMS)*, Shanghai, China, pp.457–462.

Li, P., Dang, W., Li, T. and Lu, C. (2021a) 'System-level accelerated reliability demonstration testing design based on fuzzy logic and AHP', *Journal of University of Chinese Academy of Sciences*, Vol. 38, pp.121–129. Doi: 10.7523/j.issn.2095-6134.2021.01.015.

Liu, W., Song, D., Wang, Z.P., Zhu, Y.B. and Li, Q. (2020) 'Error bounds of the GNSS/INS integrated system against GNSS fault for integrity monitoring', *International Technical Meeting of the Institute of Navigation*, pp.557–569. Available online at: Doi: 10.33012/2020.17161.

Liu, X., Wang, R., Hu, D., Mao, J. and Chen, G. (2021) 'Reliability-based design optimization approach for compressor disc with multiple correlated failure modes', *Aerospace Science and Technology*, Vol. 110. Doi: 10.1016/j.ast.2021.106493.

Nair, R.K.R., Pothiraj, S. and Nair, T.R.R. (2020) 'A novel optimization approach for partitioning-based place and route in 3D integrated circuits', *International Journal of Electrical Engineering Education*. Doi: 10.1177/0020720920930346.

Parihar, A.S. and Chakraborty, S.K. (2021) 'Token-based approach in distributed mutual exclusion algorithms: a review and direction to future research', *Journal of Supercomputing*, Vol. 77, pp.14305–14355. Doi: 10.1007/s11227-021-03802-8.

Ryu, J. and Jae, M. (2021) 'A quantification methodology of seismic probabilistic safety assessment for nuclear power plant', *Annual Nuclear Energy*, Vol. 159. Doi: 10.1016/j.anucene.2021.108296.

Umma, B., Maa, C., Oa, A. and Ia, A. (2021) 'Optimization and estimation in system reliability assignment problem', *Reliability Engineering and System Safety*, Vol. 212. Doi: 10.1016/j.ress.2021.107620.

Wei, G., Xu, L. and Wang, H-K. (2012) 'A method of complex software system reliability assignment based on ANP', *Proceedings of the 18th ISSAT International Conference on Reliability and Quality in Design*, Boston, MA, pp.86–90.

Wu, X.Y., Wu, X.Y. and Balakrishnan, N. (2018) 'Reliability assignment model and algorithm for phased mission systems with uncertain component parameters based on importance measure', *Reliability Engineering and System Safety*, Vol. 180, pp.266–276. Doi: 10.1016/j.ress.2018.07.022.

Wu, Y. and Sun, W. (2021) 'Research on the reliability assignment calculation method of a wind turbine generator set based on a vine copula correlation model', *Energy Science and Engineering*, Vol. 9, pp.1543–1553. Doi: 10.1002/ese3.927.

Xu, M., Li, D., Zhou, S.Q. and Huang, X.J. (2020) 'Reliability assignment based on importance measures', *Lect Notes Electr En*, Vol. 595, pp.441–454. Doi: 10.1007/978-981-15-1876-8_44.

Yalaoui, A., Chu, C. and Chatelet, E. (2005) 'Reliability assignment problem in a series-parallel system', *Reliability Engineering and System Safety*, Vol. 90, pp.55–61. Doi: 10.1016/j.ress.2004.10.007.

Zhang, Q., Li, J., Xie, L. and He, X. (2019) 'Integrated factor reliability assignment method considering influences of two-layer factors', *China Mechanical Engineering*, Vol. 30, pp.2301–2305.

Zhang, X. and Wu, X. (2012) 'Advances in system reliability assignment', *Fire Control and Command*, Vol. 37, pp.1–4. Doi: 10.1109/icqr2mse.2012.6246188.

Zhou, C. and Li, Z. (2011) 'Research on the approach of reliability assignment based on D-S theory', *Proceedings of the International Conference on Recent Trends in Materials and Mechanical Engineering (ICRTMME'11)*, Shenzhen, China, pp.1599–1604.