Group maintenance strategy of CNC machine tools considering three kinds of maintenance dependence and its optimization

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Abstract

Unreasonable maintenance strategy will increase maintenance cost and reduce the efficiency of CNC (Computer Numerical Control) machine tools. Therefore, not only the degradation state of components but also their coupling effect should be considered to obtain a scientific and reasonable system-level maintenance strategy because of the dependence among different components of CNC machine tools. This study proposes a group maintenance strategy of CNC machine tools considering economic dependence, structural dependence, and stochastic dependence among critical components and optimizes the group maintenance strategy. The model of group maintenance of CNC machine tools is composed of four sub-models: sub-model of component degradation, sub-model of group maintenance decision, sub-model of imperfect maintenance, sub-model of maintenance cost. Utilizing the model of group maintenance of CNC machine tools, the time, objectives, and measure of maintenance can be decided according to the degradation state and failures of components. And then, the cost of each maintenance can be calculated. In the group maintenance model, economic dependence and structural dependence among components are quantified by cost, while stochastic dependence is quantified by failure intensity. On that basis, the Monte Carlo method is used to simulate the machine tool operation process, and the long-term maintenance cost of CNC machine tools corresponding to a certain failure intensity threshold is calculated. Finally, genetic algorithm is used to optimize the failure intensity thresholds of preventive maintenance and group maintenance. A numerical example verifies the effectiveness of the proposed optimization method for the group maintenance strategy.

Keywords Group maintenance · Non-homogeneous Poisson process · Maintenance dependence · CNC machine tools

1 Introduction

CNC (Computer Numerical Control) machine tools, known as industrial master machine, play an important role in many aspects of modern industry. The efficiency and cost of processing depend on the reliability and availability of CNC machine tools to a great extent. The development of industrial technology has driven the structure of CNC machine tools more and more complex, and the dependence among components is even closer. The reliability and availability of machine tools are affected by many critical components, such as spindle [1], cooling component [2], ball screw mechanism [3], and so on. As a result, the maintenance strategy of machine tools depends on the degradation state of components not only, but also on their coupling effect, which causes considerable difficulty in formulating a proper maintenance strategy. The study of maintenance dependence has become the key to avoiding the increase of maintenance cost caused by unreasonable maintenance strategies.

Due to the complex coupling relationship among components of CNC machine tools, the optimal system-level maintenance strategy is not a simple superposition of component-level strategies. It needs adjustment and optimization based on maintenance dependence. Maintenance dependence can be classified into three main categories: economic dependence, structural dependence, and stochastic dependence [4]. Economic dependence implies that the cost of simultaneous maintenance of multiple components is different
from that of individual maintenance [5]. If the former is lower than the latter, economic dependence is positive. Otherwise, economic dependence is negative. Owing to the close relationship between cost of maintenance and economic dependence, the influence of economic dependence has been considered and studied in many aspects of formulating a maintenance strategy [6, 7], such as determining the time to execute maintenance [8, 9], selecting the objective components [10], calculating the inspection interval [11], and so on. Structural dependence means that maintenance of one component requires the disassembly or maintenance of other components [12]. The influence of structural dependence on the maintenance strategy has been studied intensively in the past few years [13, 14]. Verbert [15] proposed a strategy of timely maintenance planning for multi-component systems considering economic dependence and structural dependence to profit from spreading or combining various maintenance activities. Zhang [16] developed a multi-mission selective maintenance optimization model for a multi-component system over a finite time horizon and optimized intervention time and corresponding maintenance option of each component considering structural dependence. Dinh [17] investigated the impact of disassembly operations on the degradation process and reliability of component/system due to structural dependence and proposed an optimized maintenance strategy for multi-component systems. Stochastic dependence means that the degradation state of one component is affected by the failure of other components [18]. Considering stochastic dependence and economic dependence, Li [19] established a model of stochastic dependence with Levy copulas and analyzed the influence of dependence degree on maintenance strategy. Yildirim [20] proposed an integrated framework for wind farm maintenance that combined predictive analytics methodology with an optimization model considering economic dependence and stochastic dependence. Shahrahi [21] proposed a selective maintenance optimization method for complex systems composed of stochastically dependent components, which captures the two-way interaction between components through system performance rates. Although many models of maintenance dependence have been proposed, almost existing studies only focus on one or two types of maintenance dependence, which cannot perfectly reflect the impact of all types of dependence. Especially, CNC machine tools are composed of multiple components, so there are multiple maintenance dependencies among components. Only comprehensive consideration of all types of maintenance dependence can accurately reflect the relationship of various components so that a reasonable and scientific maintenance strategy of CNC machine tools can be generated.

Because of these concerns, this study considers three kinds of maintenance dependence among critical components of CNC machine tools and proposes a system-level group maintenance strategy, which can determine the time and objectives of group maintenance. The remainder of this paper is organized as follows. The second section states a brief description of CNC machine tools and assumptions of the group maintenance strategy model. In the third section, the model of the group maintenance strategy of CNC machine tools is established, which can be used for formulating group maintenance and calculating maintenance cost. The fourth section optimizes the group maintenance strategy to minimize long-term maintenance cost by genetic algorithm. The fifth section conducts an example for optimizing the group maintenance strategy of a certain type of machining center. The sixth section presents conclusions and future work.

2 System description and assumptions

2.1 System description

As a complex electromechanical system, CNC machine tools are usually a serial system composed of many components, such as spindle component, feed component, lubricating component, cooling component, numerical control component, chip moving component, tool storage component, protective component, and so on. Among those, spindle component, feed component, lubricating component, cooling component, and tool storage component are critical components that play an important role in the availability of the CNC machine tools. Under a normal operating condition, critical components usually suffer a continuous and heavy load, which causes a significant part of failures. For the purpose of striking a balance between accuracy and complexity of the model, only critical components including spindle system, feed component, lubricating component, cooling component, and tool storage component are considered during formulating the group maintenance strategy in this paper.

2.2 Assumptions

Aiming to simplify the model of the group maintenance strategy properly, major assumptions adopted by this study are as follows:

1) The component-level maintenance strategy is formulated in this study. Hence, each critical component is considered as a whole unit, and the dependence among parts belonging to the critical components is ignored. If a failure occurs, the broken part is replaced by a new one while the normal parts remain. If the preventive maintenance is executed, parts of components are maintained and no part is replaced.

2) Due to the neglect of replacement of the whole component, maintenance can restore the state of the component to some extent. After maintenance, the state of a component is better than that at the moment of maintenance but
worse than the new state, that is, the maintenance effect is between ‘as good as new’ and ‘as bad as old’.

3) During the detection, CNC machine tools are shut down. The state of normal components remains unchangeable while the state of failed components is quantified by the sub-model of imperfect maintenance, that is, the state of components is independent of the duration of detection. As a result, the duration of detection is ignored to simplify simulation while the operating time is utilized to calculate failure intensity of components.

4) The professional maintenance crew is employed to maintain CNC machine tools. As a result, once the system breaks down, the failure can be identified immediately, and effective maintenance measures will be taken.

3 Model of group maintenance strategy of CNC machine tools

The model for the optimization of the group maintenance strategy of CNC machine tools proposed in this paper is composed of four sub-models: sub-model of component degression, sub-model of the group maintenance decision, sub-model of imperfect maintenance, and sub-model of maintenance cost. Besides, stochastic dependence exerts an effect on the sub-model of component degression. On the other hand, economic dependence and structural dependence exert an effect on sub-model maintenance cost, as shown in Fig. 1. Failure intensity $\lambda(t)$ is the number of component failures per unit time, which reflects its deterioration state. Setting the failure intensity as maintenance decision criteria can avoid negative consequences due to excessive failure intensity. During the CNC machine tools operating, maintenance decision can be made, and then the cost of maintenance is calculated correspondingly. First of all, the failure intensity of each component can be calculated by the sub-model of component degression according to the operating time and previous maintenance situation. Secondly, the maintenance decision can be made according to failure and failure intensity of each component in the sub-model of group maintenance decisions. Thirdly, the influence of each maintenance on the degression of components can be quantified by the sub-model of imperfect maintenance. Finally, the cost of maintenance is calculated through the sub-model of maintenance cost. Each sub-model will be introduced in the following parts in detail.

Fig. 1 The whole model of group maintenance of CNC machine tools
3.1 Sub-model of component degression

For a repairable system, the reliability before and after maintenance is related, and failures are no longer independent. Therefore, traditional probability distribution function cannot accurately describe the failure process. This study adopts the non-homogeneous Poisson process [22] to model the failure process by utilizing the failure intensity function of component as the intensity. The failure intensity of CNC machine tool components can be shown as [23]:

\[
\omega(t) = \frac{\alpha}{\beta} \left( \frac{t}{\beta} \right)^{\alpha-1}
\]

(1)

where \( \omega(t) \) is the failure intensity of the component at time \( t \), \( \alpha \) is the shape parameter of Weibull distribution function, and \( \beta \) is the scale parameter of Weibull distribution function.

Then, the cumulative intensity function of the non-homogeneous Poisson process from time \( t_0 \) to time \( t \) is

\[
\Lambda(t_0, t) = \int_{t_0}^{t} \omega(u) du
\]

(2)

According to the definition of the non-homogeneous Poisson process,

\[
P[N(t) - N(t_0) = 0] = \frac{[\Lambda(t_0, t)]^0}{0!} e^{-\Lambda(t_0, t)}
\]

(3)

where \( N(t) \) is the time of failure in time interval \([0, t]\).

So, according to the definition of failure probability distribution function of next failure, it can be obtained that

\[
F_{T_1} = P\{T_1 < t\} = P\{N(t) \geq 1\} = 1 - P\{N(t) = 0\}
\]

(4)

where \( T_1 \) is time of the first failure.

Substituting Eq. (3) into Eq. (4), it can be obtained that

\[
F_{T_1} = 1 - \frac{[\Lambda(t_0, t)]^0}{0!} e^{-\Lambda(t_0, t)}
\]

(5)

3.2 Sub-model of group maintenance decision

During the long-term operation of CNC machine tools, maintenance should be executed when some components fail or the failure intensity reaches a high level. As shown in Fig. 1, if some components of CNC machine tools break down, corrective maintenance should be executed on the failed component immediately. At the same time, if the failure intensity of some components exceeds the threshold of group maintenance, those components are selected to form component group \( I \), and then preventive maintenance is carried out, which is called group maintenance caused by failure in Fig. 1. Otherwise, only the corrective maintenance on the failed components is executed, which is called only corrective maintenance in Fig. 1.

When no system component fails but the failure intensity of one component reaches the threshold of preventive maintenance, CNC machine tools should be shut down, then the preventive maintenance is executed. At the same time, if the failure intensity of some other components reaches the threshold of group maintenance, those components are selected to form group \( N \), then the corresponding group maintenance is carried out, which is called group maintenance caused by preventive maintenance in Fig. 1. Otherwise, only the preventive maintenance is executed on the components whose failure intensity exceeds the threshold of preventive maintenance, which is called only preventive maintenance.

3.3 Sub-model of imperfect maintenance

As described in Sect. 2, the replacement of components is not taken into account when applying group maintenance. Thus, maintenance cannot be considered ‘as good as new’. Maintenance measures can restore the component to some extent, so it is unreasonable to consider it ‘as bad as old’. Actual maintenance can restore a component to achieve a state between ‘as good as new’ and ‘as bad as old’, and the degradation accelerates with the increase of failure times. Thus, degradation acceleration and service age regression factors are introduced to model imperfect maintenance [24, 25].

3.3.1 Degradation acceleration factor

After a failure occurs, maintenance can restore the function of the component, but the damage still exists, and the degradation will be faster than before. When the damage accumulates to a certain degree, the component cannot be repaired anymore. Equation (6) shows the change of failure intensity considering degradation acceleration factor:

\[
\omega_{i+1}(t) = a \omega_i(t - T_i)
\]

(6)

where \( a \) is the degradation acceleration factor, \( a > 1 \), \( \omega_i(t) \) is the failure intensity function of the component before the \( i \)th corrective maintenance, \( \omega_{i+1}(t) \) is the failure intensity function of the component after the \( i \)th corrective maintenance, and \( T_i \) is the time of the \( i \)th failure.

Figure 2 shows the failure intensity curve. In Fig. 2, \( a = 1.7 \), which is chosen just to illustrate the impact of the degradation acceleration factor on the failure intensity curve. The value of the degradation acceleration factor should be assigned according to the engineering experience during formulating the actual maintenance strategy.

3.3.2 Service age regression factor

After the maintenance is carried out, the component is restored to its previous state at a certain time, to which the equivalent
service age is returned. Equation (7) shows the change of failure intensity function.

$$\omega_{i+1}(t) = \omega_i(t-bT_i)$$  \hspace{1cm} (7)

where b is the service age regression factor, $\omega_i(t)$ is the failure intensity function of the component before the ith maintenance, $\omega_{i+1}(t)$ is the failure intensity function of the component after the ith maintenance.

When b=0, the system is repaired ‘as bad as old’, that is, failure intensity remains consistent before and after maintenance. When b=1, the system is repaired ‘as good as new’, that is, it is restored to its initial state. When 0<b<1, the state of the system is between ‘as bad as old’ and ‘as good as new’, that is, it is restored to a certain state before maintenance (but not the initial one). Figure 3 shows the failure intensity curve considering the service age regression factor.

Degradation acceleration factor and service age regression factor are used to model imperfect maintenance. Equation (8) shows the failure intensity function change before and after maintenance, and Fig. 4 shows the failure intensity curve. In Fig. 4, a=1.7 and b=0.7, which are chosen for illustrating the impact of degradation acceleration and service age regression factors on the failure intensity curve. The value should be obtained according to engineering experience during formulating the actual maintenance strategy of CNC machine tools.

$$\omega_{i+1}(t) = a^i \omega_i(t-bT_i)$$  \hspace{1cm} (8)

Besides, stochastic dependence also exerts influence on the degression process of components. When component m fails, component n may be affected, and its degradation state may jump to the state which should be after the failure. The change of failure intensity function can be described as

$$\omega_{i+1}(t) = \omega_i(t-hT_L)$$  \hspace{1cm} (9)

where $\omega_i(t)$ is the failure intensity function of component n after the ith failure, $T_L$ is the jump time caused by failure, and h is the failure times of component m after the ith failure of component n and before the next failure of component n.

Therefore, considering the imperfect maintenance and stochastic dependence, the failure intensity function of a component can be expressed as Eq. (10).

$$\omega_{i+1}(t) = a^i \frac{\alpha}{\beta} \left( \frac{t+(1-b)T_i+hT_L}{\beta} \right)^{\alpha-1}$$  \hspace{1cm} (10)

Then, according to Eqs. (8), (9), and (10), the distribution function of the next failure time after the ith maintenance is described as

Fig. 2 Failure intensity curve considering the degradation acceleration factor

Fig. 3 Failure intensity curve considering the service age regression factor

Fig. 4 Failure intensity curve considering degradation acceleration factor and service age regression factor
\[ F_{T_1} = 1 - e^{-\left\{ q \left[ \left( \frac{e^{-\beta_j T_1} - 1}{e^{-\beta_j T_1} - 1} \right)^{a} \right] \right\} }, \]  

(11)

3.4 Sub-model of maintenance cost

During long-term operation of CNC machine tools, the cost of maintenance for the component is composed of the cost of preventive maintenance and the cost of corrective maintenance. So, the whole maintenance cost \( C \) of long-term operation can be calculated by Eq. (12).

\[ C = \sum_{e=1}^{p} C_{R,e} + \sum_{f=1}^{q} C_{R,f} \]  

(12)

where \( C_{P,n} \) is the cost of maintenance caused by preventive maintenance, \( C_{R,f} \) is the cost of maintenance caused by failure, \( p \) is the maintenance times caused by preventive maintenance, and \( q \) is the maintenance times caused by corrective maintenance.

The cost of maintenance caused by component failure includes preparation cost and corrective maintenance cost. Besides, if group maintenance is executed, the cost of preventive maintenance executed on other components needs to be taken into account. Preparation cost is a fixed value for preventive maintenance or corrective maintenance and incorporates maintenance personnel and tools cost. However, due to unexpected failure, the preparation cost of corrective maintenance is higher than that of preventive maintenance. Therefore, when component \( j \) fails, maintenance cost includes corrective maintenance cost, preventive maintenance cost of component \( l \) composed of components whose failure intensity reaches the threshold of group maintenance, and preparation cost. So,

\[ C_{R,n} = C_Z + C_{I}^{l} + \sum C_{P}^{l} \]  

(13)

where \( C_{R,n} \) is the total cost for the \( n \)th corrective maintenance, \( C_{Z} \) is the preparation cost, \( C_{I}^{l} \) is the corrective maintenance cost for component \( j \), and \( \sum C_{P}^{l} \) is the preventive maintenance cost for component group \( l, i \in I \).

When no component fails but the failure intensity of component \( j \) reaches the threshold of preventive maintenance, component group \( N \) includes component \( j \) and other components whose failure intensity reaches the threshold of group maintenance. Maintenance cost consists of the preventive maintenance cost and preparation cost and it can be shown as

\[ C_{P,n} = C_Z + \sum C_{P}^{l} \]  

(14)

CNC machine tools are a multi-component system, where structural dependence exists. While repairing one component, some other components need to be repaired or disassembled. Therefore, if the maintenance is executed on the components which are structurally dependent simultaneously, the number of disassembling and assembling can be reduced. If structural dependence is taken into consideration, the maintenance cost is

\[ \begin{cases} 
C_{R,n} = C_Z + C_{I}^{l} + \sum C_{P}^{l} - uC_{-} \\
C_{P,n} = C_Z + \sum C_{P}^{l} - uC_{-} 
\end{cases} \]  

(15)

where \( u \) is the judgment coefficient. If structural dependence exists among components that need to be repaired, \( u = 1 \). Otherwise, \( u = 0 \). \( C_{-} \) is the cost reduced by structural dependence, \( C_{R,n} \) is the group maintenance cost caused by the \( n \)th corrective maintenance, and \( C_{P,n} \) is the cost of group maintenance caused by the \( n \)th preventive maintenance.

What is more, the economic dependence has a significant impact on the maintenance cost of long-term operating. However, whether the economic dependence is positive or negative is determined by the time and manner of maintenance. The explicit equation of economic dependence is difficult to imply, but during the optimization of the maintenance strategy, the impact of economic dependence can be considered.

4 Optimization of maintenance strategy for CNC machine tools

4.1 Establishment of the optimization model

4.1.1 Optimization objective function

This paper optimizes the maintenance strategy aiming at the minimum long-term maintenance cost, which is composed of the group maintenance cost caused by corrective and preventive maintenance. Due to the change of component failure intensity, the group maintenance decision varies in different maintenance time. Calculating the long-term maintenance cost of the system by the analytical method is extremely difficult, so the Monte Carlo method is used to simulate the system operation process and calculate the long-term maintenance cost [26, 27].

The Monte Carlo simulation process is described as follows:

Step 1: Initialize parameters. Assign values to Monte Carlo simulation and group maintenance model parameters, such as simulation times \( X \), component failure intensity parameters \( \{ (\alpha_i, \beta_i) \} i = 1, 2, \ldots, n \), preparation cost \( C_Z \), the corrective maintenance cost of component \( C_{I}^{l} \) of \( \{ i = 1, 2, \ldots, n \} \), the preventive maintenance cost of component \( C_{P}^{l} \) of \( \{ i = 1, 2, \ldots, n \} \), reduction of maintenance cost caused by structural dependence \( C_{-} \), degradation acceleration factor \( \{ a_i \} i = 1, 2, \ldots, n \), service age
regression factor \{b_i\} i = 1, 2, \ldots, n\}, the failure intensity jump time caused by failure \(T_L\), and total operating time of the system \(T\).

Step 2: Generate a random number of the first failure time. Calculate the inverse function of the distribution function of the first failure time and set its independent variable as a random number between 0 and 1 to get the first failure time. The inverse function of the distribution function of the first failure time is represented as Eq. (16).

\[
t = \beta \left( \frac{-\ln(1-x)}{\alpha} + \left[ \frac{(1-b)T_i + hT_L}{\beta} \right]^\alpha \right)^{\frac{1}{\beta}} - (1-b)T_i + hT_L
\]

Step 3: Decide the maintenance manner. The failure intensity at each moment is calculated at hourly intervals. Once the failure intensity of a certain component reaches the threshold of preventive maintenance, the group maintenance decision will be triggered by preventive maintenance. Once the failure time of a certain component is reached, corrective maintenance will lead to group maintenance. The failure intensity function of the component is updated after every maintenance.

Step 4: Generate the next failure time of the component. The degression process should be a new non-homogeneous Poisson process since the failure intensity function changed after maintenance. Using the same method as described in Step 2, the next failure time can be obtained.

Step 5: Determine whether the time reaches the total time \(T\). If not, return to step 3 and continue the simulation. If so, proceed to step 6.

Step 6: Calculate the maintenance cost and end the simulation.

Step 7: Determine whether the number of simulations reaches the specified value \(N\). If not, return to step 2 to continue the simulation. If so, stop the simulation, and calculate the average maintenance cost.

Figure 5 illustrates the simulation process.

4.1.2 Optimization variables

The failure intensity threshold of preventive maintenance \(\omega_p\) and that of group maintenance \(\omega_g\) have a considerable influence on the maintenance cost. When the maintenance threshold is too high, the component would lack necessary maintenance, which may lead to ‘over-maintenance’. To avoid the situations mentioned above, optimizing the failure intensity thresholds of preventive and group maintenance is necessary.

4.1.3 Constraints

Obviously, the failure intensity threshold of preventive maintenance should be higher than that of group maintenance. Otherwise, group maintenance is not executed in any case. Besides, the failure intensity varies within a certain range, and it is restricted to a feasible region \([0, \omega_{\text{max}}]\) to accelerate the process of solving the problem.

4.2 Solution of the optimization problem

Genetic algorithm refers to several evolutionary laws in the biosphere and directly operates on structural objects without the limitation of derivative and function continuity, which has high adaptability and strong global search ability [28, 29]. Therefore, genetic algorithm is adopted to solve the optimization problem. The main steps are as follows.

Step 1: Initialization. Set the maximum generation \(M\) and generate the initial population.

Step 2: Calculate the fitness function of each individual.

Step 3: Select individuals in the population according to the roulette principle. Apply the crossover operator and the mutation operator to the selected individuals to create the next generation. Then, calculate the fitness function of individuals in the next generation.

Step 4: Determine whether the current generation reaches maximum. If so, end calculation. The optimal individual of the current population is the optimal solution. If not, return to Step 3.

5 Numerical example

A numerical example is presented to illustrate the effectiveness of optimization of the group maintenance strategy proposed in this study. The failure of CNC machine tools often occurs during the wear-out failure period. Hence, in this example, the parameters of the operation and maintenance model are estimated according to field test data of a certain type of machining center which is in the wear-out failure period, while the other parameters of Monte Carlo simulation and genetic algorithm are assigned according to calculation test.
5.1 Parameters of the group maintenance model

The key components of a machining center include the spindle component, feed component, lubrication component, cooling component, and tool storage component. According to actual engineering scenarios, the failure intensity function parameters $\alpha_i$, $\beta_i$, degradation acceleration factor $a_i$, service age regression factor $b_i$, preventive maintenance cost $C_p^i$, and corrective maintenance cost $C_r^i$ of the certain machining center are shown in Table 1.

Although cooling component and lubricating component differ in function, they are similar in structure and often form a whole module with structural dependence. Simultaneous maintenance of these two components can reduce the times of disassembly, and the maintenance cost is decreased by $C_\gamma = 1500$. Besides, once the cooling component or lubricating component fails, the degradation state of the spindle jumps due to untimely cooling and lubricating. According to actual engineering scenarios, each failure of cooling component or lubricating component will cause the degradation state to jump as high as $T_L = 1000h$. According to engineering
Table 1 Parameters of components of a machining center

| Component          | Spindle component | Feed component | Lubricating component | Cooling component | Tool storage component |
|--------------------|-------------------|----------------|-----------------------|------------------|------------------------|
| α                  | 2.31              | 2.30           | 2.11                  | 2.11             | 2.19                   |
| β                  | 7000              | 5600           | 6100                  | 7300             | 5900                   |
| a                  | 1.01              | 1.03           | 1.07                  | 1.07             | 1.09                   |
| b                  | 0.91              | 0.9            | 0.93                  | 0.9              | 0.93                   |
| C_p                | 3000              | 1100           | 100                   | 190              | 1500                   |
| C_r                | 9000              | 3000           | 400                   | 300              | 2950                   |

scenarios, the preparation cost for preventive maintenance is $C_{z,p} = 900$, and that for corrective maintenance is $C_{z,c} = 3000$. What is more, the simulated operating time is assigned as 30,000 h since the critical components usually break down fully after 30,000 h.

Besides the parameters of operation and maintenance, some other parameters need to be assigned to improve the accuracy of calculation and optimization. First of all, Monte Carlo simulation times $X$ should be assigned to decrease the time of calculation while ensuring accuracy. Therefore, some values of Monte Carlo simulation times have been tested with a fixed value of threshold of preventive maintenance and threshold of group maintenance. For each value of Monte Carlo simulation times, the mean and variance of 100 samples are calculated which is presented in Table 2.

According to Table 2, when the value of Monte Carlo simulation times is 1000 or 10,000, the variances are bigger than 20 which means that the maintenance cost varies in a large margin and the simulation is inaccurate. When the value of Monte Carlo simulation times is 100,000 or 1,000,000, the accuracy of the simulation is adequate for the optimization of the group maintenance strategy. However, the time for simulation running in the case of 100,000 simulations is much less than that in the case of 1,000,000 simulations. As a result, the Monte Carlo simulation times is assigned as 100,000.

On the other hand, the parameters of genetic algorithm play a significant role in the accuracy of optimization and the running time of calculation. For two variables of optimization, the best number of each population is 50, which can ensure the accuracy of optimization. Besides, the genetic algorithm maximum evolutionary generation $N = 200$, crossover factor $u = 0.8$, and mutation factor $v = 0.05$ are selected according to the principle of parameter setting for genetic algorithm.

5.2 Result of optimization

Through simulation and optimization by MATLAB 2020a, it is obtained that when the failure intensity threshold of preventive maintenance is $\omega_p = 3.542 \times 10^{-4}$ and that of group maintenance is $\omega_g = 9.402 \times 10^{-2}$, the long-term maintenance cost is the lowest, which is $C = 5.1439 \times 10^4$. The optimal failure intensity threshold of preventive maintenance is slightly lower than the failure intensity at the moment of MTBF (mean time between failures). At this time, the component is prone to fail, which can be avoided by timely preventive maintenance. Besides, unnecessary maintenance is avoided, and maintenance cost is reduced. Nevertheless, since the optimal failure intensity threshold of group maintenance is related to the dependence among components, the relationship with MTBF cannot be clearly observed.

5.3 Comparison

To prove the effectiveness of the maintenance strategy optimization method proposed in this study, curves of failure intensity under different maintenance strategies and long-term maintenance cost are compared. Strategy 1 is the group maintenance strategy proposed in this study. Strategy 2 is to carry out corrective maintenance on the failed component and preventive maintenance on the component that reaches the failure intensity threshold of preventive maintenance but forego group maintenance. Strategy 3 is to carry out maintenance on the failed component and forego preventive maintenance and group maintenance. Figure 6 demonstrates that the failure intensity of strategy 1 is the lowest, followed by that of strategy 2. The failure intensity of strategy 3 is the highest. Due to the randomness of failure, the failure intensity of strategy 1 is higher than

Table 2 The mean, standard deviation and running time corresponding to different values of Monte Carlo simulation times

| Monte Carlo simulation times X | Mean          | Standard deviation | Running time(s) |
|-------------------------------|---------------|--------------------|-----------------|
| 1000                          | 56,068.2881  | 170.8563           | 21.4481         |
| 10,000                        | 56,059.0746  | 45.3108            | 180.4075        |
| 100,000                       | 56,065.6272  | 13.6880            | 1904.5060       |
| 1,000,000                     | 56,065.1669  | 5.2685             | 21,113.1331     |
that of strategies 2 and 3 sometimes, but its overall trend is significantly lower than that of strategies 2 and 3. Besides, the long-term maintenance cost of strategies 1, 2, and 3 are $5.1439 \times 10^4$, $1.028 \times 10^5$, and $2.339 \times 10^5$, respectively. The long-term maintenance cost of strategy 1 is significantly lower than those of strategies 2 and 3. In summary, the group maintenance strategy proposed in this study not only reduces failure intensity of components to avoid the risk of downtime caused by excessive failure intensity but also reduces long-term maintenance cost and increases economic benefit.

Fig. 6  Failure intensity curves of critical components under different maintenance strategies
6 Conclusions

In this paper, a group maintenance strategy of CNC machine tools is proposed considering all types of maintenance dependence among components. To model the process of CNC machine tool operation and maintenance accurately, economic dependence and structural dependence are quantified by cost, while stochastic dependence is quantified by failure intensity. As a result, the proposed CNC machine tool group maintenance strategy can combine characteristics of operation and maintenance with the coupling effect among different components. Besides, the regression model of the CNC machine tool component is established based on the non-homogeneous Poisson process. The formulation of failure intensity is changed after each maintenance action according to degradation acceleration factor and service age regression factor. Through the inverse function of distribution function of the first failure time, the failure intensity at the time of MTBF. Preventive maintenance executed at this time can reduce the risk of failure. This conclusion is consistent with intuitive analysis, which justifies the effectiveness of the strategy proposed in this study to a certain extent. What is more, the optimal failure intensity threshold of preventive maintenance is lower than the failure intensity at the time of MTBF. Preventive maintenance executed at this time can reduce the risk of failure. This conclusion is consistent with intuitive analysis, which justifies the effectiveness of the strategy proposed in this study to a certain extent. What is more, the optimal failure intensity threshold of preventive maintenance is lower than the failure intensity at the time of MTBF. Preventive maintenance executed at this time can reduce the risk of failure. This conclusion is consistent with intuitive analysis, which justifies the effectiveness of the strategy proposed in this study to a certain extent. 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Declarations

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