

Mission reliability–centered maintenance approach based on quality stochastic flow network for multistate manufacturing systems

Indexed by:



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Highlights

- Connotations of the mission reliability and maintenance quality are expounded.
- QSFN is established to characterize the evolution of the mission reliability.
- A quality-oriented mission reliability–centered maintenance method is proposed.
- A manufacturing system example of subway flow receiver is implemented.

Abstract

Previous studies of reliability centered maintenance (RCM) rarely consider the maintenance quality for the operation condition monitoring of manufacturing system. Therefore, a quality-oriented maintenance approach for the multistate manufacturing system with the aid of mission reliability is proposed. First, connotations of the mission reliability and maintenance quality of the multistate manufacturing system are expounded on the basis of the operational mechanism. Second, a quality stochastic flow network (QSFN) model of the multistate manufacturing system is established, and a novel mission reliability model is presented. Third, a quality-oriented mission reliability–centered maintenance framework for multistate manufacturing systems is proposed, and the optimal integrated maintenance strategy is obtained by minimizing the total cost. Finally, an industrial example of subway flow receiver is presented to verify the proposed method. Results show that the proposed method can simultaneously balance the maintenance cost and maintenance quality of the multistate manufacturing system.

Keywords

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manufacturing system, reliability centered maintenance (RCM), mission reliability, maintenance quality, quality stochastic flow network.

1. Introduction

Quality reflects the degree by which the inherent characteristics of the product meet the requirements. The inherent characteristics of the product are formed in the design and manufacturing stages. Therefore, the ability to continuously output stable and reliable products is the core function of the manufacturing system. When the manufacturing system has imperfect process control, no definite maintenance plan, or irregular production operations, it leads to the production of defective products. This system is called an imperfect production system [27]. Most production systems fall into the ranks of the imperfect production systems. Product quality and machine reliability are two key manufacturing system health indicators that are often degraded by machine degradation [14]. Maintenance is an important way to ensure the performance and reliability of imperfect production systems [31]. Scholars have conducted extensive research on manufacturing system maintenance strategies to ensure the operational state of the manufacturing system.

The evolution of maintenance strategies starts from an initial reactive maintenance strategy (corrective maintenance) to regular preven-

tive maintenance and then to predictive maintenance [9, 24]. Corrective maintenance focuses on the repair of failed equipment and has a hysteresis. Preventive maintenance advocates the implementation of regular maintenance activities for complex systems; the purpose of which is to prevent or reduce equipment failures and improve equipment reliability [10, 19]. Formulating correct maintenance plans in advance is difficult owing to the immaturity of current research on prognostic technology, resulting in increased maintenance costs and resource wastes. Regular maintenance strategy based on the running time of equipment could hardly meet the current production demand. The maintenance strategy based on the prediction of health states of operational equipment has gradually attracted extensive attention from scholars [12]. The development of sensing technology and data processing technology provide rich information for reliability assessment and condition based maintenance [1, 2, 23]. Some scholars proposed imperfect maintenance decisions based on the monitoring of equipment degradation states in manufacturing systems [29, 32]. However, most of the above studies only considered the operating condition of the component and ignored the reliability of the system.

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Reliability centered maintenance (RCM) theory is widely used for maintenance requirements and the reliability analysis of the system [3, 14, 25]. Yu [30] established a reliability model based on life estimation and then proposed an RCM scheme to guide maintenance decisions. Li [20] considered the impact of maintenance activities on component reliability and proposed a dual-objective maintenance optimization method. Qiu [26] used the availability model of the system to obtain the optimal imperfect maintenance strategy. Most of the above RCM studies only focus on the reliability information of components, ignoring the performance state and reliability of the entire system.

From a perspective of systems engineering, the maintenance activities of manufacturing systems are also closely related to production scheduling and product quality [15]. In recent years, researchers have developed many integrated models of maintenance, production, and quality [4, 11]. Considering the relationship among the three, preventive maintenance strategies for multistage manufacturing systems are proposed [5, 6, 13]. The development of intelligent manufacturing modes has made the manufacturing system exhibit structural complexity and performance polymorphism. Considering the functional dependencies of components, Han [16] proposed a remaining life-driven predictive maintenance method for multistate manufacturing systems. Zhao [33] proposed a risk-oriented integrated maintenance optimization method considering the quality loss of work in process (WIP) in multistate manufacturing systems. However, most existing methods for the reliability assessment and maintenance decision-making of multistate manufacturing systems are based on system- or equipment-level performance degradation data. As a result, most of the operational quality data available to characterize the functional state of a manufacturing system are underutilized. Network theory is widely used to organize operational quality data for the reliability assessment of complex multistate systems [21]. Chen [7] and He [17] proposed an extended state task network and an extended stochastic flow network, respectively, to simplify the operation of manufacturing systems. However, the operating mechanism and functional characteristics of the manufacturing system are ignored; therefore, the real-time operating state of the manufacturing system cannot be reflected, and the maintenance activities cannot be guided scientifically.

Maintenance quality as an evaluation index of maintenance effect is often used to guide the optimization of maintenance strategy. As the quality requirement of modern manufacturing changes from “conformity” to “fitness,” maintenance quality evaluation should be carried out from the perspective of fitness quality. Most maintenance models ignore the uncertainty of maintenance quality [22]. Existing ones are limited to the maintenance effect evaluation through the establishment of an evaluation index system, which has a certain degree of subjectivity [18]. Most evaluation methods focus on the relevant performance indicators of the equipment during and after the maintenance process and rarely pay attention to the precursor indicators before failure occurs. In this case, taking scientific maintenance measures in advance to prevent the occurrence of failure is difficult. Maintenance resources should also be considered as an important factor affecting the recovery of system performance [8]. Therefore, introducing a maintenance quality evaluation method driven by the operation health state of the manufacturing system on the basis of operational quality data for optimal maintenance decisions under limited maintenance resources is needed.

A mission reliability-driven maintenance approach for multistate manufacturing systems based on the quality stochastic flow network (QSFN) is proposed in this paper to solve the above problems. The main contributions to this article are as follows.

- (1) Considering the operational mechanism of manufacturing systems, the connotations of the mission reliability and maintenance quality of multistate manufacturing systems are proposed.

- (2) A QSFN model is proposed as a tool to simplify the operation process of the multistate manufacturing system, and a mission reliability modeling method is proposed based on QSFN.
- (3) A mission reliability-centered maintenance quality evaluation method for multistate manufacturing systems is proposed based on QSFN and RCM, and an optimal integrated maintenance strategy is further obtained.

The rest of this article is organized as follows. Section 2 introduces the new connotations of mission reliability and maintenance quality, which take into account the operating mechanism and functional characteristic of the manufacturing system. Section 3 discusses the optimization of maintenance strategies of the multistate manufacturing system on the basis of mission reliability-oriented maintenance quality modeling. Section 4 verifies the effectiveness of the proposed method, and Section 5 gives the conclusions.

2. Basics of maintenance quality for manufacturing systems

2.1. Connotation of mission reliability of multistate manufacturing systems

The operating mechanism of a manufacturing system is shown in Figure 1. The goal of the manufacturing system is to convert the input material into an output product according to the requirement of the production task. With the prevalence of small batch custom production mode, the variability of production tasks, the polymorphism of the machine performance and product quality promote the polymorphism of the performance state of a manufacturing system. The performance state of its components will inevitably decline during task execution. On the one hand, the performance of the manufacturing system degrades, resulting in failures that will cause production disruptions and orders not being delivered on time. On the other hand, the degradation of the performance of the processing machine will be reflected in the quality deviation of the WIP, which is transmitted to the downstream station with the material flow and eventually leads to the quality deviation of the product. The quality state of products can be guaranteed by monitoring the key quality characteristics (KQCs) of the product.

Different tasks require different processing techniques, resulting in different system structures. The basic reliability of a manufacturing system over the life cycle is determined, but its mission reliability under different task requirements is variable. In addition, the recovery level of mission reliability is different under the intervention of different maintenance strategies as shown in Figure 2. Therefore, mission reliability assessment is superior to basic reliability in characterizing the operating state of a manufacturing system.

The production task requirements of the manufacturing system can be understood as the production of a specified number of qualified products within a specified time. Therefore, the mission reliability of manufacturing systems can be described by the evolution of the performance states of the manufacturing system in state space. The performance state of the manufacturing system can be further described as the maximum number of qualified output products of the manufacturing system under specified conditions. Correspondingly, as a component of the manufacturing system, the performance state of the processing machine is defined as the maximum production load that can be carried under normal working conditions. Therefore, depending on whether the performance state of the machine meets the requirement of the production task, the performance state of the machine can be divided into two mutually exclusive subsets. When the processing machine is within the acceptable subset, the machine is considered capable of completing production tasks; otherwise, the machine is considered unable to complete production tasks.

The performance state of the machine can be thought of as a random process in time t . The performance state set can be defined as $S_i = \{s_{i,1}, s_{i,2}, \dots, s_{i,k_i}\}$, which is composed of random variables. At any time, the corresponding state probability vector set of machine i is $P_i(t) = \{p_{i,1}(t), p_{i,2}(t), \dots, p_{i,k_i}(t)\}$ and $\sum_{j=1}^{k_i} p_{i,j}(t) = 1$. The mission reliability connotation of a manufacturing system can be defined as a set of acceptable states for a manufacturing system to satisfy task requirements under specific conditions and within a specified running time. Assuming that the machines are independent of each other, the mission reliability at any time is:

$$R_m(t) = \prod_{i=1}^N \sum_{j=1}^{k_i} p_{i,j}(t) \mathbf{1}(s_{i,j} \geq t_i) \quad (1)$$

where $\mathbf{1}(x)$ is the discriminant function, that is, $\mathbf{1}(true) = 1$ and $\mathbf{1}(false) = 0$. t_i is the task requirement for production machine i .

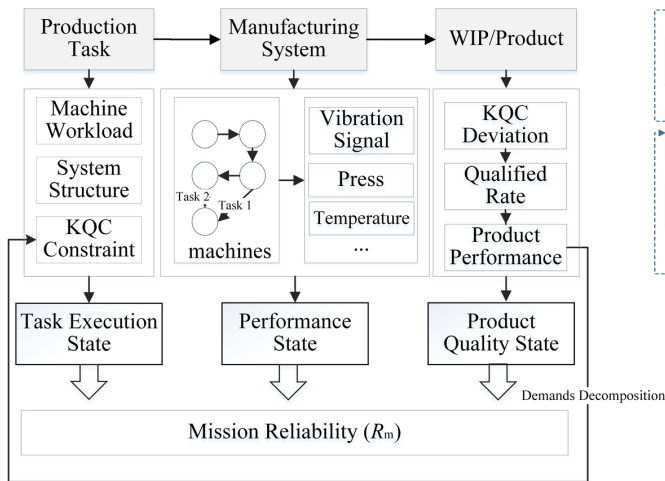


Fig. 1. Operating mechanism of the multistate manufacturing system

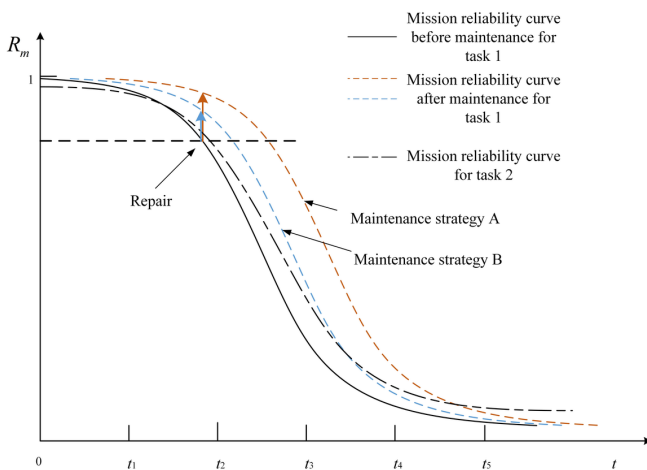


Fig. 2. Mission reliability of the manufacturing system under different production tasks and maintenance activities

2.2. Principle of RCM-oriented maintenance for multistate manufacturing systems

According to the operation mechanism of manufacturing systems, maintenance decision-making should be based on the real-time operation state of the manufacturing system. As shown in Figure 3, mission reliability integrates production machine performance state, production task execution state, and product quality state. It can characterize the operating state of multistate manufacturing systems. Therefore,

incorporating mission reliability into RCM is needed to guide the maintenance of multistate manufacturing systems.

From the perspective of fitness quality, maintenance is performed for the prevention and repair of the physical and functional failures of multistate manufacturing systems. In other words, through maintenance, the performance of the equipment can be restored, and the manufacturing system can normally complete production tasks by producing a certain number of products that meet the quality requirements. Mission reliability considers the functional characteristics of the manufacturing system, reflects the operational state of the manufacturing system, and provides a reference for maintenance decision. Therefore, the maintenance quality evaluation of manufacturing systems should also focus on the ability of maintenance activities to restore the mission reliability of manufacturing systems. Based on this analysis, maintenance quality can be defined as the degree that the mission reliability of the manufacturing system after maintenance reaches the expected mission reliability level within acceptable cost and time under the intervention of maintenance activities.

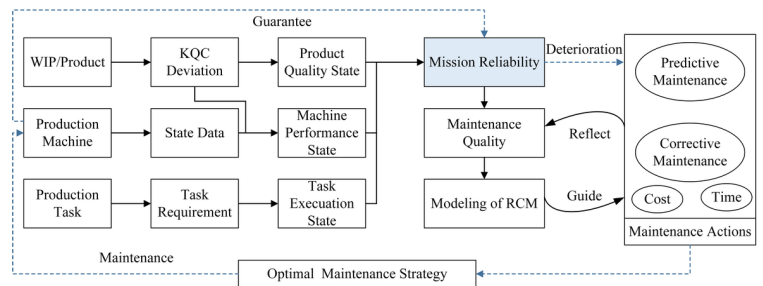


Fig. 3. Schematic diagram of RCM-oriented maintenance for multistate manufacturing systems

Based on the above analysis, maintenance quality reflects the effect of maintenance activities. When the mission reliability of the manufacturing system deteriorates to a certain extent, maintenance activities (including predictive and corrective maintenance) are needed to restore the performance of the manufacturing system. According to the maintenance quality requirements and maintenance resource constraints (cost), the optimal maintenance strategy can be obtained through RCM modeling to guide the maintenance activities of manufacturing systems to ensure the stability of the mission reliability of multistate manufacturing systems.

2.3. QSFN model of a multistate manufacturing system

Stochastic flow network (SFN) is widely used in the evaluation of network reliability. In fact, a manufacturing system can also be viewed as a SFN to represent its running process. According to the input-output characteristics (production task and product quality) of the manufacturing system, a QSFN is proposed to characterize the evolution of the mission reliability of the manufacturing system. The QSFN can clearly indicate the quantity and quality states of WIPs under different production task requirements

The QSFN model of a simple manufacturing system is shown in Figure 4. The simple manufacturing system with rework process is shown in Figure 4a. It is abstracted into a QSFN model as shown in Figure 4b. The QSFN describes the flow of materials in the manufacturing system and reflects the change in the quality states of the products. The QSFN can be used for mission reliability modeling by supplementing the parameters below.

According to graph and network theory, the relevant definitions of the QSFN are given as follows.

Definition 1: Quality states ($s_{q_{ij}}$). It represents the quality inspection results of the raw material, semi-finished products, and finished products (represented by rectangles). It includes three types: acceptable state ($s_{q_{i1}}$), reworkable state ($s_{q_{i2}}$), and discarded state ($s_{q_{i3}}$). Only $s_{q_{i1}}$ can be accepted by downstream machines, and $s_{q_{i2}}$ appears only in reworkable machines.

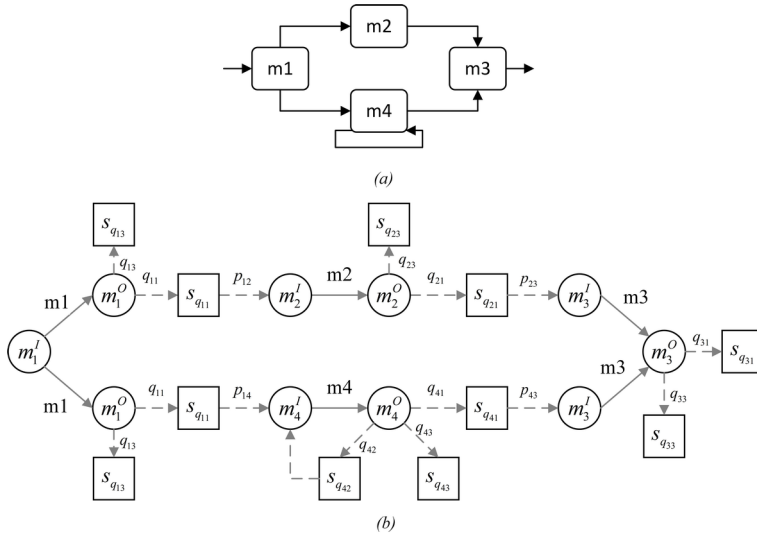


Fig. 4. QSFN model of a simple manufacturing system

Definition 2: Task (T). $T = \{t_1, t_2, \dots, t_n\}$ represents the task requirement set, including the output quantity and quality requirements of the node machine. Once the task requirements are determined, the manufacturing system structure is also determined. t_i represents the task requirements for machine i under the total task requirement.

Definition 3: Machine performance states (S). The performance state of the machine is divided into several discrete states to simplify the calculation. The performance state of machine i is represented by $S_i = \{S_{i,1}, S_{i,2}, \dots, S_{i,k_i}\}$, where $s_{i,1}$ and s_{i,k_i} represent the best and worst states of machine i , respectively, and k_i represents the number of all possible states of machine i . The state probability vector of machine i is $P(t)_i = \{p_{i,1}(t), p_{i,2}(t), \dots, p_{i,k_i}(t)\}$, $\sum_{j=1}^{k_i} p_{i,j}(t) = 1$. Given that the machine performance state follows a Markov process for machine i , the Markov transition intensity matrix of its performance state can be expressed as:

$$X_i = \begin{bmatrix} \lambda_{(N_i, N_i)} & \lambda_{(N_i, N_i-1)} & \dots & \lambda_{(N_i, 2)} & \lambda_{(N_i, 1)} \\ \lambda_{(N_i-1, N_i)} & \lambda_{(N_i-1, N_i-1)} & \dots & \lambda_{(N_i-1, 2)} & \lambda_{(N_i-1, 1)} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \lambda_{(2, N_i)} & \lambda_{(2, N_i-1)} & \dots & \lambda_{(2, 2)} & \lambda_{(2, 1)} \\ \lambda_{(1, N_i)} & \lambda_{(1, N_i-1)} & \dots & \lambda_{(1, 2)} & \lambda_{(1, 1)} \end{bmatrix} \quad (2)$$

where $\lambda_{(N_i, N_i)}$ is the transfer strength parameter. For any time t , the probability that machine i is in any performance state can be represented by vector $P_i(t)$. The state probability vector of the processing machine at any time t can be obtained by the Kolmogorov equation:

$$\frac{dp_i(t)}{dt} = p_i(t)\lambda \quad (3)$$

Definition 4: QSFN model. It can be denoted as $QSFN = (M, S, T, Q, N)$, which is a five-variable equation. $M = \{m_1, m_2, \dots, m_N\}$ is the set of arcs, and N is the number of machines. $S = \{s_1, s_2, \dots, s_N\}$ is the set of flow through each arc. p_{ij} represents the proportion of materials with quality states s_{qi1} of total materials transferred from machine i to downstream machine j . Similarly, $Q = \{q_{i1}, q_{i2}, q_{i3}\}$ is a proportion set representing the proportion of machine i outputting WIP with the quality states s_{qi1} , s_{qi2} , and s_{qi3} , respectively.

This paper proposes the following assumptions about the QSFN model to facilitate subsequent modeling and simplifying calculations:

- (1) All the nodes are highly reliable. Only the arc is considered in this paper.
- (2) The flow of each arc follows the Markov process, and the transition intensity matrix is known.
- (3) The capacity of each arc is independent of each other.
- (4) A product is only allowed to be reworked once and can only be reworked by the machine where it was first produced.

3. RCM-oriented maintenance approach for multi-state manufacturing systems

3.1. Quality-oriented mission reliability-centered maintenance framework

On the basis of Section 2, a quality-oriented mission reliability-centered maintenance framework for multistate manufacturing systems is established as shown in Figure 5.

When the task requirements are given, the manufacturing process is determined through products' KQCs, including the related machines that make up the manufacturing system. The subtask of each machine are determined by the reverse decomposition of the general tasks. Furthermore, according to the current state of the machine, the QSFN is established to obtain the mission reliability of a single machine. Finally, the mission reliability of the manufacturing system is obtained by mapping relation. When maintenance activities are involved, the mission reliability of one or several machines will change accordingly, which will affect the mission reliability of the whole manufacturing system. Therefore, the maintenance quality of the manufacturing system can be obtained on the basis of mission reliability variation. The optimal maintenance strategy is proposed considering the economic cost and maintenance quality.

The detailed steps are shown in Figure 5. A brief description of each step is detailed as follows.

Step 1: Collect quality data. This step is to prepare for QSFN modeling. Relevant operational quality data, failure, and maintenance data are collected. Production task is determined, including the quantity and quality of products. The KQCs of products are determined according to the task requirement. Accordingly, the related manufacturing processes and production machines are identified through mapping and decomposition processes.

Step 2: Establish the QSFN model. The output quality state of each machine is identified by analyzing the quality state of the WIP produced by the machine. According to the production mode determined by task requirements, the proportional set (the qualification rate of each machine q_{i1} and the flow transmission probability p_{ij} between machines) is calculated. The Markov state transition matrix of the machine is determined based on the historical fault data and maintenance data. The state probability function of the machine is based on the Kolmogorov differential equation. The evolution of the production task between the machines of QSFN is used to obtain the subtask requirement of each machine based on reverse transmission.

Step 3: Calculate the mission reliability of the manufacturing system. The minimum input flow is calculated based on the input-output relationship and task requirements. Then, whether the input flow required by subtasks meets the capacity constraint of each machine is checked. If it does not meet the capacity constraint, the production task cannot be completed, $R_m = 0$; if it meets the capacity constraint, the subtask is completed with a certain probability. Then, the minimum performance state of the machine is obtained. The state probability function of machines is updated. On the basis of previous steps, the probability that the machine performance state can provide greater than or equal to the minimum performance state is calculated. Then, the subtask reliability of each machine is calculated. The mission reliability model of manufacturing system is evaluated on the basis of the logical relationship between machines.

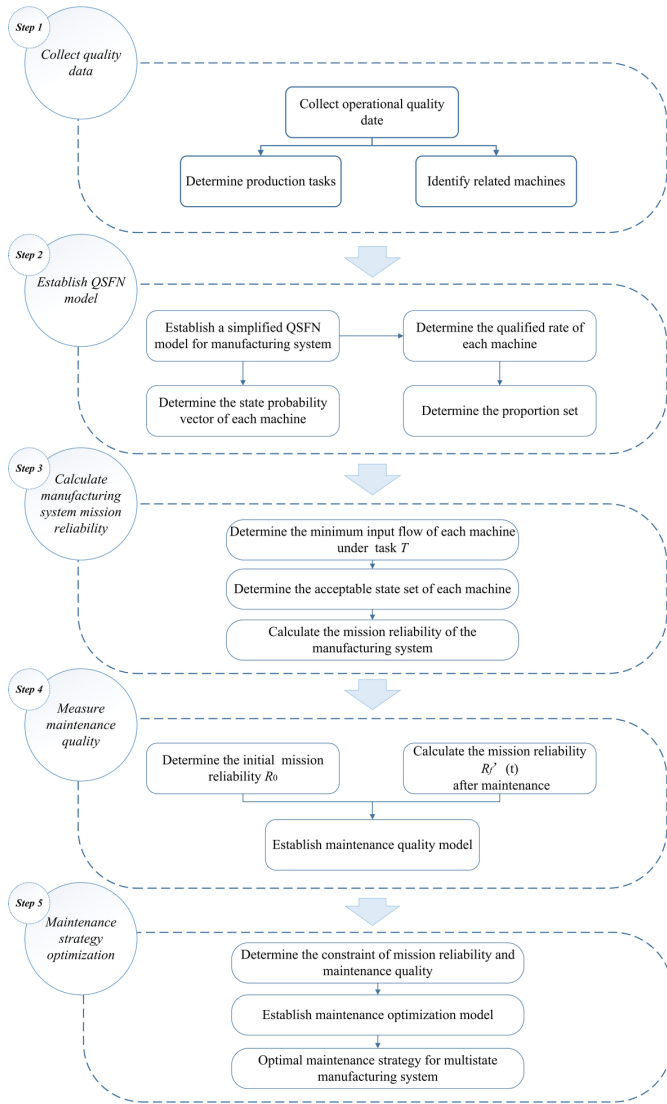


Fig. 5. Mission reliability-centered maintenance framework

Step 4: Measure the maintenance quality of manufacturing system. The initial mission reliability can be determined according to design specifications and production requirements. The mission reliability before and after maintenance can be calculated based on the QSFN model. The maintenance quality of a manufacturing system can be quantified considering the recovery time and effect.

Step 5: Optimize manufacturing system maintenance decisions. The optimal preventive maintenance decisions are outputted based on the evaluation results of the maintenance quality of the manufacturing system and with consideration of maintenance costs.

3.2. Mission reliability evaluation based on the QSFN model

3.2.1. Quantification of product quality states

The qualification rate of the WIP produced by a machine is a key parameter reflecting the quality of the manufacturing process. It can be expressed as the probability of the measured value of the sample within the design threshold range of any inspection batch under the current machine performance state. It represents the probability of the current state of the WIP within s_{qil} , namely, q_{il} .

Assuming that a certain number samples are selected to do independent observation, the qualification of the WIP obeys a binomial distribution. If the total number of trial samples is n , then the conditional probability of x qualified products when given q_{il} is expressed as:

$$\Pr \{X_s = x | q_{il}\} = \binom{n}{x} q_{il}^x (1 - q_{il})^{n-x} \quad (4)$$

where q_{il} is the qualified product rate, and $x = 1, 2, \dots, n$ represents the amount of qualified products

According to statistical principles, the qualified product rate ranges from 0 to 1 and obeys the beta distribution, $Beta(a, b)$. Therefore, we can use the standard beta distribution as the prior distribution and use Bayesian estimation to estimate it. Then, the standard beta distribution is:

$$\pi(p_{il}) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} q_{il}^{a-1} (1-q_{il})^{b-1}, 0 < q_{il} < 1 \quad (5)$$

Then, the likelihood function containing the qualified information of the WIP is:

$$L(q_{il}) = C_n^x q_{il}^x (1-q_{il})^{n-x} \quad (6)$$

Therefore, the posterior distribution of the qualified rate of the work in process is:

$$\pi(q_{il} | x) \propto L(q_{il}) \cdot \pi(q_{il}) \quad (7)$$

After simplification,

$$\pi(q_{il} | x) = \frac{\Gamma(a+b+n)}{\Gamma(a+x)\Gamma(b+n-x)} q_{il}^{a+x-1} (1-q_{il})^{b+n-x-1}, 0 < q_{il} < 1 \quad (8)$$

Finally, the mathematical mean of the posterior expectation is estimated as:

$$\hat{q}_{il} = E(q_{il} | x) = \frac{a+x}{a+b+n} \quad (9)$$

3.2.2. Calculation of mission reliability under task T

The input amount of raw materials should be determined first to ensure the normal delivery of orders and meet the minimum requirements of production tasks. The quantitative relationship between the input and output flows of each arc in the QSFN model is expressed as:

$$m_i^I = \sum m_{i-1,i}^O q_{i-1,i} p_{i-1,i} \quad (10)$$

$$m_i^O = m_i^I q_{il} \quad (11)$$

where m_i^I denotes the minimum input flow of machine i under production task T , m_i^O denotes the output flow of machine i under production task T .

The quantitative relationship between the flow variation of the arc in a general manufacturing process is represented by Equation (12), and the quantitative relationship between the flow variation of the arc with the rework process is expressed by Equation (13):

$$(m_{i,1} \quad m_{i,3}) = m_{i-1,1} (q_{il} \quad q_{i3}) p_{i-1,i} \quad (12)$$

$$(m_{i,1} \quad m_{i,2} \quad m_{i,3}) = (m_{i-1,1} \quad m_{i,2}) \begin{pmatrix} q_{i1}p_{i-1,i} & q_{i2}p_{i-1,i} & 0 \\ q_{i1} & 0 & q_{i3} \end{pmatrix} \quad (13)$$

According to the input–output relationships of the manufacturing system, the minimum input flow can be obtained as:

$$I = \frac{T}{\Phi(r) \prod_{j=1}^N p_{j,j+1} q_{i1}} \quad (14)$$

where T is the minimum amount of final product required by the production task, and r is the serial number of the machine which has a rework process. When the system has no rework process, $\Phi(r) = 1$; otherwise, $\Phi(r) = \prod_r (1 + p_{r2} q_{r2})$.

Once I is obtained, the input and output flows of each arc can be calculated. Whether the input flow meets the capacity constraint of each machine is checked in the QSFN.

The task load of each machine is determined when given a production task T . According to the definition of mission reliability from the perspective of flow conservation, the mission reliability of machine i is expressed as:

$$R_i = \Pr\{S_i \geq m_i^I\} \quad (15)$$

Obviously, $\{S_i \geq m_i^I\}$ is the set of acceptable states for processing machine i ; therefore, based on Equation (1), mission reliability can be expressed as:

$$R_m(t) = \prod_{i=1}^N \sum_{j=1}^{k_i} p_{i,j}(t) \mathbb{I}(S_i \geq m_i^I) \quad (16)$$

For a series system, the mission reliability of the manufacturing system based on the logical relationship of each processing machine in the manufacturing system is:

$$R_m(t) = \prod_{i=1}^N R_i(t) \quad (17)$$

3.3. Maintenance quality evaluation model based on mission reliability

The maintenance quality of the multistate manufacturing system can be quantified with the aid of mission reliability. When the machine performs the task, the performance of the machine will degrade; therefore, the mission reliability of the entire manufacturing system will also decline, regardless of the system being damaged and interrupted. When the mission reliability of the manufacturing system drops to an unacceptable level, maintenance actions are taken to restore the performance of the manufacturing system. Maintenance activities and repair effects are different owing to the different degradation rates of different components. The mission reliability of repaired components will be restored to varying degrees. The mission reliability of restoration is assumed to reach any desired level between the residual reliability before repair and the reliability before degradation. Here, the achievable reliability after restoration is limited to the level of maintenance rather than renewal or replacement.

A manufacturing system operating at a given mission reliability level while taking into account the effects of degradation due to aging was considered. The case described here is shown in Figure 6, where

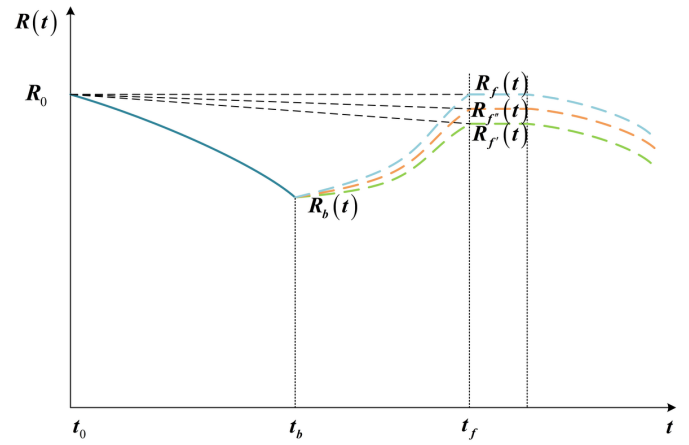


Fig. 6. Mission reliability of the manufacturing system before and after maintenance

R_0 is the initial given mission reliability of the manufacturing system at time t_0 ; $R_b(t)$ is the mission reliability when the system needs maintenance, that is, the mission reliability threshold for maintenance; and $R_f(t)$ is the maximum achievable level of mission reliability after maintenance and is equal to the initial mission reliability of the manufacturing system (R_0). The manufacturing system can be restored to any level of mission reliability between the residual and “as old” mission reliability, which is shown by $R_f'(t)$ and $R_f(t)$.

Based on previous analysis, the measure of the maintenance quality of a manufacturing system should reflect the ease of recovery work and the performance level achievable after restoration. These requirements imply that maintenance quality is a measure of the duration of the restoration process and the achievable mission reliability after restoration. Therefore, taking into account the recovery degree and recovery time of the manufacturing system at the same time, maintenance quality can be calculated by the formula:

$$Q_m(t) = \frac{R_f'(t) - R_b(t)}{R_0 - R_b(t)} \quad (18)$$

where $Q_m(t)$ represents the maintenance quality of the manufacturing system, $R_f'(t) \in [R_b(t), R_f(t)]$, when the manufacturing system can be restored to “as new,” $R_f'(t) = R_f(t) = R_0$.

3.4. Maintenance strategy optimization for multistate manufacturing systems

Scientific maintenance strategy is beneficial to ensure high maintenance quality under limited economic cost and thus improves the stability and reliability of manufacturing systems. In addition, equipment downtime can be reduced, the quality level of output products can be guaranteed, and production costs can be reduced by optimizing the maintenance strategy. Therefore, the optimization goal of the maintenance strategy is minimizing comprehensive cost under the constraints of maintenance quality and mission reliability.

During the operation of manufacturing systems, maintenance cost considers three parts: (1) corrective maintenance costs (c_1), (2) predictive maintenance costs (c_2), and (3) manufacturing equipment production capacity loss (c_3). Here, the worst state of the machine is regarded as a failure state. The values of relevant parameters regarding maintenance costs can be obtained with the help of the manufacturer.

(1) Corrective maintenance costs (c_1)

Various random failures will inevitably occur when the machine performs production tasks. Corrective maintenance is a maintenance activity aimed at restoring such failures. Obviously, the corrective maintenance cost of the machine (the cost incurred) and the number of random failures within this period of time have a linear relationship

within a certain period of time. Therefore, the corrective maintenance cost within the specified production task can be expressed as:

$$c_1 = c_r \left(\sum_{l=1}^E \int_0^{t_l} \lambda_l dt + \int_0^{\varepsilon} \lambda_{E+1} dt \right) \quad (19)$$

$$\varepsilon = T - \sum_{l=1}^E t_l - E\tau' \quad (20)$$

where $E+1$ represents the number of predictive maintenance cycles generated during the predictive time period T , and E represents the number of predictive maintenance cycles that occurred during this time period. $\int_0^{t_l} \lambda_l dt$ represents the number of equipment failures in the l predictive maintenance cycle. ε , called the remaining time, is the time interval from the end of the last predictive maintenance activity to the end of the predictive time period; it is the length of the $E+1$ th predictive maintenance cycle. τ' represents the length of equipment downtime caused by a single predictive maintenance activity.

(2) Predictive maintenance costs (c_2)

Predictive maintenance activities are those that enterprises actively carry out based on the operating states of the manufacturing system and aim at ensuring the mission reliability of the manufacturing system. Predictive maintenance activities are carried out when the operating states of the machine of the manufacturing system drops to the preset mission reliability threshold. The predictive maintenance cost depends on the number of predictive maintenance activities within the specified production task time T . This article assumes that the cost of each predictive maintenance activity is constant, and c_{pm} represents the cost of a single predictive maintenance. The predictive maintenance cost incurred during the cycle can be calculated as follows:

$$c_2 = Ec_{pm} \quad (21)$$

(3) Manufacturing equipment production capacity loss (c_3)

During the production process, downtime due to equipment failures or predictive maintenance activities will cause the loss of processing capacity in addition to maintenance costs. That is, the manufacturing system caused by the interruption of production cannot produce the loss of the original normal profit. This loss has a linear relationship with the downtime of the manufacturing equipment during the execution of the task, which is expressed as follows:

$$c_3 = \alpha C_p \left(\sum_{l=1}^{E+1} \tau \int_0^{t_l} \lambda_l dt + E\tau' \right) \quad (22)$$

$$\tau = \sum_{e=1}^K \delta_e t_e^r \quad (23)$$

Among them, α represents the cost of the loss of production and processing capacity per unit, C_p represents the loss of production and processing capacity per unit time, and τ represents the expected equipment downtime caused by a single equipment failure. The downtime caused by different failure modes are different; therefore, the value of τ can be obtained according to the proportion δ_e of different failure modes and the accumulation of the corresponding downtime t_e^r .

Hence, the final cost is:

$$C_T = c_1 + c_2 + c_3 \quad (24)$$

Assuming that the minimal expected mission reliability level is R_e , and the minimum expected maintenance quality level is Q_0 , then the

manufacturing system maintenance optimization model for maintenance quality assurance is:

$$\text{Minimum } C_T = c_1 + c_2 + c_3 \quad (25)$$

subject to:

$$\begin{aligned} R(t) &= \prod_{i=1}^M \sum_{j=1}^{g_j} p_{i,j}(t) l(s_{i,j} - C_{t_i}^I \geq 0) \geq R_e \\ Q_m &= \frac{R_{f'}(t) - R_b(t_b)}{R_0 - R_b(t_b)} \geq Q_0 \\ p_{i,j}(t) &\geq 0 \end{aligned} \quad (26)$$

The comprehensive cost of the manufacturing system maintenance is minimized under the constraints of mission reliability and maintenance quality, therefore determining the most reasonable maintenance threshold, and further guiding the improvement of maintenance strategies.

4. Case study

4.1. Background

As a key component of the receiving system, the quality of the flow receiver directly affects the power supply efficiency and effect of the subway locomotive. A stable and reliable flow receiver is the premise to ensure the power and safety of the subway. However, how to reasonably arrange maintenance activities to ensure the stability of the flow receiver's operating state is still a puzzle for many subway manufacturers. Therefore, the proposed method is applied to a flow receiver producer. The application result provides a reference for its predictive maintenance. The manufacturing process of the flow receiver is shown in Figure 7. The complex manufacturing process and high-performance requirements make the reasonable maintenance of the flow receiver manufacturing system a prerequisite to ensure the stable completion of production tasks. Therefore, the maintenance quality analysis based on the mission reliability analysis of the manufacturing system is an effective way to promote the optimization of the maintenance strategy. Therefore, the key process corresponding to the equipment M1, M2, M3, M4, and M5 and the manufacturing system comprised by these equipment are used as the research objects according to the design specification and expert analysis of the flow receiver to simplify the modeling and calculation.

4.2. Numerical example

This chapter introduces the step-by-step application of the proposed method based on Section 3. The proposed method has been verified by the application of subway flow receiver.

Step 1 Collecting quality data

Based on the design principle of the flow receiver and expert analysis, the key process of the flow receiver manufacturing system is analyzed by using the axiomatic mapping theory, and the key quality characteristics (KQCs) of the flow receiver and the corresponding manufacturing process and production machine are obtained, as shown in Table 1. Relevant quality data and parameters for maintenance modeling can be obtained from the flow receiver manufacturer.

Step 2 Establishment of the QSFN model

The manufacturing system of the flow receiver can be characterized by five machines based on Table 1, where M2 has a rework process. Therefore, the quality states of M2 are s_{q21} , s_{q22} , and s_{q23} , and the quality states of the other machines are s_{qi1} and s_{qi3} ($i = 1, 3, 4, 5$). Given that the production line of the flow receiver manufacturing system has no branch, $p_{ij} = 1$. The performance state S_i and qualified rate s_{qi1} of each machine are shown in Table 2.

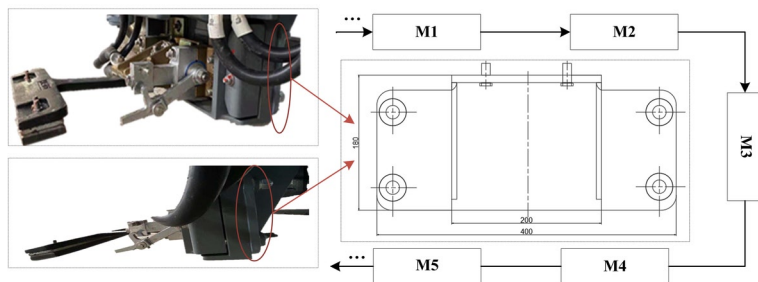


Fig. 7. The manufacturing system of the flow receiver

The QSFN model of the flow receiver is established on the basis of the previous steps as shown in Figure 8.

The state transition intensity matrices of the machines are:

$$X_1 = \begin{bmatrix} -0.8 & 0.8 & 0 & 0 & 0 & 0 \\ 0 & -0.4 & 0.4 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & -0.9 & 0.9 & 0 \\ 0 & 0 & 0 & 0 & -2 & 2 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$X_2 = \begin{bmatrix} -0.4 & 0.4 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.9 & 0.9 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.8 & 0.8 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.95 & 0.95 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.9 & 0.9 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.6 & 0.6 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$X_3 = \begin{bmatrix} -0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.7 & 0.7 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.5 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.90 & 0.90 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.8 & 0.8 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.7 & 0.7 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$X_4 = \begin{bmatrix} -0.95 & 0.95 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.65 & 0.65 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.8 & 0.8 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1.2 & 1.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.9 & 0.9 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.7 & 0.7 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$X_5 = \begin{bmatrix} -0.35 & 0.35 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.5 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1.9 & 1.9 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.85 & 0.85 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.75 & 0.75 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The state probability function of each machine at any time t can be calculated based on (3).

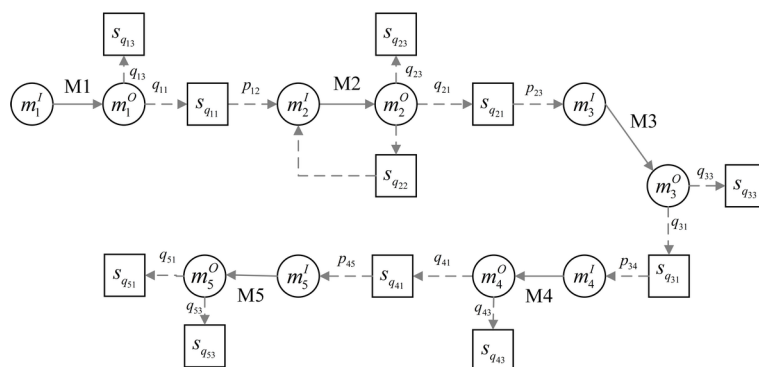


Fig. 8. QSFN model of the flow receiver manufacturing system

Step 3 Mission reliability modeling of the flow receiver manufacturing system

The task requirement of the flow receiver manufacturing system is $T=150/\text{day}$, and the minimum input flow of each machine can be obtained by Equations 10–14.

$$m_1^I = I = \frac{T}{\Phi(r) \prod_{j=1}^k p_{j,j+1} q_{i1}} = 188.949$$

Table 1. KQCs of the flow receiver

Manufacturing process	Processing machine	Machine ID	KQC	Specifications
Cutting	Wire electrical discharge machining	M1	Smoothness	$r_1 \pm 0.05$
Fine boring shaft hole	Fine boring machine	M2	Coaxiality	$\phi_1 = 0.15$
Grind the outer circle	Centerless grinder	M3	Diameter	$\phi_2 = 12.19^{+0.005}_{-0.01}$
Grind the end face	Surface grinder	M4	Length	74 ± 0.01
Welding	Special welding machine	M5	Weld length	$d_2 \pm 0.04$

Table 2. Performance state data of machines

Machine	s_{qil}	State S_i	Machine	s_{qil}	State S_i
M1	0.96	0	M4	0.97	0
		70			45
		140			90
		210			135
		280			180
		350			225
		420			270
M2	0.94	0	M5	0.93	0
		65			50
		130			100
		195			150
		260			200
		325			250
		390			300
M3	0.92	0			
		65			
		130			
		195			
		260			
		325			
		390			

$$m_2^I = 181.391 + 10.883 = 192.274$$

$$m_3^I = 180.738$$

$$m_4^I = 166.279$$

$$m_5^I = 161.291$$

The set of acceptable states of each machine that meets the mission requirements includes $s_{1,j} \geq 210$, $s_{2,j} \geq 195$, $s_{3,j} \geq 195$, $s_{4,j} \geq 180$, and $s_{5,j} \geq 200$. The subtask reliability of each machine is:

$$R_1(t) = \Pr\{s_{1,j} \geq 210\}$$

$$R_2(t) = \Pr\{s_{2,j} \geq 195\}$$

$$R_3(t) = \Pr\{s_{3,j} \geq 195\}$$

$$R_4(t) = \Pr\{s_{4,j} \geq 180\}$$

$$R_5(t) = \Pr\{s_{5,j} \geq 200\}$$

The mission reliability of the flow receiver manufacturing system can be obtained on the basis of the system logic relationship:

$$R_m(t) = \prod_{i=1}^5 R_i(t).$$

Step 4 Maintenance quality evaluation of the flow receiver manufacturing system

The maintenance quality of the flow receiver manufacturing system can be calculated using (18).

Step 5 Maintenance strategy optimization for the flow receiver manufacturing system

The comprehensive maintenance cost can be calculated using Equations 19–25. Under the premise of guaranteeing the maintenance quality, the optimal mission reliability threshold of the flow receiver manufacturing system can be obtained using (26) by analyzing the mission reliability thresholds before different maintenance activities and the corresponding comprehensive costs.

4.3. Results and discussion

(1) Result analysis

In Section 4.2, the mission reliability of the flow receiver manufacturing system is determined based on a given task. Figure 9a represents the subtask reliability of each machine, and Figure 9b represents the mission reliability of the entire manufacturing system. According to the definition of maintenance quality, the variation trend of three types of cost (c_1 , c_2 , and c_3) and total cost with the mission reliability threshold of each machine can be obtained as shown in Figure 10. Taking machine 1 as an example, its minimum acceptable maintenance quality $Q_0 = 0.04$. As shown in Figure 10a, the corrective maintenance cost gradually decreases, the predictive maintenance cost gradually increases, and the production capacity loss during the maintenance period initially decreases and then increases with the increase in mission reliability threshold. This outcome is due to low mission

reliability threshold, in which frequent failure leads to frequent corrective maintenance, increased machine downtime, and increased production capacity loss. The requirement of machine performance is raised, the probability of random failure is reduced, and the corrective maintenance cost and production capacity loss decrease correspondingly with the increase in mission reliability threshold. However, the preventive maintenance activities and costs will increase, the downtime of the machine will increase, and the production capacity loss will increase accordingly as the mission reliability threshold increases to guarantee the healthy operation of the manufacturing system.

Therefore, the optimal maintenance strategy can be obtained by adjusting the mission reliability threshold. As shown in Figure 10f for machine 1, the minimum cost is 137300 when the mission reliability threshold is 0.974. In other words, when the minimum acceptable maintenance quality is 0.4, the optimal mission reliability threshold for maintenance for machine 1 is 0.974.

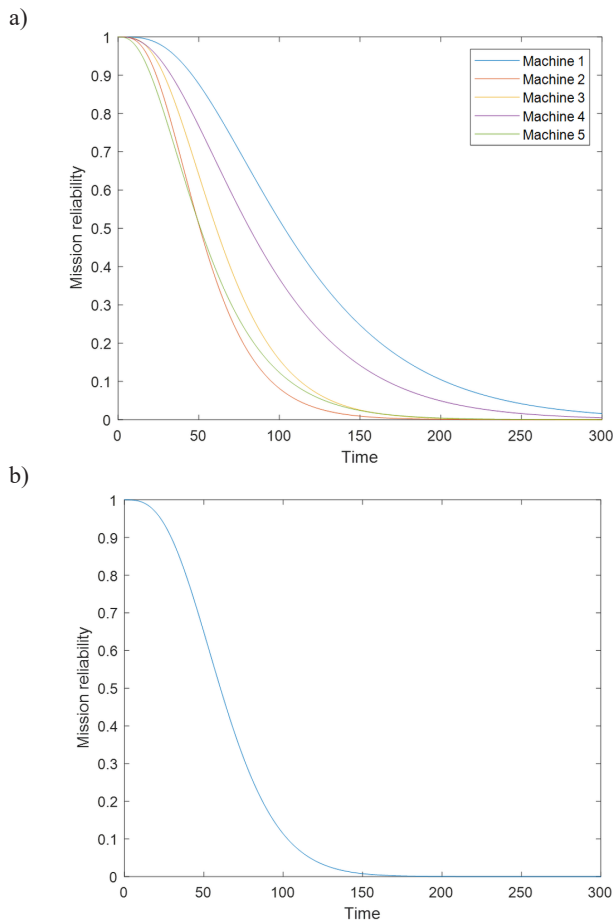


Fig. 9. Mission reliability model for the flow receiver manufacturing system: a) mission reliability model of each machine, b) mission reliability model of the overall manufacturing system

(2) Sensitivity analysis

The MATLAB software is adopted to explore the effect of critical factors on the manufacturing system's mission reliability and maintenance strategy as shown in Figure 11.

First, assuming that the qualified rate and performance state of each machine is constant, the mission reliability of the manufacturing system under different task requirements varies with time as shown in Figure 11a.

With the increase in task requirement, the input flow of each machine increases accordingly, under a given performance state, and the number of failures that allowed for the machine is reduced, which results in the decrease in the mission reliability of the manufacturing system.

Second, assuming that the machine's performance state is determined under a given task requirement, the change trend of the system's mission reliability under different levels of qualified rates is as shown in Figure 11b, because the high qualified rate will reduce the amount of input flow for the same amount requirement of the product under task T .

The change trends of three curves in Figure 11b show that a high qualified rate contributes to the increase in mission reliability levels.

Third, the total maintenance costs of the manufacturing system under different mission reliability thresholds are analyzed as shown in Figure 12. The total maintenance cost initially decreases and then increases when the mission reliability threshold increases. This outcome is because when the mission reliability threshold is low, the manufacturing system's performance takes a long time to degrade to the preventive maintenance threshold during the long cycle; frequent corrective maintenance will be needed, and the maintenance cost will be high. The number of predictive maintenance becomes higher and the maintenance interval becomes shorter with the improvement of predictive maintenance threshold. The number of corrective maintenance required is reduced and the cost decreases accordingly owing to the high mission reliability of the system. However, when the maintenance threshold is high, the maintenance interval will be shorter, and the maintenance costs will increase as the number of preventive maintenance increases.

In addition, when the mission reliability threshold is given, the maintenance cost of the manufacturing system will increase with the improvement of maintenance quality threshold as shown in Figure 12. This outcome is because the improvement of maintenance quality threshold means higher requirements for the mission reliability recovery level of the system after maintenance. Therefore, investing more economy to improve the maintenance effect is necessary, and the corresponding maintenance cost will be higher.

According to the above analysis, the most economical and effective maintenance strategy can be determined by adjusting the mission reliability threshold that meets the maintenance quality requirements, which is beneficial to support the manufacturer to make optimal maintenance decisions.

5. Conclusions

In this paper, a mission reliability-centered maintenance approach is proposed, which provides valuable reference for the optimization of maintenance strategies. According to the operation mechanism of manufacturing systems, a new connotation of the mission reliability of the manufacturing system is put forward considering the functional output characteristic of manufacturing systems. Then, the QSFN model is proposed to characterize the operation process of manufacturing systems, which comprehensively analyzed the relationship between the task execution state, the machine performance state, and the product quality state. A mission reliability evaluation method based on the established QSFN was proposed to characterize the operation state of the manufacturing system. A new connotation and modeling method of maintenance quality with the aid of mission reliability are proposed based on the RCM theory. Finally, an optimization method for maintenance decisions is proposed based on the mission reliability and maintenance quality modeling. The proposed method provides guidance for manufacturers to make better maintenance decisions.

The following directions can be discussed and expanded in future research to further improve the maintenance quality modeling and optimize the maintenance strategy of the multistate manufacturing system:

- 1) Further mining of state data for the mission reliability modeling and maintenance quality analysis of the multistate manufacturing system;
- 2) Mission reliability modeling method of the multistate manufacturing system considering inventory buffer;

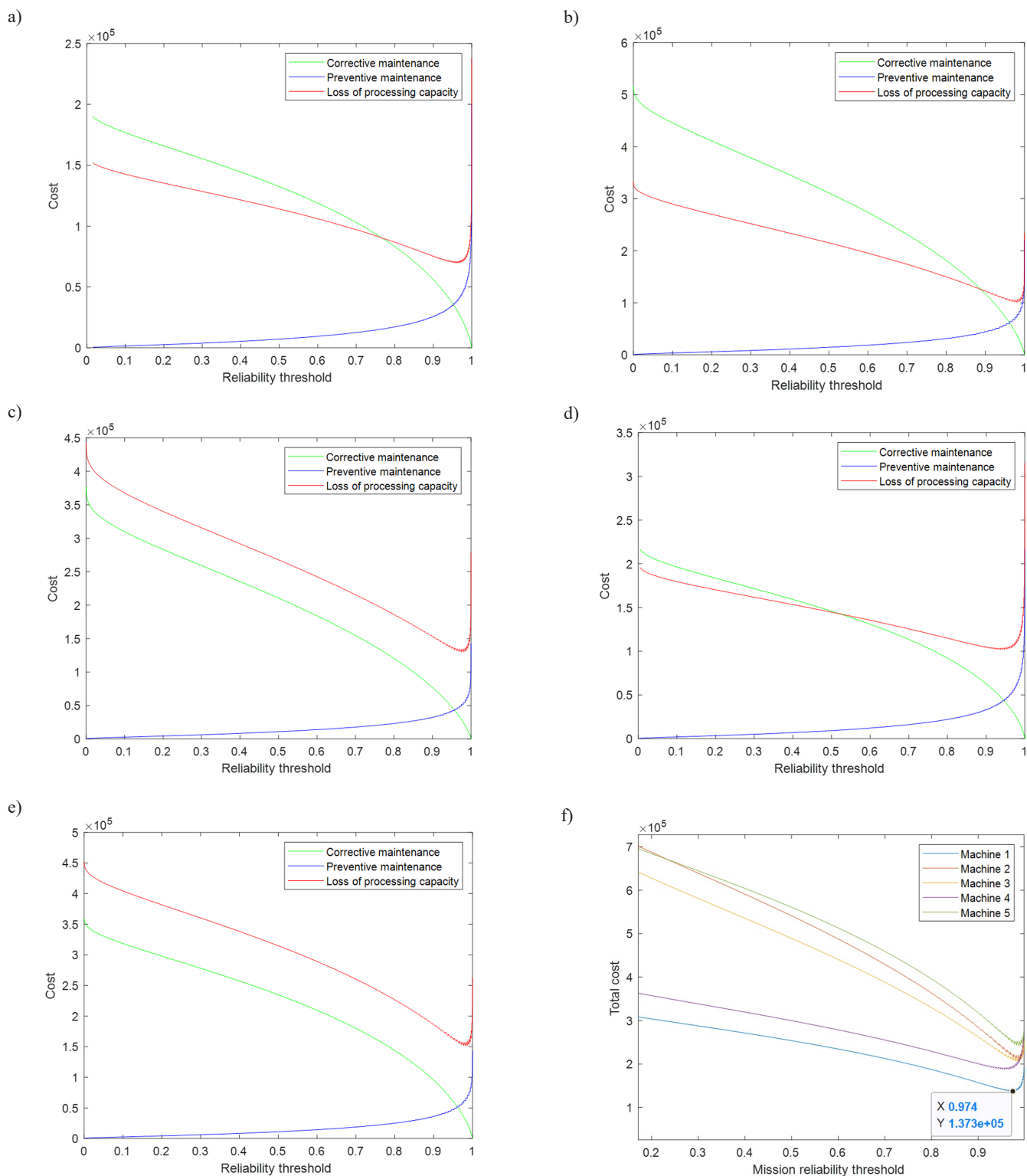


Fig. 10. Maintenance costs of the flow receiver manufacturing system: a) three types of maintenance cost for Machine 1, b) three types of maintenance cost for Machine 2, c) three types of maintenance cost for Machine 3, d) three types of maintenance cost for Machine 4, e) three types of maintenance cost for Machine 5, f) total maintenance cost for each machine

- 3) Production scheduling decision of the multistate manufacturing system based on mission reliability analysis and maintenance quality analysis.

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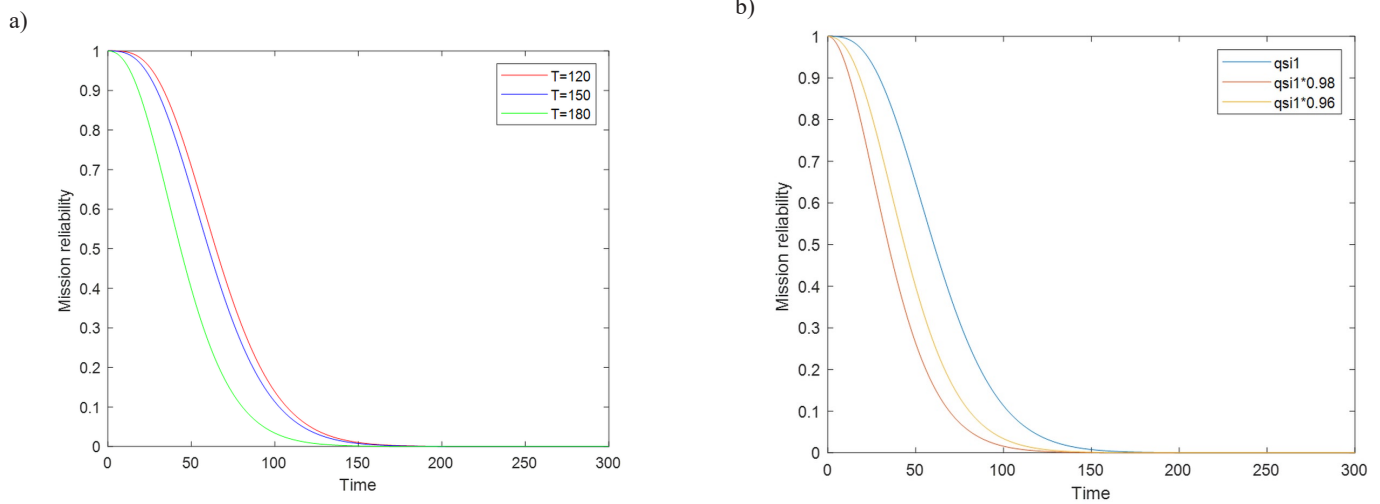


Fig. 11. Sensitivity analysis of the mission reliability model for the flow receiver manufacturing system: a) mission reliability under different task requirements, b) mission reliability under different qualified rate levels

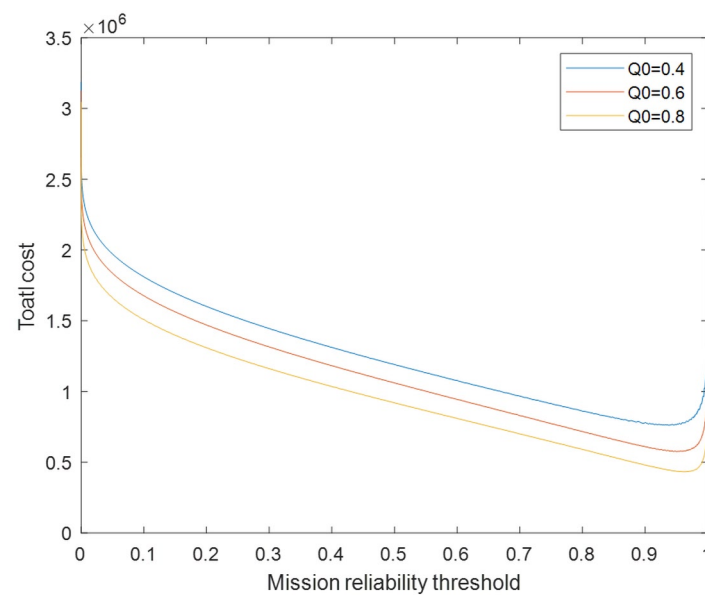


Fig. 12. Maintenance cost C_T versus mission reliability threshold R_b under different maintenance qualities Q_0

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