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Mission Reliability-Oriented Selective Maintenance Optimization for Intelligent Multistate Manufacturing Systems With Uncertain Maintenance Quality

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ABSTRACT Selective maintenance is widely used as a reliability-centered maintenance strategy due to the limited maintenance resources. However, existing selective maintenance studies only consider basic reliability, which cannot systematically describe the operating mechanism of a multistate system, thereby resulting in the inability to obtain an optimal maintenance strategy. Moreover, intelligent manufacturing systems are highly representative of typical multistate industrial systems. In this study, a mission reliability-oriented selective maintenance optimization model for intelligent manufacturing systems that considers the uncertain maintenance effect was proposed. First, a new connotation and modeling method for mission reliability based on multistate system theory was presented to comprehensively characterize the operating mechanism of intelligent manufacturing systems. Second, a quantitative model between maintenance resources and quality based on real-time data was established to reflect the uncertain characteristics caused by repairmen and tools. Third, a selective maintenance decision model of a multistate manufacturing system was developed under the constraints of maintenance cost and time. This constraint combination optimization problem was solved using the particle swarm optimization algorithm. Finally, a case study of selective maintenance optimization for a cylinder head manufacturing system was presented to verify the proposed method.

INDEX TERMS Multistate system, manufacturing system, selective maintenance, mission reliability, particle swarm optimization algorithm.

I. INTRODUCTION

The key to guaranteeing the normal operation of multistate manufacturing systems and accomplishing the anticipated tasks is to develop an effective and reasonable maintenance strategy [1]. An intelligent manufacturing system is a typical multistate industrial system with strict maintenance demands and that requires good quality and high productivity [2]. However, all faulty and aging machines may be unable to complete all types of maintenance due to resource constraints [3]. In such case, the repairman must reasonably allocate resources on the basis of reliability-centered maintenance (RCM), i.e., selective maintenance [4], [5].

At present, selective maintenance research for multistate systems focuses on two aspects: maintenance method and system characteristic [5]. Maintenance method include the degree of maintenance and the required amount of resource consumption that can affect maintenance decisions [6]. Most scholars' research on maintenance methods includes imperfect, minimal, and perfect maintenance [7]–[11]. In addition to maintenance and failure costs, Pandey *et al.* [12] considered maintenance break duration and shutdown cost to the

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selective maintenance model. In order to ensure flexible and cost-effective resource allocation, Yang *et al.* [13] proposed a maintenance strategy for the production waiting process to obey the homogeneous Poisson process. Zhang *et al.* [14] introduced a selective maintenance plan (SMP) that considers the team's maintenance capabilities, and developed a two-stage method based on λ fuzzy measure and dynamic multi-objective artificial bee colony (DMABC) for fuzzy Choquet integration to optimize the SMP model.

In addition, the difficulty in developing and solving maintenance decision models has increased considerably due to the multistate characteristics of complex systems and internal and external complex factors that lead to system degradation and failure, that is system characteristic [15]. Markov models, binary and multivalued decision diagrams, and universal generating functions are widely used in modeling multistate systems [16]. Dao *et al.* [17] considered the selective maintenance problem of multistate systems with two types of stochastic dependent (S-dependent) components. For multistate components under variable load conditions, Dao and Zuo [18] proposed a load-related degradation model in which the failure rate of a component depends on the state of other components. For a multicomponent system that performs multitasking, Khatab *et al.* [19] developed a condition-based selective maintenance model.

The existing literature on the selective maintenance of multistate systems has been highly comprehensive. However, most studies ignore the impact of repairmen and tools on the quality of maintenance. Current research on repairmen is focused on the allocation of repairmen [20], [21]. A few studies on maintenance quality uncertainty due to differences in maintenance personnel and tools are only focused on binary systems [22].

Furthermore, selective maintenance is a typical RCM with the objective of reducing maintenance resources while increasing system reliability [23]. However, the existing research on the selective maintenance of industry systems disregards the task requirements and output of such systems. In addition, the selective maintenance strategy of multistate systems exhibits certain limitations in the practical application process. Multistate manufacturing systems differ from general multistate systems. The reliability modeling of multistate manufacturing systems should comprehensively analyze machines, raw materials, and production tasks [24], [25]. Evidently, a multistate manufacturing system should be modeled with the complete understanding of its operating mechanism. In addition, modern intelligent data collection tools, such as sensors, should be utilized to enable dynamic assessment of the performance state of intelligent manufacturing systems.

Many scholars use sensors to collect quality data in real time to further research and develop the reliability modeling of intelligent manufacturing systems. Chen and Jin [26] hypothesized that the degradation of upstream stations may affect the quality of downstream products in multistation manufacturing systems. A quality and reliability chain (QR chain) was proposed on this basis. He *et al.* [27] presented a manufacturing system modeling method based on an extended QR chain, namely, the RQR chain, which comprehensively analyzes manufacturing systems, processes, and products. These studies still use component-level information data, but multi-level system-level data is necessary to ensure mission success and system security [28]. Moreover, selective maintenance is mission-oriented [5]. Thus, this strategy fails to fully describe the operational process of manufacturing systems because production task is disregarded. Fiondella *et al.* [29] proposed a manufacturing system modeling method for a stochastic-flow production network to meet customer requirements and expected confidence levels as the standard. He *et al.* [30] established a reliability modeling method for multistation manufacturing systems based on the quality state task network, which considers the process quality deviation of a product. Mi *et al.* [31] developed an empirical network method for the reliability analysis and evaluation of complex multistate systems.

However, the lack of understanding of the operating mechanism of multistate manufacturing systems leads to deviations in reliability modeling and the inability to obtain reliability-centered optimal selective maintenance strategies. Therefore, the current study proposes a mission reliability-oriented selective maintenance optimization model for multistate manufacturing systems with uncertain maintenance effect conditions. Compared with previous studies on selective maintenance, the main contributions of this work are as follows.

1) To aid in selective maintenance, a mission reliability modeling method for multistate manufacturing systems is proposed based on the operating mechanism of manufacturing systems and reliability-centered maintenance.
2) A mission reliability oriented selective maintenance method based on the operating mechanism of a multistate manufacturing system is proposed, and the particle swarm optimization (PSO) algorithm is used to search for the global optimal solution.
3) A quantitative model between maintenance resources and quality is established by considering the uncertainty caused by differences in maintenance personnel and tools.

The remainder of this paper is organized as follows. Section 2 states the problem. The basic characteristics of the studied multistate manufacturing system and the uncertainty of maintenance quality are discussed. Section 3 develops a novel mission reliability connotation and modeling method for the multistate manufacturing system. It also establishes a quantitative model for maintenance quality. The resulting selective maintenance optimization model is presented in Section 4, and the PSO algorithm is used to search for the global optimal solution. Section 5 provides a selective maintenance example of a multistate manufacturing system of engine cylinder heads to verify the performance of the proposed method. Section 6 provides the conclusion of the study and outlook for future work.

II. NOTATIONS AND PROBLEM DESCRIPTION

A. NOTATIONS

g_i	Number of states of multistate machine i
$l_{i,x_i}^{y_i}$	Maintenance action that restores machine i from x_i state to y_i state
$\widetilde{c_{i,x_i}^{y_i}}$	Cost required for maintenance action $l_{i,x_i}^{y_i}$
$\widetilde{t_{i,x_i}^{y_i}}$	Time required for maintenance action $l_{i,x_i}^{y_i}$
$\boldsymbol{M}$	Number of machines included in multistate manufacturing system
s_{i,x_i}	Machine i is in x_i state
$s_{i,1}$	Machine$i$is in best state
s_{i,g_i}	Machine i is in worst state
$p_{i,x_i}(t)$	Probability that machine i is in x_i state at time t
s_{pij}	Output quality of machine i is in j state
s_{pi1}	The output quality of machine i is in qualified state
s_{pi2}	The output quality of machine i is in defective repairable state
s_{pi3}	The output quality of machine i is in unqualified state
C_{ti}^{O}	The minimum number of output qualified products of machine i required by the subtask t_i
O_i	The number of output qualified products of machine i
C_{ti}^{I}	The minimum input load of machine i required by the subtask t_i
q_i	The qualification rate of machine i
X_i	The Markov transfer strength matrix of machine i
$p_{i,j}^{a}$	The probability that machine i is in state j after being maintained
$R_i(t)$	Mission reliability of multistate machine i at time t
$R(t)$	Mission reliability of multistate manufacturing system at time t
c_{x_i}	Maintenance costs required for machine i in x_i state before being maintained
$r_{i,x_i}(c_{x_i})$	The degree of membership of c_{x_i} for maintenance action $l_{i,x_i}^{y_i}$
t_{x_i}	Maintenance costs required for machine i in x_i state before being maintained
$r_{i,x_i}(t_{x_i})$	The degree of membership of t_{x_i} for maintenance action $l_{i,x_i}^{y_i}$
R_i	The membership matrix of machine i
$p_{i,j}$	The probability that machine i is in state j before being maintained
C_i	The total maintenance cost of machine i
$c_{i,fix}$	The fixed maintenance cost of machine i
c_i	The maintenance cost of machine i
T_i	The total maintenance time of machine i
$t_{i,fix}$	The fixed maintenance time of machine$i$
t_i	The maintenance time of machine i
$c_{i,R}$	Maintenance cost required for machine i to perform perfect maintenance
$t_{i,R}$	Maintenance time required for machine i to perform perfect maintenance
t_k	The operational time required for the kth task
C_m	The fixed maintenance cost for monitoring manufacturing system
T_m	The fixed maintenance time for monitoring manufacturing system
C_0	The upper limit of the total maintenance cost of manufacturing system
T_0	The upper limit of the total maintenance time of a manufacturing system

B. PROBLEM DESCRIPTION AND ASSUMPTION

In this study, we consider a multistate manufacturing system that consists of multiple machines. The multistate characteristic of the manufacturing system is produced by that of the machine. This study aims to show that a manufacturing system produces a certain number of conform products within a specified limited time. In actual production, a manufacturing system is required to continuously perform a series of missions and can only maintain machines during break. In general, maintenance resources (only maintenance costs and time are considered in this study) are insufficient to restore a manufacturing system to a perfect state. Each machine has multiple repair options (including minimum, imperfect, and perfect maintenance), which is related to recovery to a different state. Decision makers should allocate limited maintenance resources to each machine to maximize the mission reliability of the next phase of the manufacturing system. Correspondingly, manufacturing process stability and product quality are improved, and the efficiency of resource benefits is maximized. This study presents a mission reliability-oriented selective maintenance optimization model for multistate manufacturing systems and provides a framework for the establishment of this model.

As shown in Fig. 1, selective maintenance optimization for multistate manufacturing systems is required to consider maintenance effects and mission reliability. Meanwhile, multistate manufacturing systems not only include production machines, but also production mission and products. Therefore, the formulation of a selective maintenance strategy should comprehensively analyze machine performance and product quality states and mission requirements. Furthermore, the key quality characteristic (KQC) data is the key indicator for assessing product quality state. Meanwhile, machine performance state can be evaluated using machine maintenance and product KQC data. Then, a mission reliability model for manufacturing systems is established by combining production mission requirements. Simultaneously, the selective maintenance strategy that maximizes the mission reliability of the next stage of the manufacturing system is obtained by considering the relationship between maintenance resources and effects, with maintenance time

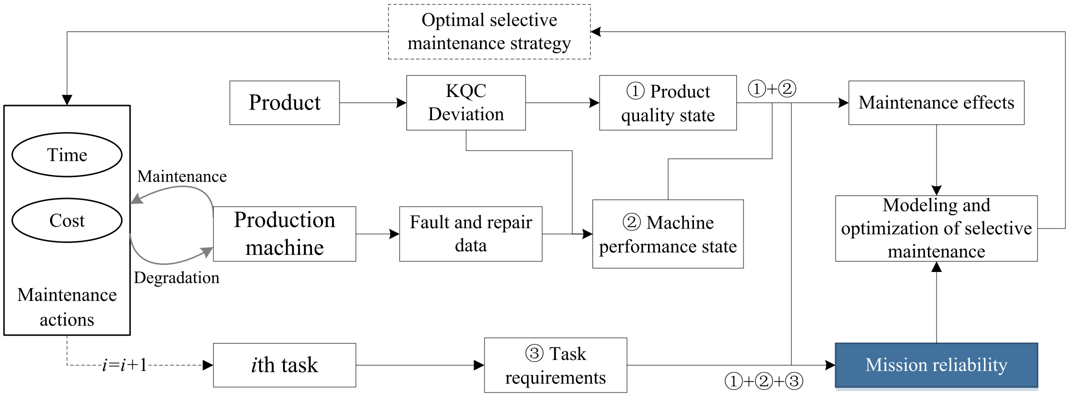

FIGURE 1. Framework for building the selective maintenance optimization mode.

and cost as constraints. The repairman is instructed to perform the corresponding maintenance actions during the task interval based on the optimal selective maintenance strategy.

Meanwhile, machine i is assumed to have g_i states. At the end of the previous mission, machine i can be in any state $\{1, 2, \ldots, g_i\}$. The maintenance actions of the machine can be divided into the following categories according to the effect of maintenance:

1) Minimum maintenance. The machine will remain in its current state, i.e., "as good as old." No maintenance resources (cost and time) will be consumed by this maintenance action.
2) Imperfect maintenance. Imperfect maintenance will change the machine from its current state to a better one (not the best one), i.e., between the "as good as old" and "as good as new." Simultaneously, more efficient maintenance actions will be achieved with an increase in resource consumption.
3) Perfect maintenance. The machine will be restored to its perfect state, i.e., "as good as new."

In particular, for a machine i with g_i states, all possible maintenance actions are $l_{i,g_i}^{g_i}(\widetilde{c_{i,g_i}^{g_i}}, \widetilde{t_{i,g_i}^{g_i}}), \ldots, l_{i,g_i}^{1}(\widetilde{c_{i,g_i}^{1}}, \widetilde{t_{i,g_i}^{1}})$, $l_{i,g_i-1}^{g_i-1}(\widetilde{c_{i,g_i-1}^{g_i-1}}, \widetilde{t_{i,g_i-1}^{g_i-1}}), \ldots$, and $l_{i,1}^{1}(\widetilde{c_{i,1}^{1}}, \widetilde{t_{i,1}^{1}})$, where $l_{i,x}^{y}$ indicates that the maintenance action restores machine i from the x state to the y state; and $\widetilde{c_{i,x}^{y}}$ and $\widetilde{t_{i,x}^{y}}$ represent the cost and time required for maintenance action $l_{i,x}^{y}$, respectively. The cost and time of maintenance action will be obtained inaccurately due to the difference in repairmen and tools, but is represented by fuzzy values $\widetilde{c_{i,x}^{y}}$ and $\widetilde{t_{i,x}^{y}}$, respectively. The maintenance action is minimum and perfect maintenance when $x = y$ and $y = 1$, respectively.

This study aims to develop a selective maintenance decision model for multistate manufacturing systems by integrating mission requirements, machine performance, and product quality. Moreover, this study involves the following assumptions.

Assumption 1: A multistate manufacturing system consists of M repairable multistate machines. The machines are independent of each other.

Assumption 2: The maintenance actions of a manufacturing system can only occur during break.

Assumption 3: The degradation procedure of machines follows the homogeneous Markov process [32], and the transfer strength between states is determined, where the state is defined as the maximum working load that a machine can withstand.

Assumption 4: Machine i has g_i states. Variables 1 and g_i represent the best and worst states, respectively. At time t, the state set of machine i is $S_i(t) = \{s_{i,1}, s_{i,2}, \ldots, s_{i,g_i}\}$ and the corresponding probability set is $P_i(t) = \{p_{i,1}(t), \cdots, p_{i,g_i}(t)\}$.

Assumption 5: The outputs of machine i have three quality states: conform (s_{pi1}), defective repairable (s_{pi2}), and not conform (s_{pi3}) states. Only s_{pi1} can be sent to the next machine.

Assumption 6: s_{pi2} can only appear in a machine that can be reworked and will only be repaired once on the current machine; that is, if it is still not conform after repair, then it will be regarded as s_{pi3}.

III. BASICS OF SELECTIVE MAINTENANCE FOR MULTISTATE MANUFACTURING SYSTEMS

A. MISSION RELIABILITY CONNOTATION OF MULTISTATE MANUFACTURING SYSTEMS

A selective maintenance strategy should be developed and optimized through a comprehensive analysis of mission demand, machine performance, and product quality data. Simplifying the manufacturing process and clarifying the operating mechanism are new concepts to improve effective decision support for the operation and maintenance of multistate manufacturing systems. Therefore, a multistate manufacturing system is simplified into a complex system that consists of machines, products, and tasks, as shown in Fig. 2.

Fig. 2(a) shows an example of a multistate manufacturing system, and machine n exhibits a rework process. Fig. 2(b) illustrates an example of a simplified manufacturing process. In this figure, the solid and dotted lines indicate the material and information flows, respectively. The product is divided into three quality states: conform (s_{pi1}), defective repairable (s_{pi2}), and not conform (s_{pi3}) states. Only s_{pi1} can be sent

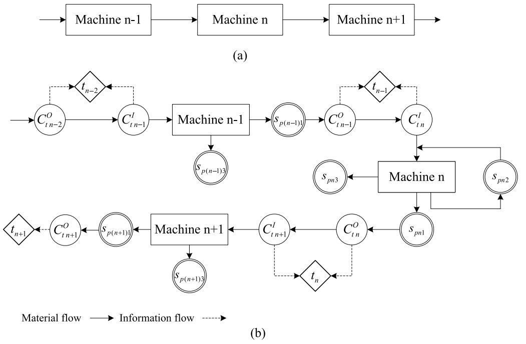

FIGURE 2. **Simplified manufacturing process of a multistate manufacturing system.**

to the next machine. In addition, s_{pi2} can only appear in the machine that can be reworked and will only be repaired once on the current machine; that is, if it is still not conform after repair, then it will be regarded as s_{pi3}. Therefore, the number of outputs of machine i is the number of work-in-progress in the conform state (s_{pi1}), i.e.,C^O_{ti}.

On the other hand, modern manufacturing systems have multiple work efficiency states that indicate the ability of the manufacturing system to complete mission. Moreover, the performance state of a machine is defined as the maximum working load that it can withstand under normal operating conditions. The performance state set of machine i is $\{s_{i,1}, \cdots, s_{i,g_i}\}$. At time t, the state probability that corresponds to machine i is $P_i(t) = \{p_{i,1}(t), \cdots, p_{i,g_i}(t)\}$. t_i represents the task execution status of machine i.

Meanwhile, the objective of a multistate manufacturing system is to meet the demands of production tasks, i.e., to produce a certain number of products. Therefore, the mission reliability of a multistate manufacturing system can be defined as the ability to produce a sufficient number of quality products under specified task requirements and within a stipulated period. Therefore, the mission reliability of the manufacturing system can be expressed by the following equation.

$$R = \Pr\{O \geq d\} \tag{1}$$

where O is the total output of the produced product of the manufacturing system, and d is the minimum total amount of products required by the mission. Hence, the mission reliability of machine i can be described by the following equation:

$$R_i = \Pr\left\{O_i \geq C^o_{t_i}\right\}, \tag{2}$$

where O_i is the number of qualified work-in-process (WIP) items exported by machine$i$, and $C^o_{t_i}$ is the minimum output WIP quantity required by machine i for the task. Eq.(1) can be rewritten from the input perspective as follows:

$$R_i = \Pr\left\{S_{i,x} \geq C^I_{t_i}\right\}, \tag{3}$$

where $S_{i,x}$ indicates that machine i is in the x state, which is defined as an acceptable working load. $C^I_{t_i}$ is the minimum input load that is required by the task.

B. MISSION RELIABILITY MODEL FOR MULTISTATE MANUFACTURING SYSTEMS

Quantifying $P_i(t)$ and $C^I_{t_i}$ is the basis for accurately assessing mission reliability according to the mission reliability connotation in Section A.

The minimum output WIP of machine i, namely $C^o_{t_i}$, can be determined on the basis of the production task. To meet the needs of production mission, the first step is to determine the amount of input material I. I can be expressed as follows.

$$I = d \Bigg/ \prod_{i=1}^{M} q_i + rq_i(1 - q_i), \tag{4}$$

where r is a binary variable, q_i is the qualification rate of machine i. If the machine has a rework process, then $r = 1$; otherwise, $r = 0$. Then, $C^I_{t_i}$ can be obtained on the basis of the qualification rate q_i.

$$C^I_{t_i} = \frac{C^o_{t_i}}{q_i + rq_i(1 - q_i)}, \tag{5}$$

Another parameter that should be quantified is $P_i(t)$. In this study, the performance state of a multistate machine is assumed to follow the homogeneous Markov process. The transfer strength matrix X_i of machine i is determined and shown in Eq. (6).

$$\mathrm{X}_i = \left|\begin{array}{ccccc} \lambda_{(1,1)} & \lambda_{(1,2)} & \cdots & \lambda_{(1,g_i-1)} & \lambda_{(1,g_i)} \\ \lambda_{(2,1)} & \lambda_{(2,2)} & \cdots & \lambda_{(2,g_i-1)} & \lambda_{(2,g_i)} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \lambda_{(g_i-1,1)} & \lambda_{(g_i-1,2)} & \cdots & \lambda_{(g_i-1,g_i-1)} & \lambda_{(g_i-1,g_i)} \\ \lambda_{(g_i,1)} & \lambda_{(g_i,2)} & \cdots & \lambda_{(g_i,g_i-1)} & \lambda_{(g_i,g_i)} \end{array}\right| \tag{6}$$

$\lambda_{(i,i)}$ and $\lambda_{(i,j)}$ respectively indicate the transition strength leaving state i and the transition strength from state i to state j at any time. For a continuous degradation manufacturing system, $\lambda_{(i,j)} = 0$ When $i > j$. The formula below is the solution formula for the transfer strength.

$$\lambda_{ii}(t) = \lim_{\Delta t \to 0} \frac{p_{ii}(t,0) - p_{ii}(t,\Delta t)}{\Delta t} = \lim_{\Delta t \to 0} \frac{1 - p_{ii}(t,\Delta t)}{\Delta t} \tag{7}$$

$$\lambda_{ij}(t) = \lim_{\Delta t \to 0} \frac{p_{ij}(t,0) - p_{ij}(t,\Delta t)}{-\Delta t} = \lim_{\Delta t \to 0} \frac{p_{ij}(t,\Delta t)}{\Delta t} \tag{8}$$

where $p_{ii}(t, \Delta t) = \Pr\{G(t + \Delta t) = i|G(t) = i\}$ indicates the probability that the machine did not have a state transition during time Δt, and $p_{ii}(t, \Delta t) + \sum_{j \neq i} p_{ij}(t, \Delta t) = 1$. For homogeneous Markov process, $\lambda_{ii}(t)$ and $\lambda_{ij}(t)$ are time-independent constants, denoted as $\lambda_{(i,i)}$ and $\lambda_{(i,j)}$.

At time $t = 0$ (the next phase that the mission starts), the state probability vector of machine i, i.e., the state probability after being maintained, is $P^a_i = \left\{p^a_{i,1}, p^a_{i,2}, \cdots, p^a_{i,g_i}\right\}$.

The calculation process of this is described in Section C. Moreover, $\sum_{j=1}^{g_i} p_{i,j}^{a} = 1$. Therefore, at any time t, the state probability of machine i can be obtained on the basis of the Kolmogorov differential equation group, i.e., Eq. (9).

$$dP_i(t)\big/dt = P_i(t)\mathrm{X}_i \tag{9}$$

As discussed in Section A, the mission reliability of machine i is a set of states in which machine performance states meet task requirements. Thus, the state space of a multistate machine can be divided into acceptable and unacceptable state sets on the basis that the task requirements are met. Therefore, the mission reliability of multistate machine i at time t is expressed as follows:

$$R_i(t) = \sum_{j=1}^{g_i} p_{i,j}(t) 1(s_{i,g_j} - C_{t_i}^{I} \geq 0), \tag{10}$$

where $1(\bullet)$ is a decision function, i.e., $1(\text{true}) = 1$ and $1(\text{false}) = 0$. The mission reliability for a series of multistate manufacturing systems that consist of M multistate machines at time t is expressed as follows:

$$R(t) = \prod_{i=1}^{M} \sum_{j=1}^{g_i} p_{i,j}(t) 1(s_{i,g_j} - C_{t_i}^{I} \geq 0). \tag{11}$$

C. MAINTENANCE EFFECT MODEL UNDER UNCERTAIN MAINTENANCE QUALITY

If the pre- and post-repair states of machine i, namely x_i and y_i $(1 \leq y_i \leq x_i \leq g_i)$, are determined, then maintenance action, costs, and time are $l_{i,x_i}^{y_i}$, $\widetilde{c}_{i,x_i}^{y_i}$, and $\widetilde{t}_{i,x_i}^{y_i}$, respectively. However, the relationship between maintenance resources and effects is uncertain due to the difference in repairmen and tools. A triangle membership function is utilized to obtain an accurate maintenance effect model. Using maintenance cost as an example, when the state x_i $(1 \leq x_i \leq g_i)$ before machine i is maintained is determined, the membership function between maintenance cost c_{i,x_i} and action $l_{i,x_i}^{y_i}$ is shown in Fig. 3.

As shown in Fig. 3, the lines with different colors represent the membership functions for various maintenance actions. Each vertex represents a critical value of maintenance action under different conditions, and several thresholds coincide. $c_{i,R}$ represents the maintenance cost under perfect maintenance conditions, i.e., the maximum cost of maintenance. Let $r_{i,y_i}(c_{x_i})$ $(1 \leq y_i \leq x_i \leq g_i)$ denote the degrees of membership for each maintenance action. Evidently, $r_{i,y_i}(c_{x_i}) = r_{i,l_{i,x_i}^{y_i}}(c_{x_i})$.

$$r_{i,x_i}(c_{x_i}) = \begin{cases} 1, & (c_{x_i} = c_{i,x_i}^{x_i}) \\ \overline{c_{i,x_i}^{x_i}} - c_{x_i} \Big/ \overline{c_{i,x_i}^{x_i}} - c_{i,x_i}^{x_i} \\ \quad (c_{i,x_i}^{x_i} < c_{x_i} < \overline{c_{i,x_i}^{x_i}}) \\ 0, & (c_{x_i} \geq \overline{c_{i,x_i}^{x_i}}), \end{cases} \tag{12}$$

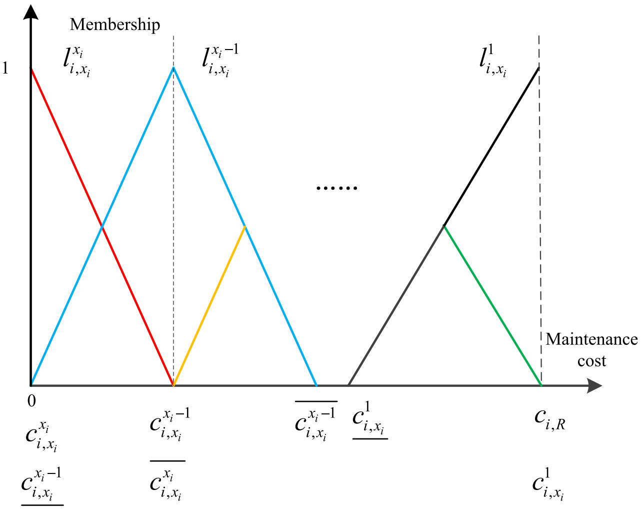

FIGURE 3. Triangle membership function between maintenance cost and action.

$$r_{i,x_i-1}(c_{x_i}) = \begin{cases} 0, & (c_{x_i} \leq \underline{c_{i,x_i}^{x_i-1}}) \\ c_{x_i} - \underline{c_{i,x_i}^{x_i-1}} \Big/ c_{i,x_i}^{x_i-1} - \underline{c_{i,x_i}^{x_i-1}}, \\ \quad (\underline{c_{i,x_i}^{x_i-1}} < c_{x_i} < c_{i,x_i}^{x_i-1}) \\ 1, & (c_{x_i} = c_{i,x_i}^{x_i-1}) \\ \overline{c_{i,x_i}^{x_i-1}} - c_{x_i} \Big/ \overline{c_{i,x_i}^{x_i-1}} - c_{i,x_i}^{x_i-1} \\ \quad (c_{i,x_i}^{x_i-1} < c_{x_i} < \overline{c_{i,x_i}^{x_i-1}}) \\ 0, & (c_{x_i} \geq \overline{c_{i,x_i}^{x_i-1}}), \end{cases} \tag{13}$$

$$r_{i,1}(c_{x_i}) = \begin{cases} 0, & (c_{x_i} \leq \underline{c_{i,x_i}^{1}}) \\ c_{x_i} - \underline{c_{i,x_i}^{1}} \Big/ c_{i,x_i}^{1} - \underline{c_{i,x_i}^{1}}, \\ \quad (\underline{c_{i,x_i}^{1}} < c_{x_i} < c_{i,x_i}^{1}) \\ 1, & (c_{x_i} = c_{i,x_i}^{1}), \end{cases} \tag{14}$$

where c_{i,x_i} is the cost of repairing machine i when it is in the $\mathrm{x_i}$ state before maintenance. $\underline{c_{i,x_i}^{y_i}}$, $c_{i,x_i}^{y_i}$, and $\overline{c_{i,x_i}^{y_i}}$ are the vertices of the corresponding maintenance action $l_{i,x_i}^{y_i}$ in Fig.3. $\underline{c_{i,x_i}^{y_i}}$, $c_{i,x_i}^{y_i}$, and $\overline{c_{i,x_i}^{y_i}}$ are assumed to be determined.

Similarly, in the case where the state of machine i is determined, the membership function between maintenance time and action can be obtained. When the maintenance effects of maintenance time and cost are unequal, the variable the with poor maintenance effect is regarded as the final maintenance effect $r_{i,y_i}(x_i)$. Therefore, the membership matrix R_i of machine i is shown in Eq. (15), as shown at the bottom of the next page, where R_i is the lower triangular matrix; and the value $r_{i,y_i}(x_i)$ in matrix R_i represents the membership of maintenance action $l_{i,x_i}^{y_i}$, i.e., the probability that machine i recovers from the x_i state to the y_i state. Therefore, when the state probability vector of machine i before being maintained $P_i = \{p_{i,1}, p_{i,2}, \cdots, p_{i,g_i}\}$ is determined, the state

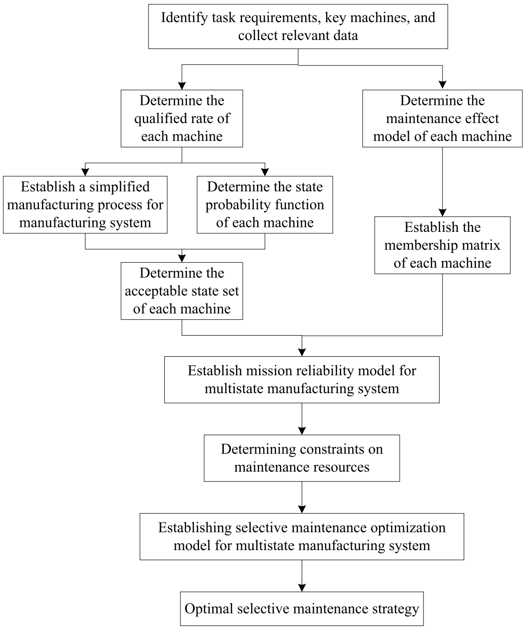

FIGURE 4. **Workflow of selective maintenance optimization modeling for multistate manufacturing systems.**

probability vector P_i^a after repair is

$$P_i^a = \left\{p_{i,1}^a, p_{i,2}^a, \cdots, p_{i,g_i}^a\right\} = P_i R_i. \tag{16}$$

IV. SELECTIVE MAINTENANCE OPTIMIZATION FOR MULTISTATE MANUFACTURING SYSTEMS

A. SELECTIVE MAINTENANCE OPTIMIZATION MODEL FOR MULTISTATE MANUFACTURING SYSTEMS

In accordance with the theory and method proposed in Section 3, the modeling process of the selective maintenance optimization for multistate manufacturing systems is proposed as shown in Fig. 4.

The relevant data as shown in Fig. 1 are collected when the task requirements and key machines are determined. Subsequently, a simplified manufacturing process of a multistate manufacturing system is established. Moreover, the subtask requirements $C_{t_i}^I$ and $C_{t_i}^o$ of machine i are estimated on the basis of Eqs. (4) and (5) when the qualified rate q_i of multistate machine i is determined. Meanwhile, the set of acceptable states of each machine is determined on the basis of the pre-divided state space. In addition, the maintenance effect model of each machine is obtained on the basis of the historical maintenance and fault data. The membership matrix R_i of machine i is calculated using Eqs. (12), (13), and (14). In the case where the state probability vector $P_i = \left\{p_{i,1}, p_{i,2}, \cdots, p_{i,g_i}\right\}$ at the end of the previous phase task is known, the state probability vector P_i^a of machine i after being maintained is calculated using Eq. (16). Furthermore, the state probability function of the machine is calculated on the basis of the transfer strength matrix X_i of machine i and Eq. (9). Finally, the mission reliability model of the multistate manufacturing system is obtained on the basis of Eq. (11), assuming that the manufacturing system is in series configuration.

The purpose of the selective maintenance of a multistate manufacturing system is to produce quality products that meet the mission requirements. Therefore, the objective function of the selective maintenance optimization model for multistate manufacturing systems is that mission reliability is maximized when the duration t_k of the kth task is known.

Meanwhile, the maintenance cost and time of machine i are

$$C_i = c_{i,fix} + c_i, \tag{17}$$

$$T_i = t_{i,fix} + t_i, \tag{18}$$

where $c_{i,fix}$ and $t_{i,fix}$ represent the fixed maintenance cost and time required for machine i, respectively; and c_i and t_i are the maintenance effects of machine i. When c_i and t_i are larger, the maintenance effect of machine i is better. When minimum maintenance is applied, $c_i = 0$, $t_i = 0$, $c_{i,fix} = 0$, $t_{i,fix} = 0$, $C_i = 0$, and $T_i = 0$. Maintenance costs and times are the cost and time required to replace a new part, namely $c_{i,R}$ and $t_{i,R}$, when applying perfect maintenance. Moreover, $0 \le c_i \le c_{i,R}$ and $0 \le t_i \le t_{i,R}$ when implementing imperfect maintenance.

Assuming that the upper limit of maintenance cost and time are C_0 and T_0, respectively, the selective maintenance optimization model for multistate manufacturing systems is

$$\text{Maximize } R(t_k) = \prod_{i=1}^{M} \sum_{j=1}^{g_j} p_{i,j}(t) 1(s_{i,j} - C_{t_i}^I \ge 0). \tag{19}$$

subject to

$$C_m + \sum_{i=1}^{M} (c_{i,fix} + c_i) \le C_0, \tag{20}$$

$$T_m + \sum_{i=1}^{M} (t_{i,fix} + t_i) \le T_0, \tag{21}$$

$$c_{i,fix} \ge 0, 0 \le c_i \le c_{i,R}, \tag{22}$$

$$t_{i,fix} \ge 0, 0 \le t_i \le t_{i,R}, \tag{23}$$

where C_m and T_m are the fixed maintenance costs and times for monitoring a manufacturing system, respectively, which

$$R_i = \begin{pmatrix} r_{i,1}(1) & 0 & \cdots & 0 & 0 \\ r_{i,1}(2) & r_{i,2}(2) & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ r_{i,1}(g_i - 1) & r_{i,2}(g_i - 1) & \cdots & r_{i,g_i-1}(g_i - 1) & 0 \\ r_{i,1}(g_i) & r_{i,2}(g_i) & \cdots & r_{i,g_i-1}(g_i) & r_{i,g_i}(g_i) \end{pmatrix}, \tag{15}$$

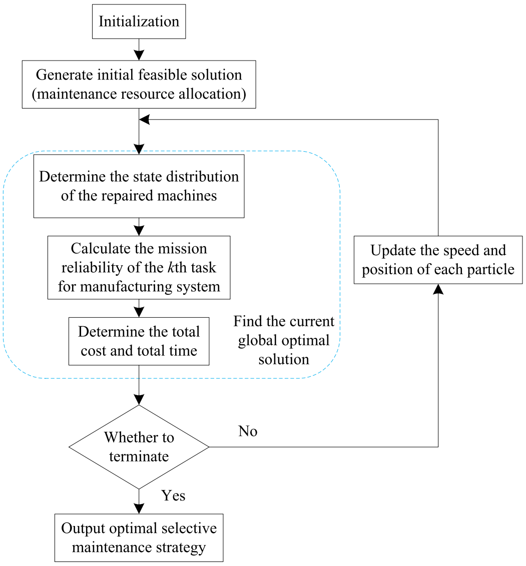

FIGURE 5. **Flowchart of selective maintenance decision optimization based on the PSO algorithm.**

have constant values. The specific solution process of the selective maintenance optimization is described in Section B.

B. SELECTIVE MAINTENANCE DECISION OPTIMIZATION BASED ON THE PSO ALGORITHM

As shown in Eqs. (19)–(23), the selective maintenance optimization problem of a multistate manufacturing system is a complex, nonlinear problem. Solving this type of problem is unrealistic using the traditional enumeration optimization method due to the limitation in calculation time. The PSO algorithm is an intelligent algorithm that simulates the foraging behavior of birds and determines the global optimal value by following the current searched optimal value. The PSO algorithm is one of the most widely used optimization methods because of its advantages, such as simple operation and fast convergence. The PSO algorithm has a higher convergence speed than other optimization algorithms and the application of the PSO algorithm has been extended to various scientific fields [33]. The PSO algorithm uses the velocity vector and the position of the best local and global values to update the current position of each particle and find the corresponding function value in the new location.

Calculating the maintenance resources allocated to each machine is necessary to obtain the mission reliability of a multistate manufacturing system. Therefore, the maintenance decision aims to calculate the mission reliability of a multistate manufacturing system. If the cost and time meet the constraints, then the maintenance activity of machine i is feasible. Otherwise, the mission reliability of machine i is 0. The specific selective maintenance decision-making optimization process based on the PSO algorithm is shown in Fig. 5.

The basic steps shown in Fig. 5 are described as follows.

Step 1: Initialize. Each machine state probability distribution and the length of the task are established in accordance with the manufacturing system structure. The maintenance effect model is clarified on the basis of the basic information of the multistate manufacturing system (e.g., state transition strength and machine qualified rate).

Step 2: An initial feasible solution particle swarm is generated. The N particles are generated as the initial particle swarm of the PSO algorithm, i.e., the allocation of maintenance resources.

Step 3: The state distribution of each machine after maintenance is calculated. The state distribution of each machine after maintenance is obtained according to the state distribution and maintenance resources of the machine before maintenance, such as the initial condition for the start of the kth task.

Step 4: The mission reliability and total maintenance resources for the kth mission are calculated. The mission reliability of the kth task and the total maintenance cost and time are obtained according to Eqs. (19), (20), and (21).

Step 5: The condition judgment is terminated. If the number of iterations is less than the present value, then the speed and position of each particle are updated and return to Step 3. Otherwise, proceed to Step 6.

Step 6: The optimal selective maintenance strategy is outputted.

V. CASE STUDY

A. BACKGROUND

In the present study, an engine cylinder head manufacturing system is used as an example to validate the mission reliability-oriented selective maintenance strategy considering the uncertain maintenance quality. The cylinder head is one of the most important components of an engine. Moreover, the role of the engine cylinder head is to ensure engine ventilation, cooling, and lubrication and to guarantee the proper assembly of various auxiliary systems, components, and engines. The main intelligent manufacturing equipment is shown in Fig. 6. Therefore, the high-precision requirements make the reasonable maintenance of a cylinder head manufacturing system an important basis for ensuring the completion of a task. However, the selective maintenance strategy that modern companies frequently use is unable to balance the relationship between manufacturing and maintenance tasks. Perfecting the selective maintenance strategy based on the system operation mechanism and improving maintenance efficiency are the most effective approaches for enhancing the competitiveness of engine manufacturers' products given the increasingly fierce market competition pressure.

According to quality experts, an intelligent manufacturing system includes five types of machines, namely, machining center, numerical control machine, cleaning machine, pressing machine, and testing machine, which ensure the excellent performance of the manufactured cylinder head. Therefore, the effectiveness of the selective maintenance strategy proposed in this study is verified on a small manufacturing system that consists of the aforementioned five machines.

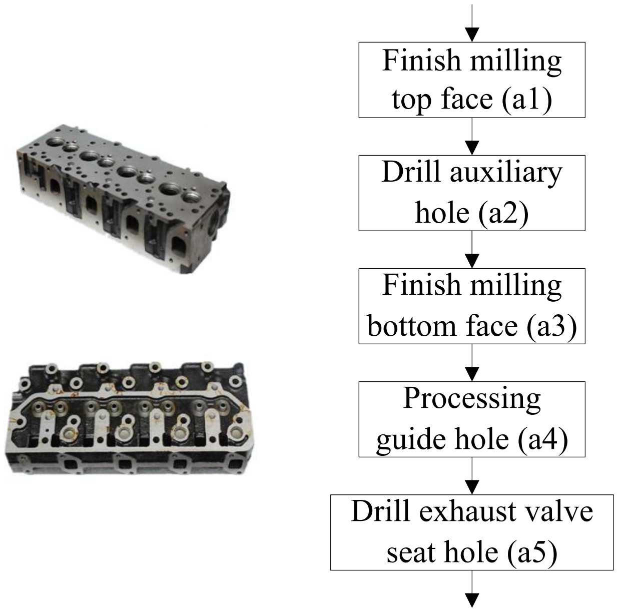

FIGURE 6. Operation flow of a cylinder head manufacturing system.

TABLE 1. The mission requirements and key machines of the numerical example.

Machine	Rework	KQC	Mission requirements
a1	No	Flatness Surface roughness	0.08 $Ra = 3.2\ \mu\text{m}$
a2	Yes	Diameter	$\phi = 12.2^{+0.025}_{-0.05}$ mm
a3	No	Flatness Surface roughness	0.04 $Ra = 1.6\ \mu\text{m}$
a4	No	Diameter	$\phi = 26.2^{+0.2}_{-0.08}$ mm
a5	No	Proper alignment	$\phi = 0.06$ mm

B. ILLUSTRATED EXAMPLE

The key machines and specific mission requirements for the cylinder head multistate manufacturing system are provided in Table 1 with the aid of quality experts and production line workers.

From Table 1, only Machine 2 has a rework process. Therefore, the output quality state of Machine 2 is s_{p21}, s_{p22}, and s_{p23}. The output quality state of the remaining machines is s_{pi1} and s_{pi3} (i = 1, 3, 4, and 5). Furthermore, based on sensor data, the qualified rate of each machine is determined as $q_1 = 0.96$, $q_2 = 0.94$, $q_3 = 0.92$, $q_4 = 0.97$, and $q_5 = 0.93$.

TABLE 2. The task requirements and key machines of the numerical example.

Machine	$c_{i,fix}$	$c_{i,R}$	$t_{i,fix}$	$t_{i,R}$
a1	110	2500	0.13	1.60
a2	120	2400	0.14	1.74
a3	140	3300	0.16	1.86
a4	100	3000	0.12	1.80
a5	130	2400	0.15	1.74

Meanwhile, the simplified production process for the cylinder head manufacturing system is established as shown in Fig. 7.

In addition, the state sets of each multistate machine are $S_1 = \{0, 70, 140, 210, 280, 350\}$, $S_2 = \{0, 65, 130, 195, 260, 325, 390\}$, $S_3 = \{0, 65, 130, 195, 260, 325, 390\}$, $S_4 = \{0, 45, 90, 135, 180, 225, 270\}$, and $S_5 = \{0, 50, 100, 150, 200, 250, 300\}$. The real-time based transfer intensity matrix of the machines is as follows, $X_1 - X_5$, as shown at the bottom of the next page.

For the cylinder head manufacturing system, the task requirement T is 150 pieces per day, i.e., the output O is 150. The subtask for each machine can be obtained according to Eq. (6).

$$\begin{aligned} C^I_{t_5} &= \frac{O}{q_5 + rq_5(1-q_5)} = 161.291 \\ C^I_{t_4} &= \frac{C^o_{t_4}}{q_4 + rq_4(1-q_4)} = 166.279 \\ C^I_{t_3} &= \frac{C^o_{t_3}}{q_3 + rq_3(1-q_3)} = 180.738 \\ C^I_{t_2} &= \frac{C^o_{t_2}}{q_2 + rq_2(1-q_2)} = 192.274 \\ I = C^I_{t_1} &= \frac{C^o_{t_1}}{q_1 + rq_1(1-q_1)} = 188.949 \end{aligned} \tag{24}$$

Evidently, the acceptable state sets for each multistate machine are$s_{1,x} \geq 210$, $s_{2,x} \geq 195$, $s_{3,x} \geq 195$, $s_{4,x} \geq 180$, and $s_{5,x} \geq 200$. Meanwhile, the state probability vectors of each multistate machine at the end of the $k-1$th task are P1 = {0.2534, 0.1413, 0.2591, 0.2070, 0.0925, 0.0467}, P_2 = {0.1216, 0.1874, 0.1761, 0.1605, 0.1974, 0.1106, 0.0464}, P_3 = {0.0824, 0.2865, 0.2029, 0.1487, 0.1955, 0.0485, 0.0355}, P_4 = {0.1179, 0.1533, 0.1729, 0.1769, 0.2476, 0.0683, 0.0631}, and P_5 = {0.1216, 0.1106, 0.1605, 0.1874, 0.1761, 0.1974, 0.0464}.

The fixed and perfect maintenance resources of each machine are shown in Table 2. Meanwhile, the maintenance action membership matrix R_i of each machine is obtained. The total maintenance cost C_0 = 8600\$, the monitoring cost T_0 = 4 days, the total maintenance time C_m = 300\$, the monitoring time T_m = 0.3 day, and the mission run-

ning time of the next phase $t_k = 5$ weeks. Evidently, the total maintenance resources are insufficient to complete the maintenance of all machines. Therefore, the maintenance resources should be allocated reasonably to maximize the mission reliability in the next stage.
Unit: $ or d.

Therefore, we can obtain the selective maintenance optimization model for the cylinder head multistate manufacturing system on the basis of Eqs. (20) to (23).

C. RESULTS AND DISCUSSION

1) RESULT ANALYSIS

In the "Numerical example" section, a selective maintenance strategy for the cylinder head manufacturing system is obtained on the basis of the given task and maintenance resource constraints. However, the resulting selective maintenance strategy is still non-optimal due to the limitation of the performance state of the machine. For example, the minimum input of Machine 3 is $C^I_{t_3} = 180.738$ and the its acceptable set is $s_{3,x} \geq 195$. Therefore, the objective function, i.e., the mission reliability model, is still inaccurate, which results in a non-optimal selective maintenance strategy. The resulting selective maintenance strategy is better when the separation between performance states is particularly small.

2) COMPARATIVE STUDY

In this section, a comparative study of the proposed method and traditional selective maintenance model is conducted to verify the advancement and effectiveness of the suggested technique.

The traditional selective maintenance model evaluates the reliability of a multistate system given that the acceptable state set of each component is known. According to experts and production line workers, the acceptable state sets for each machine are $s_{1,x} \geq 140$, $s_{2,x} \geq 130$, $s_{3,x} \geq 130$, $s_{4,x} \geq 90$,

$$X_1 = \begin{vmatrix} -0.011 & 0.011 & 0 & 0 & 0 & 0 \\ 0 & -0.012 & 0.012 & 0 & 0 & 0 \\ 0 & 0 & -0.029 & 0.029 & 0 & 0 \\ 0 & 0 & 0 & -0.043 & 0.043 & 0 \\ 0 & 0 & 0 & 0 & -0.09 & 0.09 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$X_2 = \begin{vmatrix} -0.023 & 0.023 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.044 & 0.044 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.04 & 0.04 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.048 & 0.048 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.045 & 0.045 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.031 & 0.031 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$X_3 = \begin{vmatrix} -0.023 & 0.023 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.035 & 0.035 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.025 & 0.025 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.046 & 0.046 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.042 & 0.042 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.037 & 0.037 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$X_4 = \begin{vmatrix} -0.027 & 0.027 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.013 & 0.013 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.014 & 0.014 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.06 & 0.06 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.016 & 0.016 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.035 & 0.035 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$X_5 = \begin{vmatrix} -0.018 & 0.018 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.05 & 0.05 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.024 & 0.024 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.096 & 0.096 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.042 & 0.042 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.037 & 0.037 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

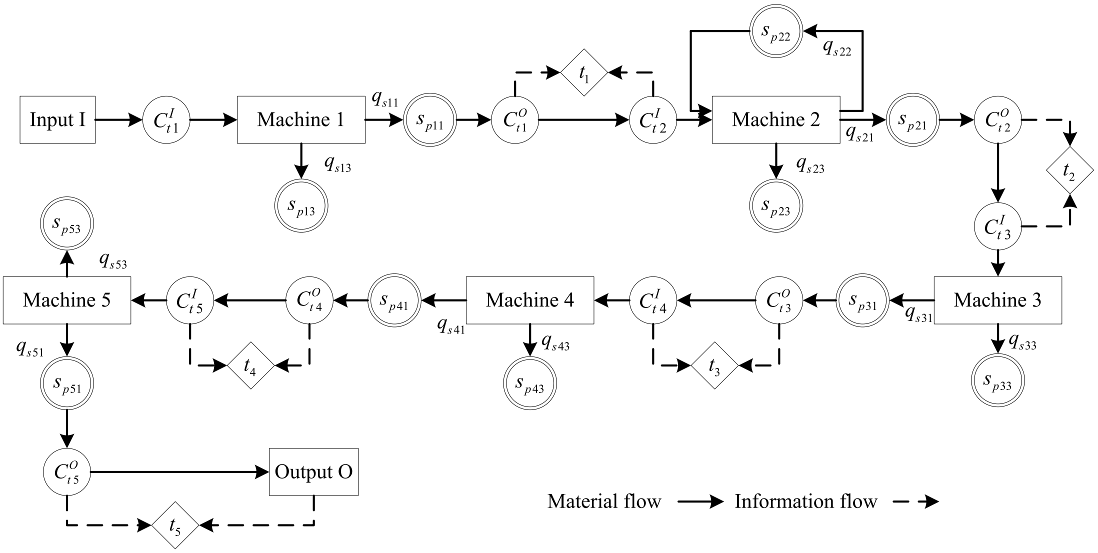

FIGURE 7. Simplified manufacturing process of the cylinder head manufacturing system.

TABLE 3. Optimal selective maintenance strategy and corresponding results.

Machine	Maintenance cost c_i	Maintenance time t_i	Mission reliability $R(t_k)$
a1	1144.44	0.7325	0.7955
a2	555.59	0.4028	
a3	2385.02	0.0013	
a4	1480.19	0.8884	
a5	1343.52	0.9750	

TABLE 4. Comparison of the proposed method and the traditional selective maintenance mode.

Proposed method			Traditional method		
Machine	c_i	t_i	Machine	c_i	t_i
a1	1144.44	0.7325	a1	1095.91	0.7014
a2	555.59	0.4028	a2	959.94	0.6960
a3	2385.02	0.0013	a3	1271.49	0.3202
a4	1480.19	0.8884	a4	1066.14	0.6406
a5	1343.52	0.9750	a5	883.99	0.6410
$R(t_k)$	0.7955		$R(t_k)$	0.8807	

and $s_{5,x} \geq 100$. We obtain the selective maintenance strategy of the cylinder head manufacturing system using the two methods: the proposed method and the traditional selective maintenance model (Table 4).

As shown in Table 4, the selective maintenance strategy for the two decision methods is obtained for the multistate manufacturing system. However, the optimal selective maintenance strategy is not obtained, and the mission reliability of the multistate manufacturing system is overestimated because the machine, product, and task, also known as the operating mechanisms of the manufacturing system, are not considered. In addition, the maintenance resources are not effectively utilized because the expected mission reliability is particularly high. Furthermore, this condition can lead to unplanned downtime of the manufacturing system during task execution.

The results show that the proposed selective maintenance optimization model for multistate manufacturing systems fully considers product quality, machine performance, and task execution states. Therefore, the method improves the utilization of maintenance resources and can accurately guide maintenance activities.

VI. CONCLUSION

In this study, a novel selective maintenance optimization model for intelligent multistate manufacturing systems is proposed to consider mission reliability and the uncertainty of maintenance quality. Mission reliability was developed on the basis of the operating mechanism of a multistate manufacturing system. Meanwhile, a quantitative model of maintenance quality is proposed to characterize the uncertainty caused by maintenance workers and tools. The PSO algorithm is used to solve the constrained combinatorial optimization problem. As demonstrated in the case study, disregarding the operating mechanism of the manufacturing system will result in a poor selective maintenance strategy compared with the proposed method. Meanwhile, the proposed method can be used in various intelligent multistate systems considering that the operation mechanism of a multistate system can be clarified.

The following are three issues that are worth exploring in our future research on selective maintenance:

(1) Consider the dependency between maintenance cost and time in the selective maintenance optimization model

(2) Reliability-centered selective maintenance decision questions for a multistate manufacturing system under multistage tasks. And machine degradation obeys non-homogeneous Markov processes.

(3) Assume that all maintenance actions are not performed in a sequential manner but in parallel mode.

REFERENCES

[1] Y. Su, X. R. Liang, H. Wang, J. J. Wang, and M. G. Pecht, "A maintenance and troubleshooting method based on integrated information and system principles," *IEEE Access*, vol. 7, pp. 70513–70524, 2019.

[2] L. Hu, D. Yue, and G. Zhao, "Reliability assessment of random uncertain multi-state systems," *IEEE Access*, vol. 7, pp. 22781–22789, 2019.

[3] E. Ruschel, E. A. P. Santos, and E. de Freitas Rocha Loures, "Industrial maintenance decision-making: A systematic literature review," *J. Manuf. Syst.*, vol. 45, pp. 180–194, Oct. 2017.

[4] D. Yang, H. Wang, Q. Feng, Y. Ren, B. Sun, and Z. Wang, "Fleet-level selective maintenance problem under a phased mission scheme with short breaks: A heuristic sequential game approach," *Comput. Ind. Eng.*, vol. 119, pp. 404–415, May 2018.

[5] W. Cao, X. Jia, Q. Hu, J. Zhao, and Y. Wu, "A literature review on selective maintenance for multi-unit systems," *Qual. Rel. Eng. Int.*, vol. 34, no. 5, pp. 824–845, 2018.

[6] Z.-Q. Wang, C.-H. Hu, X.-S. Si, and E. Zio, "Remaining useful life prediction of degrading systems subjected to imperfect maintenance: Application to draught fans," *Mech. Syst. Signal Process.*, vol. 100, pp. 802–813, Feb. 2018.

[7] Y. Wang, E. Elahi, and L. Xu, "Selective maintenance optimization modelling for multi-state deterioration systems considering imperfect maintenance," *IEEE Access*, vol. 7, pp. 62759–62768, 2019.

[8] H. Zhu, F. Liu, X. Shao, Q. Liu, and Y. Deng, "A cost-based selective maintenance decision-making method for machining line," *Qual. Rel. Eng. Int.*, vol. 27, no. 2, pp. 191–201, Mar. 2011.

[9] A. Khatab, E.-H. Aghezzaf, I. Djelloul, and Z. Sari, "Selective maintenance optimization for systems operating missions and scheduled breaks with stochastic durations," *J. Manuf. Syst.*, vol. 43, pp. 168–177, Apr. 2017.

[10] A. Khatab, E. L. H. Aghezzaf, C. Diallo, and I. Djelloul, "Selective maintenance optimisation for series-parallel systems alternating missions and scheduled breaks with stochastic durations," *Int. J. Prod. Res.*, vol. 55, no. 10, pp. 3008–3024, 2017.

[11] W. Cao, X. Jia, Y. Liu, and Q. Hu, "Selective maintenance optimization for fuzzy multi-state systems," *J. Intell. Fuzzy Syst.*, vol. 34, no. 1, pp. 105–121, 2018.

[12] M. Pandey, M. J. Zuo, and R. Moghaddass, "Selective maintenance scheduling over a finite planning horizon," *Proc. Inst. Mech. Eng., O, J. Risk Rel.*, vol. 230, no. 2, pp. 162–177, 2016.

[13] L. Yang, Y. Zhao, R. Peng, and X. B. Ma, "Opportunistic maintenance of production systems subject to random wait time and multiple control limits," *J. Manuf. Syst.*, vol. 47, pp. 12–34, Apr. 2018.

[14] L. Zhang, L. Zhang, H. Shan, and H. Shan, "Selective maintenance planning considering team capability based on fuzzy integral and dynamic artificial bee colony algorithm," *IEEE Access*, vol. 7, pp. 66553–66566, 2019.

[15] M. Pandey, M. J. Zuo, and R. Moghaddass, "Selective maintenance modeling for a multistate system with multistate components under imperfect maintenance," *IIE Trans.*, vol. 45, no. 11, pp. 1221–1234, 2013.

[16] G. Levitin and L. D. Xing, "Multi-state systems," *Rel. Eng. Syst. Saf.*, vol. 166, pp. 1–2, Oct. 2017.

[17] C. D. Dao and M. J. Zuo, "Selective maintenance for multistate series systems with S-dependent components," *IEEE Trans. Rel.*, vol. 65, no. 2, pp. 525–539, Jun. 2016.

[18] C. D. Dao and M. J. Zuo, "Optimal selective maintenance for multi-state systems in variable loading conditions," *Rel. Eng. Syst. Saf.*, vol. 166, pp. 171–180, Oct. 2017.

[19] A. Khatab, C. Diallo, E.-H. Aghezzaf, and U. Venkatadri, "Condition-based selective maintenance for stochastically degrading multi-component systems under periodic inspection and imperfect maintenance," *Proc. Inst. Mech. Eng., O, J. Risk Rel.*, vol. 232, no. 4, pp. 447–463, 2018.

[20] A. Khatab, C. Diallo, U. Venkatadri, Z. Liu, and E.-H. Aghezzaf, "Optimization of the joint selective maintenance and repairperson assignment problem under imperfect maintenance," *Comput. Ind. Eng.*, vol. 125, pp. 413–422, Nov. 2018.

[21] C. Diallo, U. Venkatadri, A. Khatab, Z. Liu, and E.-H. Aghezzaf, "Optimal joint selective imperfect maintenance and multiple repairpersons assignment strategy for complex multicomponent systems," *Int. J. Prod. Res.*, vol. 57, no. 13, pp. 4098–4117, 2018. doi: 10.1080/00207543.2018.1505060.

[22] A. Khatab and E.-H. Aghezzaf, "Selective maintenance optimization when quality of imperfect maintenance actions are stochastic," *Rel. Eng. Syst. Saf.*, vol. 150, pp. 182–189, Jun. 2016.

[23] C. Diallo, U. Venkatadri, A. Khatab, and Z. Liu, "Optimal selective maintenance decisions for large serial k-out-of-n: G systems under imperfect maintenance," *Rel. Eng. Syst. Saf.*, vol. 175, pp. 234–245, Jul. 2018.

[24] Y. He, C. Gu, Z. Chen, and X. Han, "Integrated predictive maintenance strategy for manufacturing systems by combining quality control and mission reliability analysis," *Int. J. Prod. Res.*, vol. 55, no. 19, pp. 5841–5862, Jul. 2017.

[25] Y. He, X. Han, C. Gu, and Z. Chen, "Cost-oriented predictive maintenance based on mission reliability state for cyber manufacturing systems," *Adv. Mech. Eng.*, vol. 10, no. 1, pp. 1–15, 2018.

[26] Y. Chen and J. Jin, "Quality-reliability chain modeling for system-reliability analysis of complex manufacturing processes," *IEEE Trans. Rel.*, vol. 54, no. 3, pp. 475–488, Sep. 2005.

[27] Y. He, C. Gu, Z. He, and J. Cui, "Reliability-oriented quality control approach for production process based on RQR chain," *Total Qual. Manage. Bus. Excellence*, vol. 29, nos. 5–6, pp. 652–672, 2018.

[28] X. Wang, Y. Zhang, L. Wang, J. Wang, and J. Lu, "Maintenance grouping optimization with system multi-level information based on BN lifetime prediction model," *J. Manuf. Syst.*, vol. 50, pp. 201–211, Jan. 2019.

[29] L. Fiondella, Y.-K. Lin, and P.-C. Chang, "System performance and reliability modeling of a stochastic-flow production network: A confidence-based approach," *IEEE Trans. Syst., Man, Cybernetics, Syst.*, vol. 45, no. 11, pp. 1437–1447, Nov. 2015.

[30] Y. He, C. Gu, X. Han, J. Cui, and Z. Chen, "Mission reliability modeling for multi-station manufacturing system based on quality state task network," *Proc. Inst. Mech. Eng., O, J. Risk Rel.*, vol. 231, no. 6, pp. 701–715, 2017.

[31] J. Mi, Y.-F. Li, W. Peng, H.-Z. Huang, "Reliability analysis of complex multi-state system with common cause failure based on evidential networks," *Rel. Eng. Syst. Saf.*, vol. 174, pp. 71–81, Jun. 2018.

[32] Y. He, F. Liu, J. Cui, X. Han, Y. Zhao, Z. Chen, D. Zhou, and A. Zhang, "Reliability-oriented design of integrated model of preventive maintenance and quality control policy with time-between-events control chart," *Comput. Ind. Eng.*, vol. 129, pp. 228–238, Mar. 2019.

[33] B. Roshanravan, H. Aghajani, M. Yousefi, and O. Kreuzer, "Particle swarm optimization algorithm for neuro-fuzzy prospectivity analysis using continuously weighted spatial exploration data," *Natural Resour. Res.*, vol. 28, no. 2, pp. 309–325, 2019.

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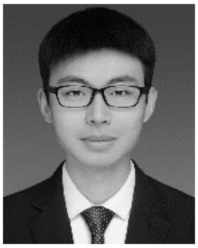

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