Economic Maintenance Planning of Complex Systems Based on Discrete Artificial Bee Colony Algorithm

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ABSTRACT In recent years, system maintenance has become a hot topic that has attracted significant research interests from both academia and industry, and has found applications in many areas. A modern system usually consists of many components, among which there may be different dependencies. The maintenance strategy that ignores the dependencies among components cannot meet the actual engineering requirements and may even affect the usability of the entire system. Therefore, in this paper, we study the economic dependence of equipment cost and duration sharing when components are replaced at the same time. By characterizing the relationship between the effective service age and reliability of components using the Weibull distribution, we establish a selective maintenance model of multi-state complex system with economic dependence. The discrete artificial bee algorithm is used as the global optimization method to solve the dual-objective optimization model and obtain the Pareto solution set of the maintenance level of each component. A case study of the Shooman network system is performed to demonstrate the usefulness of the model and the importance of considering the economic dependencies between components in maintenance decisions.

INDEX TERMS Selective maintenance, multi-state systems, economic dependence, Weibull distribution, artificial bee colony.

I. INTRODUCTION
Maintenance is a preventive or repair measure to keep a system in a normal or specified state. It is designed to provide optimal system reliability, availability, or safety performance at a low maintenance cost. As modern equipment becomes more and more large-scale, complex, and sophisticated, and system failure mechanisms and underlying principles are gradually explored in-depth, maintenance has become a hot topic in the academia and industry, and achieved rapid development in many areas, such as mechanical engineering, computer and network systems, communication systems, energy systems, supply systems, urban infrastructures, strategic defense systems and so on. In [1], Do et al. developed a number of strategies for maintaining single-component systems. These maintenance strategies can be applied to multi-component systems when components in the system are assumed to be independent of each other. Rice et al. [2] firstly established a maintenance model to optimize the selective maintenance model, and then designed an algorithm to obtain the feasible solution, so as to help decision makers determine the maintenance subset before the next mission. Schneider and Cassady [3] developed a selective maintenance model to maximize system reliability. Subsequently, some scholars [4]–[10] established corresponding maintenance strategy models by adapting the model to different
practical scenarios and raised the computational efficiency by optimizing the algorithm.

However, for many systems, it is not reasonable to assume that their components are independent. A system usually consists of many components, and there may be different dependencies among the components. For example, the common maintenance cost of a group of components may not be equal to the sum of the individual maintenance cost of these components. The maintenance of one failed part often means the maintenance (or at least the removal) of the remaining parts. The state of one component affects the life of another component. As a result, the maintenance strategy adopted by ignoring the dependencies between components cannot meet the requirement of a practical project, and may even affect the usability of the whole system. Therefore, it is necessary to study efficient system maintenance strategies considering the interaction between components and considering the dependencies between components.

It is increasingly popular among researchers and practitioners to consider dependencies between components when modeling maintenance of multi-component systems [11], [12]. The study reported in [13] summarizes the research progress in the maintenance of condition-based multi-related component systems in recent years, and divides the dependencies among components into three main types: economic dependence, structural dependence, and stochastic dependence. Economic dependence has attracted more and more attention due to its direct impact on system maintenance cost and has been studied and integrated into many main-tenance models of multi-component systems. Dao et al. [14] proposed an economically dependent selective maintenance model, in which multiple components are repaired simultaneously to save time and cost. Nourelfath and Châtelet [15] proposed the integration of preventive maintenance and production planning for a production system consisting of parallel components in the case of economic dependence and common cause failures. Maarouf et al. [16] proposed a strategy for selecting components of a binary system that are affected by propagation failures with global effects and fault isolation phenomena. Table 1 lists key contributions in recent years in the area of maintenance strategy design that considers dependencies in multi-component systems.

It can be seen from Table 1 that most of the existing research mostly focused on two-component systems or series-parallel multi-component systems, thereby having significant limitations. It is difficult to apply them to some of the complex network systems in the real world, such as a remote communication system, computer network system, electric power facilities and the water delivery system and so on. These complex networks are difficult to be categorized as series, parallel, series, parallel, or k/n system. Therefore, more research is needed to study maintenance strategies with economic dependence of complex system structure, such as network structures. In order to solve this problem, this paper proposes a novel maintenance strategy model of complex systems under economic dependence. A discrete artificial bee algorithm is used to solve the dual-objective optimization model.

The rest of this article is organized as follows. Section II describes the maintenance decision problem of a complex system with economic dependence and develops its mathematical model. In Section III a dual-objective discrete artificial bee algorithm is proposed. Section IV presents the computational result and analysis of the experiment. Section V summarizes the entire paper.

II. PROBLEM STATEMENT

A. PROBLEM REPRESENTATION

This work deals with the problem of selective maintenance of multi-state complex systems under the perspective of economic dependence. Selective maintenance aims to make the system in excellent state under limited resources. Therefore, the maximization of system reliability is an optimization goal; another goal is the minimization of maintenance cost. As the two goals contradict with each other, with the increase of reliability, the maintenance cost also rises. Therefore, the problem is transformed into finding the Pareto optimality.

However, in many industrial systems, such as aerospace, medical devices and other fields, when repairing many components, especially identical components, the cost and time of disassembly only need to be spent once, that is, the cost and time of disassembly are shared. In this case, the system is considered to be economically dependent. In addition, for a subsystem, the time to repair two identical components is less than repairing one component twice. That is, when repairing the second component, the maintenance workers will be more skilled, so the time will be shorter. The two situations above are called economic dependence. This paper addresses a multi-objective planning problem, with the goals of improving reliability and minimizing maintenance cost,
and a decision model under economic dependence is established.

B. WEIBULL MODEL AND AGE REDUCTION MODEL

The notations are summarized as follows:

1) $i$ the index of component, $i \in \{1, 2, 3, \cdots , N\}$
2) $A_i (m)$ Effective age of component $i$ at the beginning of the $m$-th mission
3) $B_i (m)$ Effective age of component $i$ at the end of the $m$-th mission
4) $c_i^0$ Fixed maintenance cost for component $i$
5) $c_i^{rp}$ Corrective repair cost for replacement of the failed component $i$
6) $c_i^{pp}$ Preventive repair cost for replacement of the functioning component $i$
7) $c_i (m)$ Corrective/preventive repair cost allocated for the failed/functioning component $i$ after the $m$-th mission
8) $C_i (m)$ Total maintenance cost allocated for component $i$ after the $m$-th mission
9) $C_e (m)$ Total maintenance cost allocated for the complex system after the $m$-th mission under economic dependence
10) $b_i (m)$ Age reduction factor of component $i$ resulting from the maintenance subsequent to the $m$-th mission
11) $\eta_i$ Scale parameter of Weibull distribution of component $i$
12) $\beta_i$ Shape parameter of the Weibull distribution of component $i$
13) $m_i^{rf}$ Characteristic constant associated with the corrective repair cost of component $i$
14) $m_i^{rp}$ Characteristic constant associated with the preventive repair cost of component $i$
15) $r_i (m)$ Probability of component $i$ surviving at the end of the $m$-th mission
16) $t_i (m)$ Corrective/preventive repair time allocated for the failed/functioning component $i$ after the $m$-th mission
17) $T (m)$ Total maintenance time allocated for complex system after the $m$-th mission
18) $T_e (m)$ Total maintenance time allocated for complex system after the $m$-th mission under economic dependence
19) $c_i$ the unit downtime cost due to production loss during maintenance.
20) $R_i$ the state function of the system after the next operating mission, $R_i \in \{0, 1, 2, \cdots , K\}$

The state of complex systems change from good to bad when they are performing intended missions. According to the Kijima type II age reduction model, the effective age of any component $i$ after the maintenance subsequent to the $m$-th mission is given by

$$A_i (m + 1) = b_i (m) \cdot B_i (m)$$  

$b_i (m)$ ($0 \leq b_i (m) \leq 1$) is the age reduction factor representing maintenance quality. If $b_i (m) = 1$ meaning that there is no age reduction after repair, then the state of system is as bad as old. If $b_i (m) = 0$, then the component is as good as new after repair.

If the failure time of component $i$ follows the Weibull distribution and the effective age at the beginning the $m$th mission is $A_i (m)$, the probability of component $i$ surviving after the $m$th mission is written as:

$$r_i (m) = \exp \left[ - \left( \frac{L (m) + A_i (m)}{\eta_i} \right)^{\beta_i} \left( \frac{L (m) + A_i (m)}{\eta_i} \right)^{\beta_i} \right]$$  

C. INDIVIDUAL MAINTENANCE COST AND TIME

The maintenance cost of component $i$ consists of two parts: one is the fixed cost $c_i^0$, the other is the preventive or corrective maintenance cost of component $i$, denoted as $c_i (m)$. In this way, we define the cost of component $i$ as

$$C_i (m) = c_i (m) + c_i^0$$

In general, the more maintenance cost that is allocated, the better the maintenance quality. The maintenance cost and the age of system are two factors that affect the improvement of the system. The improvement factor is denoted as $b_i (m)$ for component $i$. Let $c_i^{rf}$ denote the corrective repair cost for replacement of failed component $i$. The age reduction factor as a function of the corrective repair cost is then defined as

$$b_i (m) = 1 - \left( \frac{c_i (m)}{c_i^{rp}} \right)^{\frac{1}{m_i^{rf}}}$$

where $m_i^{rf}$ ($m_i^{rf} > 0$) is a characteristic constant that determines the exact relationship between corrective repair cost and age reduction factor through (4). It relates the allocated cost to the age reduction $b_i (m)$. The larger $m_i^{rf}$ is, with the same maintenance cost $c_i (m)$, the greater the age reduction factor $b_i (m)$ is. In other words, a larger $m_i^{rf}$ corresponds to a younger component. Thus, inherent characteristics of components and their age are both important factors to determine the parameter $m_i^{rf}$. In this way, the age reduction factor as a function of the preventive repair cost is defined as

$$b_i (m) = 1 - \left( \frac{c_i (m)}{c_i^{pp}} \right)^{\frac{1}{m_i^{rp}}}$$

where $m_i^{rp}$ ($m_i^{rp} > 0$) is a characteristic constant that determines the exact relationship between preventive repair cost and the corresponding age reduction factor through (5). The total maintenance cost of component $i$ is the preventive repair cost allocated, plus the fixed maintenance cost.

D. THE MAINTENANCE TIME AND COST UNDER ECONOMIC DEPENDENCE

In most realistic systems, maintenance cost can be reduced when multiple component are selected to be repaired simultaneously, as usually require similar initial setting up, labor and equipment. In addition, the joint replacement or maintenance can reduce the duration of time. This is because share not only
the setting up but also the advantages of ordering materials and using the same process of maintenance on those components. Therefore, additional cost savings for this type of repair should be considered. We define the economic dependence and time saving as:

\[
TS_\text{-} = b \cdot \sum_{i=1}^{N} t_i (m) = b \cdot T (m)
\]

where, \(0 \leq b \leq \min (t_1 (m), t_2 (m), \ldots, t_N (m)) / T (m)\);

\(b\) is the duration-saving factor for joint preventive or corrective maintenance;

\(t_i (m) (i = 1, 2, \ldots, N)\) can be either the preventive or corrective component maintenance time. In the same way, we define the economic dependence and cost saving as:

\[
CS_\text{-} (m) = a \cdot \sum_{i=1}^{N} C_i (m) + TS_\text{-} \cdot c_i
\]

where, \(0 \leq a \leq \min (c_1 (m), c_2 (m), \ldots, c_N (m)) / C (m)\);

\(a\) is the cost-saving factor for joint repair or replacement of many components.

\(c_i (m) (i = 1, 2, \ldots, N)\) can be either the preventive or corrective maintenance; As is mentioned in literature [12], the total cost saving of components is about 5% of all the preventive or corrective cost. That is to say, the value of \(a\) is 0.05. \(c_i\) is the unit downtime cost due to production loss during maintenance. \(TS_\text{-} \cdot c_i\) is the downtime cost saving due to economic dependence.

If \(a = 0\) and \(b = 0\), the components are said to be economic independent. The larger \(a\) and \(b\) are, the stronger dependence there is between components. The cost-saving \(CS_\text{-}\) and time-saving \(TS_\text{-}\) are considered positive in this paper \(CS_\text{-} \geq 0\). So the total cost of preventive or corrective maintenance under economic dependence is as follows:

\[
C_e (m) = \sum_{i=1}^{N} C_i (m) - CS_\text{-}
\]

The total time of preventive or corrective maintenance under economic dependence is given by:

\[
T_e (k) = \sum_{i=1}^{N} t_i - TS_\text{-}
\]

E. MATHEMATICAL MODEL

Upon the arrival of the system for maintenance, the selective maintenance for multi-state complex system is a non-linear integer programming problem. The maintenance crew has to find out what maintenance activities associated with each component to be performed to achieve the maintenance objective of increasing the system reliability under limited resources. As the effective age \(B_i (m)\) of each component in the system after the completion of the \(m\)th mission is known, under the constraints of limited maintenance time, some components of the system are selected for preventive or corrective maintenance and corresponding maintenance cost \(c_i (m)\) and maintenance time \(t_i (m)\) are allocated. \(c_i (m)\) and \(t_i (m)\) are the decision variables. A non-linear programming is formulated to search a selective maintenance subset for maximizing the probability of successfully completing the \((m + 1)\)th mission and minimizing the maintenance cost. This type of problem can be formulated as follows:

\[
\max R_S (m + 1) = \prod_{i=1}^{N} \left[ 1 - \prod_{j=1}^{z} (1 - R_{ij} (m + 1)) \right]
\]

\[
\min C_e (m) = \min \left( \sum_{i=1}^{N} C_i (m) - CS_\text{-} \right)
\]

st. \(T_e (m) \leq T_0\)

(10) (11)

(12) (13)

Formula (10) defines the reliability of complex system; Formula (13) indicates that the effective age of repairable components is determined by the Kijima II model.

III. ALGORITHM DESIGN

The decision optimization problem of selective maintenance for multi-state complex systems is a nonlinear, complex and continuous programming problem as shown in (10)-(13). It is impossible to calculate the Pareto solutions in limited time. In order to solve this kind of problem, intelligent algorithms such as genetic algorithm (GA), particle swarm optimization (PSO), ant colony algorithm (ACO) and artificial bee colony algorithm (ABC) [16]–[21] have been widely used in combinatorial optimization. Artificial bee colony algorithm has been widely used in optimization, clustering and path planning problem because of its advantage of simple implementation and strong robustness. This paper uses artificial bee colony algorithm to solve the multi-objective decision problem.

The artificial bee colony algorithm randomizes the initial population that consists of \(D\)-dimensional FN vectors (FN is the number of food sources which equal to PopSize/2, where PopSize is the population size). Then each employed bee generates a candidate solution and makes a greedy selection among the candidate solutions. After the searching of all employed bees, each onlooker bee selects a solution to search based on the fitness value with roulette selection. After predefined limit cycles, if a solution is not improved, then its employed bee becomes a scout bee, and generates a new solution randomly. Our goal is to obtain the Pareto solutions among them to maximize the reliability of system and minimize the total maintenance cost under economic dependence.

In order to apply the artificial bee colony algorithm to solve the problem, the coding scheme should be determined first, because the cost that allocated to each component can be any real value under the total maintenance cost. To reduce the complexity of calculation, the decision variable is firstly transformed into a real number, that is, a feasible solution of

\[
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\]
an individual can be represented by a real number string
\[ s = \{s_1, s_2, \cdots, s_n\} \]

where, \(0 \leq s_i \leq N_L\), \(s_i\) represents the maintenance level of component \(i\), and \(N_L\) is the maximum maintenance level of component. For functioning components, the value of \(s_i\) represents different maintenance quality; the corresponding cost and time are defined in Table 2.

**TABLE 2. The preventive maintenance cost and time corresponding to maintenance action.**

| \(s_i\) | Maintenance action | Maintenance time \(t_i(m)\) | Maintenance cost \(C_i(m)\) |
|--------|-------------------|------------------|-----------------|
| 0      | Do Nothing        | 0                | 0               |
| \(i\)  | Imperfect PM      | \(i \cdot t_i^P/N_L\) | \(i \cdot c_i^P/N_L\) |
| M      | Preventive        | \(t_i^P\)        | \(c_i^P\)       |
| \(N_L\)|                  |                  |                 |

For failed components, the corresponding cost and time are defined in Table 3.

**TABLE 3. The corrective maintenance cost and time corresponding to maintenance action.**

| \(s_i\) | Maintenance action | Maintenance time \(t_i(m)\) | Maintenance cost \(C_i(m)\) |
|--------|-------------------|------------------|-----------------|
| 0      | Do Nothing        | 0                | 0               |
| \(i\)  | Imperfect CM      | \(i \cdot t_i^C/N_L\) | \(i \cdot c_i^C/N_L\) |
| M      | Corrective        | \(t_i^C\)        | \(c_i^C\)       |
|        | maintenance       |                  |                 |

Based on decoding solution, suppose that the initial state of the system consists of four components and the state of component is \{functioning, failed, functioning, failed\}. The corrective maintenance cost for replacement is 10 for component 2 and 4; while the preventive maintenance cost for replacement is 8 for component 1 and 3. And the maintenance of system is The maintenance level of component \(N_L = 5\), the duration of maintenance time is \(t = \{3, 5, 3, 5\}\). If the feasible solution is \(s = \{2, 3, 4, 5\}\), then the maintenance cost of first component is \(c_1(m) = \frac{3 t_1}{N_L} \cdot c_1^P = 3 \cdot 8 = 3.2\). In the same way, we can calculate the maintenance cost of the other components \(c_2(m) = 6, c_3(m) = 6.4, c_4(m) = 10, t_1(m) = 1.2, t_2(m) = 3, t_3(m) = 2.4, t_4(m) = 5\). If the cost-saving factor \(a = 0.1, b = 0.2, c_1 = 1.2\), according to Eq.(8), we can calculate the economic dependence and time saving \(TS_-(m) = b \cdot \sum_{i=1}^{N} t_i(m) = 2.32\), the cost saving \(CS_-(m) = a \cdot \sum_{i=1}^{N} c_i(m) + TS_\cdot c_i = 5.344\), the maintenance cost and time under dependence economic can be calculated according to Eq.(8) and Eq.(9) So, we can calculate the maintenance cost and time after the feasible solution is determined.

The standard artificial bee colony algorithm consists of the following four phases [16]–[21]. It has been used to solve a large number of complex optimizations, and we intend to use the ABC to solve the proposed problem.

**A. SOLUTION CODING**

The coding method directly affects the efficiency of the algorithm. In this paper, the maintenance level is used for coding. According to the characteristics of selective maintenance, the maintenance level of each component is set as a natural string. If the maintenance solution is shown in Fig.1, \(s_i\) represents the maintenance level. It is ranged from 0 to \(N_L\). For example, the string \(s = \{3, 5, 2, 4, 4\}\), it represents that the maintenance level of the first component is 3, and the corresponding maintenance cost and time can be calculated through equation listed in Table 2 and Table 3.

**FIGURE 1. Solution coding.**

**B. GENERATING INITIAL POPULATION**

The population size is denoted by PopSize. The values of initial individuals are generated randomly by the range of maintenance level \(N_L\). Generate uniformly distributed random population, \(P(n); n\) is the population size.

**Algorithm 1 Generation of Initial Population**

**Input:** PopSize, \(N_L\)

**Output:** Employed11(PopSize, \(N_L\))

(1) While(\(i \leq\) PopSize) Do
(2) \(Flag = 0\)
(3) While(\(Flag = 0\)) Do
(4) Randomly generate an integer-valued
including \(N\) elements and satisfying the range of maintenance level
(5) Construct an individual \(Si\)
(6) End While;
(7) \(i++\)
(8) End While;

**C. CALCULATING FITNESS VALUES AND SCREENING PARETO SOLUTIONS**

The formulation (10) and (11) consists of two objectives. It is essential to calculate individuals by comparing their fitness values. The initial value of each individual is considered as initial personal best (Pbest). The global best is chosen
from all the initial personal best values. The reliability and cost can be calculated via the formula of reliability and cost when the maintenance level is known. After the calculation of fitness values, the next mission is to search the Pareto solutions from population. Pareto optimality means there is no other solution that in every objective evaluation is equal or better than the solutions in the Pareto optimal solution set. Algorithm 2 describes how to obtain Pareto solutions via screening all solutions.

Algorithm 2 The Process of Screening Pareto Solutions

Input: Employed11(PopSize, NL),
Output: Y(g), A(g)
(1) Calculate the fitness value of each individual in current population Employed11(PopSize, NL)
via the formula of reliability and maintenance cost;
(2) For $i = 1 : \text{PopSize}$
(3) If $Y_i(g)$ dominates $Y_{i-1}(g)$, then
(4) $P_{best}(i) = Y_i(g)$;
(5) End If;
(6) If $Y_i(g)$ and $Y_{i-1}(g)$ are non-dominated each other, then
(7) Randomly choose one of them as $P_{best}(i)$;
(8) End IF;
(9) End For;
(10) Then the new Pareto solutions in $Y(g)$ are merged into $A(g-1)$
(11) Again screen the Pareto solutions because domination relations may exist between the new Pareto solutions and $A(g-1)$
(12) Produce $A(g-1)$
(13) Randomly choose one of individuals in $A(g)$ as $G_{best}$;

D. CROSSOVER

Each gene of individuals in employed bee carries out a crossover operation. First, a random real number $c_1$ is produced between 0 and $M - 1$. $M$ is the length of sequence. Then the second random real number $c_2$ is produced in the same way. Compared $c_1$ with $c_2$, the minimization of $c_1$ and $c_2$ is the starting point of intersection and the maximization of $c_1$ and $c_2$ is the end point of intersection.

Then the employed bee performs a crossover operation in which a crossover section is obtained from another randomly chosen employed bee in current population as stated above and inserted into the same position of initial employed bee such that a child employed bee is produced. See Fig. 2. Then, the child employed bee is evaluated with the original one.

E. ARTIFICIAL BEE COLONY PROCEDURE

The artificial bee colony algorithm terminates with a number of iterations. If the number of iterations is reached, output the Pareto solutions and terminate the algorithm.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

To demonstrate the advantages of the proposed selective maintenance model, an illustrative example is presented in this section. It is followed by detailed results and related discussions. System reliability and cost based on the performance of individual components are established.
There are some typical systems, such as telecommunication system, computer network and water supply system whose networks are complex systems consisting of $M$ dependent components. They cannot be categorized as series, parallel, serial-parallel or $K/N : F$ systems. Fig. 4 illustrates one of these systems’ structures. The reliability of the systems can be calculated by a decomposition method. An important component can be expressed as Eq. (15)

$$R = P(\text{normal system}|x) P(x) + P(\text{normal system}|\bar{x}) P(\bar{x})$$ (14)

The reliability of system can be expressed as Eq. (16)

$$R_S = R_k \cdot \left[ 1 - \prod_{j=1}^{z} (1 - R_j) \right] + (1 - R_k) \cdot \left[ 1 - \prod_{j=1}^{N} \left( 1 - \sum_{j=1}^{z} R_{ij} \right) \right]$$ (15)

where

- $R_k$: the reliability of important components;
- $j$: component index;
- $i$: parallel path index;
- $z$: number of path; and
- $N$: number of components.

According to the Eqs. (14)-(16) and Fig. 4, the Eq. (16) can be described as

$$\max R (k + 1) = (R_4(k+1)+R_5(k+1)-R_4(k+1)\cdot R_5(k+1))\cdot R_2(k+1) + (R_1(k+1)\cdot R_4(k+1) + R_5(k+1) \cdot R_3(k+1) \cdot R_5(k+1) - R_1(k+1) \cdot R_4(k+1) \cdot R_3(k+1) \cdot R_5(k+1)) \cdot (1 - R_2(k+1))$$

The cost-saving factor for joint maintenance of components is set as $a = 0$, the duration-saving factor $b = 0$, and the upper bound of time for maintenance $t = 2.2$. The components of system become economic independence. Suppose that the duration of the $(k+1)$th mission is 10. The states of components $A-E$ are {functioning, functioning, failed, functioning, failed} respectively. That is the component $A$ adopted the preventive maintenance, component $C$ adopted the corrective maintenance. We have to allocate the maintenance cost to each component to maximize the reliability. The problem stated above is a non-linear programming. The parameters of the Weibull life distribution, maintenance cost, and effective age are tabulated in Table 4. The ABC method proposed in Section III is used to search the Pareto optimal solution with $N_L = 7$. The ABC algorithm is implemented in MATLAB 2013a and executed on a computer with a Windows 7 operation. According to the method in [22]-[28], the algorithm parameters are optimized and adjusted as follows in order to obtain better algorithm performance:

1. The population size $PopSize = 50$, which is equal to the number of employed bee and onlooker bee.
2. The maximum iteration number of ABC iter = 50.
3. To avoid the food iteration of ABC limit = 50.

As shown in Fig. 4, component 2 is chosen as the important component. Therefore, the reliability of system can be expressed as Eq. (15)

$$R = P(\text{normal system}|x_2) P(x_2) + P(\text{normal system}|\bar{x}_2) P(\bar{x}_2)$$ (15)

The reliability of system can be expressed as Eq. (16)

$$R_S = R_k \cdot \left[ 1 - \prod_{j=1}^{z} (1 - R_j) \right] + (1 - R_k) \cdot \left[ 1 - \prod_{j=1}^{N} \left( 1 - \sum_{j=1}^{z} R_{ij} \right) \right]$$ (16)

According to the Eqs. (14)-(16) and Fig. 4, the Eq. (16) can be described as

$$\max R (k + 1) = (R_4(k+1)+R_5(k+1)-R_4(k+1)\cdot R_5(k+1))\cdot R_2(k+1) + (R_1(k+1)\cdot R_4(k+1) + R_5(k+1) \cdot R_3(k+1) \cdot R_5(k+1) - R_1(k+1) \cdot R_4(k+1) \cdot R_3(k+1) \cdot R_5(k+1)) \cdot (1 - R_2(k+1))$$

The curves of maintenance cost versus reliability of system are plotted in Fig. 5. The blue point represent the Pareto optimal solutions which is one of running by the ABC algorithm with the constraint of time $T_0 = 2.2$. Generally, the more maintenance cost is allocated to component; the higher reliability of system will be achieved.

The results are shown in Table 5 after the ABC algorithm is executed for three runs. The reliability of the solutions shown in Table 5 exceeds 0.93. Thus we choose the solution {1, 6, 4, 2, 7}, as it has the lowest maintenance cost. The time spent on maintenance is also the least.

As shown in [16], the cost-saving factor for joint saving is typically equal to 5% of the total maintenance cost of the components, that is $a=0.05$. The total maintenance duration is reduced by 20%, that is $b=0.2$. In addition, when the system
Then the Pareto solutions can be obtained by the ABC algorithm. The Pareto optimal solutions are listed in Fig. 6 for one of running by the ABC algorithm with the constraint of time $T_0 = 2.0$.

The ABC algorithm is executed for three runs. The maintenance solutions with reliability of system greater than 0.93 are listed in Table 6.

Table 6 shows the Pareto solutions obtained from the ABC. When the reliability is higher after maintenance, more cost is needed, and more cost is saved by the economic dependence model. As can be seen from the Table 5, after the economic dependence maintenance according to the Pareto solution \{1,7,2,4,7\}, the system reliability reaches 0.9379, and the maintenance cost is 54.3447. If the components of system are independent, the maintenance cost will research 58.1428. Based on the trend, the decision-maker might get more insights on determining the trade-off between the budget constraint and the reliability of system. Fig. 7 shows the comparison of two types of Pareto solutions.

Figure 7 shows the relationship between maintenance costs and the probability of successful completion of the mission.
The results of model 1 are represented by blue dots representing Pareto solutions considering component independence. The results of model 2 are represented by the cross symbol, which represents the Pareto solution obtained by the ABC algorithm under the consideration of the dependence between the components under the time constraint. Obviously, with the increase of maintenance cost, the mission completion rate of the system obtained by the two models increases continuously. Therefore, the higher the maintenance cost, the more reliable the system is, regardless whether economic dependencies between components are considered. It can be observed that at the same mission completion rate, the maintenance cost of model 2 is lower than that of model 1, the biggest difference occurred when the mission completion rate was 0.9408, and the maintenance cost of model 2 was 12.30 lower than that of model 1, which was 18.24% lower than that of model 1. The weighted arithmetic mean of model 2 and model 1 maintenance costs were 42.2683 and 43.5967. The average maintenance cost of model 2 is 1.3264 lower than that of model 1, saving 3.14% compared with model 1. This means that given the economic dependencies between components, it is cheaper to maintain for the same reliability or achieve more reliability at the same cost.

V. CONCLUSIONS

In this paper, the selective maintenance decision problem of complex multi-state systems considering the effect of incomplete maintenance is studied from the perspective of economic dependence. The Weibull distribution model is used to describe the relationship between the age and reliability of components, and the constructor function is used to describe the relationship between the maintenance cost allocated by components and the age reduction factor. This paper studies the economic dependence of equipment cost and duration sharing when parts are replaced at the same time and establishes the selective maintenance model of multi-state complex system with economic dependence. Since the selective maintenance decision is a complex nonlinear programming problem of continuous decision variables, the traditional enumeration search optimization method cannot obtain the optimal solution within a limited time. In this paper, the discrete artificial colony algorithm is adopted as the global optimization method to solve the dual-objective optimization model. The Pareto solution set of maintenance for support equipment involving multiple maintenance actions, “Eur. J. Oper. Res., vol. 129, no. 2, pp. 252–258, Mar. 2001.”

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