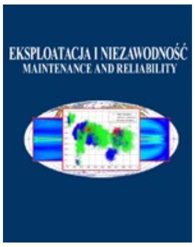

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Preventive maintenance of multiple components for hydraulic tension systems

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Highlights

- Hydraulic tension system of conveyor belt is introduced to SPM.
- Preventive maintenance model for multiple components is proposed.
- Joint integrated importance measure (JIIM) is applied to a hydraulic tension system.
- Maintenance plan of hydraulic tension is analysed to optimize the system performance.

Abstract

Automatically controlled hydraulic tension systems adjust the tension force of a conveyor belt under different working conditions. Failures of an automatically controlled hydraulic tension system influence the performance of conveyor belts. At present, the maintenance of automatically controlled hydraulic tension systems mainly considers the replacement of components when failures occur. Considering the maintenance cost and downtime, it is impossible to repair all the failed components to improve the hydraulic tension system. One of the key problems is selecting the most valuable components for preventive maintenance. In this paper, preventive maintenance for multiple components in a hydraulic tension system is analyzed. An index is proposed to select more reliable preventive maintenance components to replace the original ones. A case study is given to demonstrate the proposed method. When the cost budget increases, there are three different variations in the number of components for selective preventive maintenance (SPM).

Keywords

preventive maintenance; reliability; importance measure; maintenance cost.

1. Introduction

In recent years, with the development of automation technology and increasing demand in industry, an automatically controlled hydraulic tension system is increasingly being used in conveyor belts [26]. An automatically controlled hydraulic tension system is used to provide stable tension to a conveyor belt. Routine maintenance only considers the maintenance of faulty components and only in the event of obvious system failure. Preventive maintenance of other components can be carried out at the same time when the failure components are repaired. This saves the maintenance time, and the components that may fail can be replaced in advance before the next system failure to ensure long-term system reliability.

Many scholars have studied the maintenance of hydraulic systems [18, 20, 25], but few researchers focus on the preventive maintenance of hydraulic tension systems due to their high system complexity. A hydraulic tension system plays an important role in ensuring the stable transportation of a conveyor belt [18]. An automatically controlled hydraulic tension system is composed of a series of hydraulic components, such as a pump, relief valve, accumulator, and one-way valve. When the components in the system fail, they will reduce the system reliability and even cause the whole system to fail [20]. Because the maintenance resources are limited, preventive maintenance is widely used as a reliability-centered maintenance strategy.

Jia and Cui [12] gave a joint maintenance strategy for safety-critical hydraulic tension systems. Wu and Castrob [27] developed maintenance policies for a system under condition monitoring. Zhao et al. [37] proposed an optimization model of an opportunistic maintenance strategy. Cai et al. [1] analyzed the system failure of engineering systems based on Bayesian networks. Based on the expected value and variance of system reliability as an objective function, the optimization problem of selective maintenance bi-objective optimization problem was modeled.

Jiang and Liu [11] developed a new selective maintenance model for systems that execute multiple consecutive missions. The preventive maintenance uses the optimal allocation of limited resources to improve the reliability of the system as much as possible under the constraints of cost resources. Wu and Zhou [30] analyzed a predictive maintenance policy with nonperiodic inspection. After the preventive maintenance, Jia et al. [14] studied the improvement of the reliability and safety of safety-critical hydraulic tension systems. Preventive maintenance can obtain strategies to maximize hydraulic tension system performance under cost constraints.

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Zhu et al. [39] proposed a stochastic analysis and applied it to predict the reliability of a hydraulic tension system. Cai et al. [3] proposed a hybrid model and data-driven methodology for remaining useful-life estimation for a hydraulic tension system. Zhao et al. [36] considered two variable types of costs for periodic replacement policies to make the preventive replacement policies perform generally. Wu et al. [29] analyzed the optimization of a maintenance policy under parameter uncertainty using portfolio theory. Based on an aggregated Markov model, Jia et al. [13] gave a maintenance policy and showed the reliability improvement of a hydraulic tension system under combined dynamic environments.

Selecting the most valuable components is a key problem in preventive maintenance. Identifying the factors influencing system reliability is most important [16, 17]. Importance measures are widely used in repairable systems, which can be used to identify weak components in the system and replace weak components in advance. At present, the importance measures are not considered in the preventive maintenance of hydraulic tension system. Yan et al. [35] developed a maintenance policy optimization method to determine the optimal maintenance threshold joint considering the availability constraints and the system aging. Fan et al. [9] proposed a group maintenance optimization approach that combines maintenance activities to reduce maintenance costs.

Although an automatically controlled hydraulic tension system ensures stable work of a conveyor belt, the system is more complex. If it fails, it will bring great harm to the system. Joint importance measures are applied to an automatically controlled hydraulic tension system, the important components in the system are identified, and the weak components are replaced in advance to ensure the reliability of the hydraulic system. By identifying and evaluating system weaknesses, importance measures have been widely applied in system reliability, decision making, and risk analysis [4, 24, 19, 21, 38].

For example, Gao et al. [10] analyzed the joint importance of components in a coherent system. Dui et al. [6] studied an integrated importance measure and the mean absolute deviation with respect to the changes in an optimal system structure throughout the system's lifetime. Dui et al. [5] proposed an importance measure that could help select components for improving the system performance. Si et al. [22, 23] analyzed the system reliability optimization based on the importance measures. Dui et al. [8] proposed importance measures and resilience recovery strategy to optimize the resilience management of maritime transportation systems.

An automatically controlled hydraulic tension system is widely used in conveyor belts with the development of logistics and transport [2]. Due to the system complexity, some methods can be used to find the approximate solution for the system maintenance and reliability optimization. For example, Xiao et al. [31, 32, 33] proposed some efficient simulation procedures for some stochastic constraints and uncertainty in a hydraulic tension system. Wu et al. [28] introduced an importance measure to give a component maintenance priority for preventive maintenance. Dui et al. [7] investigated the applications of the proposed measures for multi-state systems in optimization of maintenance policies and proposes algorithms to minimize maintenance cost. Kou et al. [15] suggested a reliability evaluation algorithm based on the representation function of the system states and the optimal performance sharing policy. Xiao et al. [34] suggested a heuristic sequential simulation procedure with the objective of maximizing the probability of correct selection to implement the simulation budget allocation rule with a fixed finite simulation budget.

However, the following problems exist in preventive maintenance of a hydraulic tension system: choosing how to identify other key components in the system during maintenance and choosing how to perform preventive maintenance on these key components under different cost constraints to increase system reliability. This paper studies the preventive maintenance of key components in hydraulic tension system under cost constraints. First of all, importance measure is used to search for the key components in the remaining components of the system so that preventive maintenance can be performed on the remaining components when the failed components are repaired. Secondly, a SPM model based on importance measures is proposed to select key components that require preventive maintenance under different cost constraints.

The rest of this paper is organized as follows. In Section 2, a simulation system for hydraulic tension is introduced. Section 3 proposes a simulation method for preventive maintenance of multiple components based on an importance measure. According to the hydraulic tension system in Section 2, a simulation is used to verify the proposed methods in Section 4. In Section 5, conclusions are given to summarize this paper.

2. Hydraulic tension systems

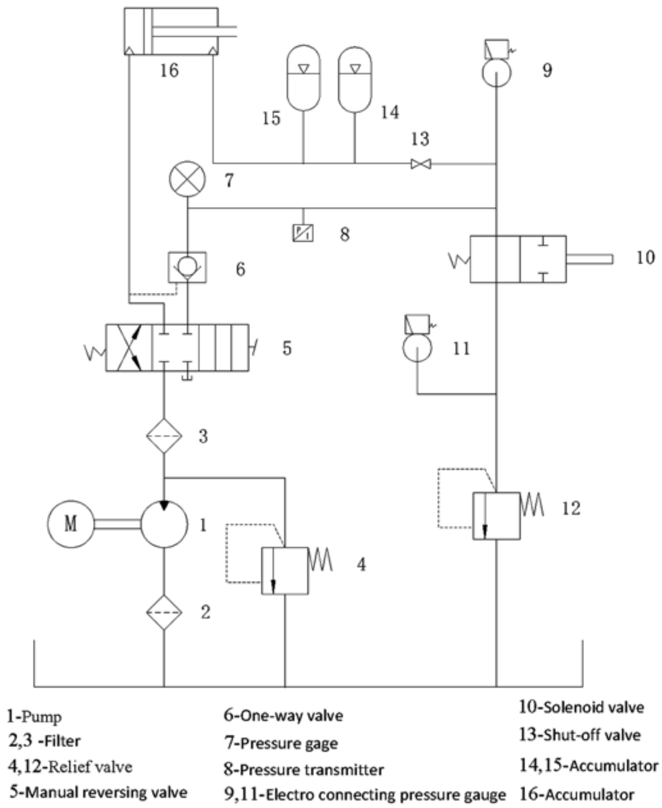

Fig. 1. Diagram of hydraulic tension system

Table 1. Main components of hydraulic tension system

Code	Name	Code	Name
X_1	Pump	X_9	Electro connecting pressure gauge No. 1
X_2	Filter No. 1	X_{10}	Solenoid valve
X_3	Filter No. 2	X_{11}	Electro connecting pressure gauge No. 2
X_4	Relief valve No. 1	X_{12}	Relief valve No. 2
X_5	Manual reversing valve	X_{13}	Shut-off valve
X_6	One-way valve	X_{14}	Accumulator No. 1
X_7	Pressure gauge	X_{15}	Accumulator No. 2
X_8	Pressure transmitter	X_{16}	Hydro-cylinder

There are 16 components in the hydraulic tension system, as shown in Fig. 1. The different locations and types of components determine their roles in the system. The pressure gauge is only a measuring tool and has no direct influence on the operation of the system.

The names of the main components of the hydraulic tension system are displayed in Table 1. When the motor of the system is turned on by a worker, the pump starts to work. Hydraulic oil goes from the tank through filter 1 into the oil pump under the action of the pump. Then the hydraulic oil is transported to manual reversing valve 5 through filter 2. When the spool of manual reversing valve 5 is in the middle position, the hydraulic oil directly flows back to the oil tank through the relief valve. At this time, the oil tank is in an unloaded state, the whole system has no pressure, and the hydraulic cylinder does not do any movement.

When the spool of manual reversing valve 5 is in the right position, the hydraulic system takes hydraulic oil from the oil tank through the oil pump. The hydraulic oil flows to check valve 6 and finally flows to the rod chamber of the hydraulic cylinder through the open globe valve. Finally, the piston rod is pushed to the left by hydraulic oil while driving the tension car to the left. The hydraulic oil in the left cavity of the hydraulic cylinder flows back to the tank.

The hydraulic pressure in the hydraulic cylinder on the side of rod chamber is increasing. When a certain value is reached, the hydraulic oil will flow into accumulator 11. When the pressure of the hydraulic system continues to increase and reaches the upper limit, relief valve 13 opens. The system begins to unload, and the internal pressure of the system tends to be constant. When the oil pressure in the hydraulic system exceeds the upper limit specified by electro connecting pressure gauge 9 or pressure transmitter 16, the oil pump begins to terminate the oil suction.

When the oil pressure is lower than the lower limit specified by electro connecting pressure gauge 9 or pressure transmitter 16, the system begins to take in oil. During the working process, the hydraulic system is constantly self-regulating to ensure the normal operation of the system. A block diagram of the system components is shown in Fig. 2.

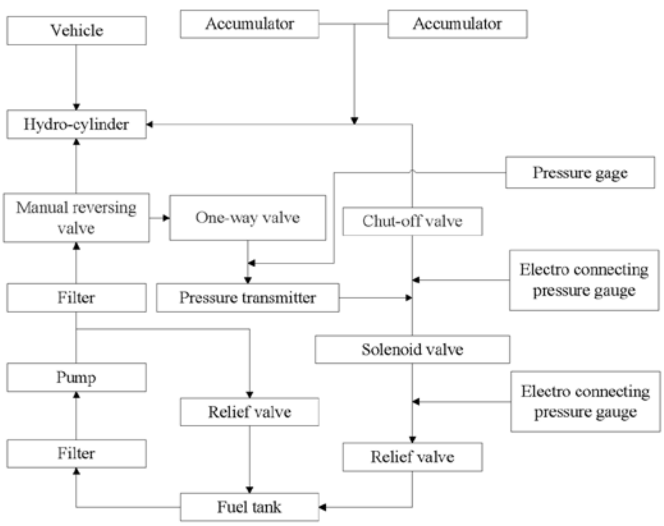

Fig. 2. Block diagram of the components

There are two types of components. The first type is critical components, and the failure of any critical component will cause the whole system to fail. The second type is non-critical components. For non-critical components, some similar components can achieve similar functions in the system. When one of them fails, the whole system still works until all similar components fail.

When some similar components fail, the state of the system is between perfect and complete failure. For example, component 14 and component 15 are similar components. When component 14 fails, the whole system still works, but the performance of the system will be reduced. It is assumed that the filter failure will cause the system performance to decrease to 0.6 times the original value. An accumulator failure will reduce the system performance to 0.7 times the original value. If an electro connecting pressure gauge fails, the system performance will decrease to 0.8 times. According to the assumptions, the system has 26 intermediate states, as shown in Table 2.

Table 2. Hydraulic system states and the corresponding performance levels

K	System state		a_k	k	System state			a_k
1	X_2		0.600	15	X_9	X_{14}		0.560
2	X_3		0.600	16	X_9	X_{15}		0.560
3	X_9		0.800	17	X_{11}	X_{14}		0.560
4	X_{11}		0.800	18	X_{11}	X_{15}		0.560
5	X_{14}		0.700	19	X_2	X_9	X_{14}	0.336
6	X_{15}		0.700	20	X_2	X_9	X_{15}	0.336
7	X_2	X_9	0.480	21	X_2	X_{11}	X_{14}	0.336
8	X_2	X_{11}	0.480	22	X_2	X_{11}	X_{15}	0.336
9	X_3	X_9	0.480	23	X_3	X_9	X_{14}	0.336
10	X_3	X_{11}	0.480	24	X_3	X_9	X_{15}	0.336
11	X_2	X_{14}	0.420	25	X_3	X_{11}	X_{14}	0.336
12	X_2	X_{15}	0.420	26	X_3	X_{11}	X_{15}	0.336
13	X_3	X_{14}	0.420	27	Perfect state			1
14	X_3	X_{15}	0.42	28	Complete failure state			0

Hydraulic tension systems are widely used in belt conveyors. The reliability of the hydraulic tension system determines the stability of the conveyor. When a component in the hydraulic tension system fails, the component needs to be repaired. At this time, the system is in a shutdown state. The time for repairing a failed component is used to perform preventive maintenance on other components in this paper. The purpose is to replace components before other components fail to improve system reliability.

3. Preventive maintenance of multiple components

3.1. Joint integrated importance measure

The premise of component maintenance is to identify important components that need maintenance. Integrated importance can be used to search for important components of a system. The integrated importance measure (IIM) describes the change of system performance from state m to state 0 at time t because of the degradation of component i:

$$I_i^{IIM}(t) = P_i^m(t)\lambda_i^{m,0}(t)\sum_{j=1}^{M} a_j\left\{\Pr\left[\Phi\left(m_i, X(t)\right) = j\right] - \Pr\left[\Phi\left(0_i, X(t)\right) = j\right]\right\}, \tag{1}$$

where $P_i^m(t)$ represents the probability of component i is in state m at time t. $\lambda_i^{m,0}(t)$ represents the degradation rate of component i from state m to state 0 at time t. a_j represents the performance levels of the system in state j. $\Phi\left(X(t)\right)$ is the structure function of the system at time t. $\Pr\left[\Phi(m_i, X(t)) = j\right]$ is the probability that the system is in state j when component i is in state m. $\Pr\left[\Phi\left(0_i, X(t)\right) = j\right]$ is the probability that the system is in state j when component i is in state 0.

Based on the integrated importance measure, Dui et al. [6] proposed a JIIM for preventive maintenance when a component is under repair. JIIM represents the contribution of component i to the change of system performance in unit time t by repairing component m:

$$I_i^{IIM}(t)_{X_{m(t)}} = I_i^{IIM}(t)_{X_{m(t)=1}} - I_i^{IIM}(t)_{X_{m(t)=0}}, \quad (2)$$

where $I_i^{IIM}(t)_{X_{m(t)=0}}$ represents the contribution of component i to the change of system performance in unit time when component m fails. $I_i^{IIM}(t)_{X_{m(t)=1}}$ represents the contribution of component i to the change of system performance in unit time when component m is perfect:

$$I_i^{IIM}(t)_{X_{m(t)=1}} = P_i^m(t)\lambda_i^{m,0}(t)\sum_{j=1}^{M} a_j\left\{\Pr\left[\Phi(1_m,1_i,X(t))=j\right]-\Pr\left[\Phi(1_m,0_i,X(t))=j\right]\right\}. \quad (3)$$

In Equation (3), the $\Pr\left[\Phi(1_m,1_i,X(t))=j\right]$ is the probability that the system is in state j when component i and component m are perfect. $\Pr\left[\Phi(1_m,0_i,X(t))=j\right]$ is the probability that the system is in state j when component i is in a complete failure state and component m is in a perfect state:

$$I_i^{IIM}(t)_{X_{m(t)=0}} = P_i^m(t)\lambda_i^{m,0}(t)\sum_{j=1}^{M} a_j\left\{\Pr\left[\Phi(0_m,1_i,X(t))=j\right]-\Pr\left[\Phi(0_m,0_i,X(t))=j\right]\right\}. \quad (4)$$

In Equation (4), $\Pr\left[\Phi(0_m,1_i,X(t))=j\right]$ is the probability that the system is in state j when component i is perfect and component m is in a complete failure state. $\Pr\left[\Phi(0_m,0_i,X(t))=j\right]$ is the probability that the system is in state j when component i and component m are both in a complete failure state.

$I_i^{IIM}(t)_{x_{m(t)}}$ is the joint importance of components m and i when component m is repaired. When component m is not working, the component i with maximal $I_i^{IIM}(t)_{x_{m(t)}}$ is selected as a preventive maintenance component. This is a strategy of one-component maintenance selection. The higher the cost budget, the more components are chosen as preventive maintenance components.

Because $I_i^{IIM}(t)_{x_{m(t)}}$ is additive, $I_{i_1,i_2,\cdots i_n}^{IIM}(t)_{x_{m(t)}}$ is used to discuss the combined influence of components $i_1,i_2,\cdots i_{n-1}$, and i_n to the system:

$$I_{i_1,i_2,\cdots i_n}^{IIM}(t)_{x_{m(t)}} = I_{i_1}^{IIM}(t)_{x_{m(t)}} + I_{i_2}^{IIM}(t)_{x_{m(t)}} + \cdots + I_{i_n}^{IIM}(t)_{x_{m(t)}}. \quad (5)$$

In Equation (5), $I_{i_1,i_2,\cdots i_n}^{IIM}(t)_{x_{m(t)}}$ means the improvement of system performance by selecting components $i_1,i_2,\cdots i_{n-1}$, and i_n as preventive maintenance components at time t when component m is repaired.

3.2. Maintenance method of multiple components

The hydraulic tension system must be shut down for maintenance after a component failure. Preventive maintenance can be carried out simultaneously during the repair of a failed component. This can improve the reliability of the system and save maintenance time. The cost budget of hydraulic components is limited, and the preventive maintenance of different components is different for the improvement of system performance. In order to coordinate SPM of multiple components, a strategy selection model considering cost and system performance is proposed:

$$\text{Max} = \sum_{m\epsilon S_j}\left(I_{j,m}^{IIM}(t)_{y_i(t)}+a\right)y_m \quad (j=1,2,\cdots,n), \quad (6)$$

$$C_1y_1+C_2y_2+\cdots+C_{j-1}y_{j-1}+C_{j+1}y_{j+1}+\cdots+C_ny_n \le \text{cos}t, \quad (7)$$

$$y_1,y_2,\cdots y_n = 0 \text{ or } 1, \quad (8)$$

$$PM_{number} = \sum_{\substack{m=1 \\ m\ne j}}^{n} y_m, \quad (9)$$

where c_i represents the cost of component i. The objective of the model is to maximize the value of preventive maintenance with limited cost. Variable y has two states. For example, $y_1=1$ means the first component is selected as a preventive maintenance component, and $y_1=0$ means that the first component cannot be selected as a preventive maintenance component.

A better JIIM value with limited cost can be found. This model is used to select the maximal $I_{i_1,i_2,\cdots i_n}^{IIM}(t)_{x_{m(t)}}$ with limited cost when component m is repaired. Because JIIM values may be negative, a constant a is used so that the model can obtain the optimal solution without changing the objective function.

When a preventive maintenance component is selected, the same components are used to replace the preventive maintenance components. But when there are many components with the same function that can replace them, the preventive maintenance strategy under the cost constraint continues to be studied. Firstly, according to the SPM model, preventive maintenance components are selected. The SPM model is used to select the best preventive maintenance strategy under different cost constraints. When the cost budget changes continuously, the optimal strategies are not always changing. It will change until the cost budget reaches a certain value. Therefore, the increasing cost budget is not used effectively.

Between the two SPM strategies, the cost budget is used to update the preventive maintenance components. More reliable and move advanced components are selected to replace original components. For example, there may be two types of pumps that could be selected as a preventive maintenance component. Type 1 is the original component in the system, and type 2 is more reliable and expensive than type 1. When another component fails and a pump is selected for preventive maintenance, one of the two types of pumps is selected for preventive maintenance according to different cost budgets. If the cost budget is sufficient, type 2 is selected; otherwise, type 1 is selected.

Each component has several types that can completely replace the original component. An updated model is proposed for the selection of more advanced and reliable substitutes for preventive maintenance:

$$\text{Max} = \sum_{m\in S_j} I_{j,m}^{JIIM}(t)_{y_j(t)}y_m - Jsum\left(x_{1,1},x_{1,2},\cdots x_{m,n_m}\right), \quad (10)$$

$$x_{1,1}+x_{1,2}+\cdots+x_{1,n_1}=y_1, \quad (11)$$

$$x_{2,1}+x_{2,2}+\cdots+x_{2,n_2}=y_2, \quad (12)$$

$$\cdots\cdots,$$

$$x_{m,1}+x_{m,2}+\cdots+x_{m,n_m}=y_m, \quad (13)$$

$$c_{1,1}x_{1,1} + c_{1,2}x_{1,1} + \cdots + c_{1,n_1}x_{1,n_1} + c_{2,1}x_{2,1} + \cdots + c_{m,n_m}x_{m,n_m} < \cos t\,, \quad (14)$$

$$x_{1,1}, x_{1,2}, \cdots, x_{1,n_1}, x_{2,1} \cdots, x_{m,n_m} = 0 \text{ or } 1\,, \quad (15)$$

n_i represents a type of component i. $x_{i,j}$ means that type j of component i is selected. When the type of components is changed, the distribution parameter of components and JIIM values will change.

Each update strategy selects several more reliable components to replace the original components. The failure distribution parameters of these new types of components are different from the original components. As a result, when calculating the sum of the JIIM values of the replaced components, the failure distribution parameters need to be replaced first. $J_{sum}()$ is used to calculate the sum of the JIIM values of the replaced components. Then according to the new JIIM values, the sum of original JIIM values of selected components is used to subtract the sum of new JIIM values of selected components to find the benefit value of the new update strategy.

4. Result analysis

In this section, the model in Section 3 is applied to the hydraulic tension system in Section 2. The components of the hydraulic tension system are shown in Table 1. There are 11 types of components. Table 2 gives different states of the system, including the perfect state, complete failure state, and 26 states between perfect and complete failure. Schematic diagram of the hydraulic tension system is shown in Fig. 1. Then the importance measure values of the system based on the system in Section 2 are calculated. Finally, the preventive maintenance strategies are selected according to the value of the importance measure values.

The components of the hydraulic tension system can be classified into two types according to the life distribution of each component. One type of component fits an exponential distribution, and the other is suitable for the Weibull distribution. The Weibull distribution is the theoretical basis of reliability analysis and life test, which is widely used in reliability engineering, especially in the distribution of cumulative wear failure of electromechanical products. Because the distribution parameters can easily be inferred by using probability values, it is widely used in data processing with various life tests.

$P_i^m(t)$ represents the reliability of the component i at time t. Because this study is based on a two-state system, m is equal to 0 or 1. When m is equal to 1, $P_i^1(t)$ is equal to $e^{-\left(\frac{t}{\theta}\right)^{\beta}}$. If component i is in state 0, $P_i^0(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}}$. $\lambda_i^{1,0}(t)$ represents the probability of the component i changing from perfect state to failure state. $\lambda_i^{1,0}(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}$. β represents the shape parameter of each component's failure time, and θ is the scale parameter of components failure time. The parameters of components in the hydraulic system are shown in Table 3 and Table 4.

The exponential distribution is the probability distribution that describes the time between events in a Poisson process. Although the exponential distribution cannot be used as the distribution law of the functional parameters of mechanical parts, it can be approximately used as the failure distribution model of complex parts, machines, or systems with high reliability, especially in a whole machine test of parts or machines. In the reliability study of electronic components, it is usually used to describe the measurement results of the number of defects or the number of system failures that occur. If a component's failure time fits an exponential distribution, $P_i^1(t) = e^{-\lambda t}$. According to Equation (1), the IIM of each component from 0 to 3000 h is calculated. The curve of IIM over time is shown in Fig. 3.

Table 3. Parameters of the components that follow a Weibull distribution

No.	Component	Code	θ	β
1	Pump	X_1	1850	2.3600
2	Solenoid valve	X_{10}	3657	1.8530
3	Accumulator	X_{14}, X_{15}	3304	1.4600
4	Hydro-cylinder	X_{16}	3501	2.0230

Table 4. Parameters of components that follow an exponential distribution

No.	Component	Code	λ (10^{-6})
1	Filter	X_2, X_3	0.6849
2	Relief valve	X_4, X_{12}	5.7000
3	One-way valve	X_6	3.1133
4	Pressure transmitter	X_8	6.6667
5	Electro connecting pressure gauge	X_9, X_{11}	40.0000
6	Shut-off valve	X_{13}	0.2283
7	Manual reversing valve	X_5	10.0000

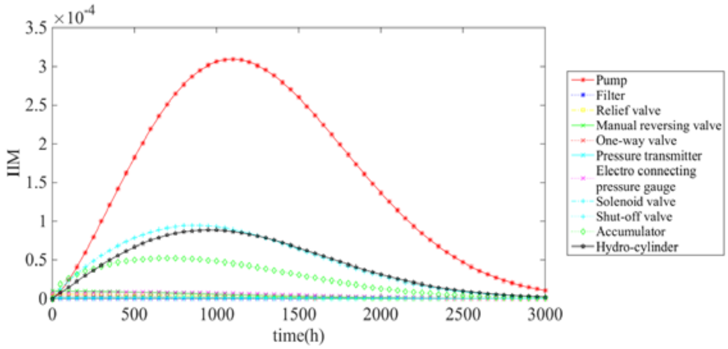

Fig. 3. The change of IIM values of the components

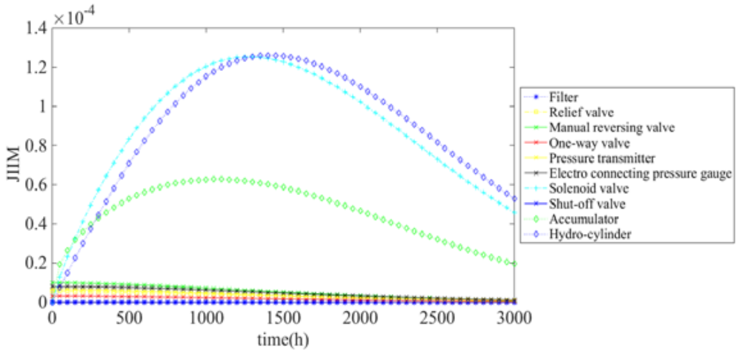

Fig. 4. The change s of JIIM values when component 1 fails

When time changes from 0 to 3000 h, the IIM values of components that fit a Weibull distribution first increase and then decrease from 0. But the IIM values of components that fit an exponential distribution decrease all the time. Of all components, the pump has the maximal IIM value at most times. For this system, the pump will be a critical component to keep the system reliable. According to Equation (3), the JIIM value at different times is calculated, as shown in Fig. 4.

The JIIM values of other components when component 1 is under maintenance are shown in Fig. 4. The hydro-cylinder and solenoid valve have maximal JIIM values at most times. The JIIM values of the hydro-cylinder, solenoid valve, and accumulator rise first and then decrease when time changes from 0 h to 3000 h. JIIM values of other components decrease the whole time.

For a different cost budget, the selection of preventive maintenance components will change. The optimization equation is an optimization solution for a specific cost value, and the optimization equation is applied considering the continuous change of the cost budget. The change of a preventive maintenance component's quantity can be obtained with the change of cost budget. The cost of each component is shown in Table 5.

Table 5. The cost of each component

NO.	Component	Price (RMB)
1	Pump	500
2	Filter	100
3	Relief valve	150
4	Manual reversing valve	200
5	One-way valve	35
6	Pressure transmitter	110
7	Electro connecting pressure gauge	45
8	Solenoid valve	30
9	Shut-off valve	20
10	Accumulator	160
11	Hydro-cylinder	240

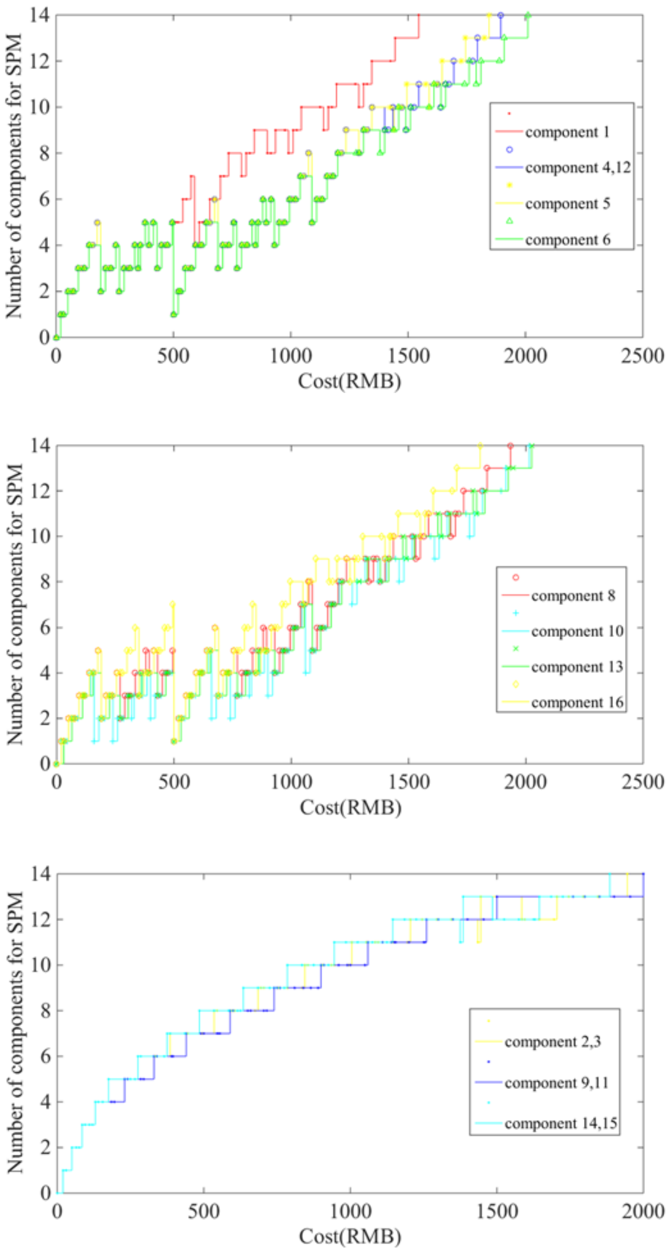

Fig. 6. SPM strategy when different components fail

Each point represents a selection strategy for preventive maintenance components in Fig. 5. As the cost increases and the selection strategy may change, the total number of preventive maintenance components may change. There are three cases as follows.

The first case is where the number of preventive maintenance components will increase. As the cost budget increases, more components are purchased for preventive maintenance. In many cases, the improvement of maintenance benefits results from the addition of components. When the cost budget changes from 30 RMB to 50 RMB, the optimal selection strategy changes from component 10 to components 10 and 13.

The second case is where the number of preventive maintenance components will remain the same. This is because the increased cost budget does not allow for the purchase of a new component, but the increased cost budget allows components with less maintenance revenue to be replaced with components with higher maintenance costs. As a result, the optimization scheme is changed, and the maintenance efficiency of the entire system is improved. When the cost budget is 65 RMB, the optimal strategy is selecting components 6 and 10. When the cost budget is 75, the optimal strategy is selecting components 9 and 10 for preventive maintenance. Replacing component 6 with component 9 improves the overall maintenance benefit of the system.

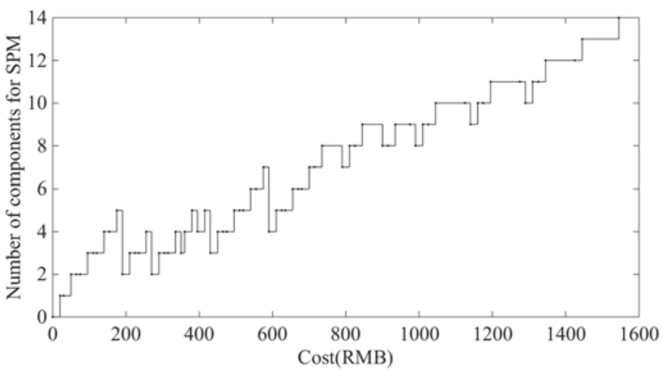

Fig. 5. SPM strategy when component 1 fails

The third case is where the number of preventive maintenance components will be reduced, there are some components with high cost and high maintenance benefit, and their cost may be the sum of several other components. When the cost budget is sufficient, the maintenance benefit of selecting a component with high maintenance may be better than selecting several other components. That leads to a reduction in the number of preventive maintenance components.

When the preventive maintenance cost budget is 175 RMB, components 6, 9, 10, 11, and 13 are selected as the optimal selection strategy for the system. When the maintenance cost increases to 190 RMB, the optimal strategy will change. Component 14 is selected as a preventive maintenance component, while components 6, 9, 11, and 13 are replaced. The overall maintenance benefit of components 6, 9, 11, and 13 is $0.1494*10^{-4}$. The JIIM value of component 14 is $0.6267*10^{-4}$. The total preventive maintenance cost is not out of range due to the constraints of the condition in the optimization model.

In general, the number of preventive maintenance components increases with the increase of cost. The relationships between the number of components and cost budget are shown in Fig. 6. The number of preventive maintenance components increases faster during repair of component 1. Because the cost of component 1 is 500 RMB, which is the highest of all components, more components can be used as preventive maintenance components at a lower cost.

When component 16 is repaired, the number of preventive maintenance components increases faster than with other components. The cost of component 16 is 240 RMB, which is the second most expensive component of all components. This is a normal phenomenon because when repairing expensive components, there is no need to reserve a high cost budget for preventive maintenance. The components with the same function in the system have the same SPM.

There are many strategies for SPM at different costs. The selection strategy of component 1 for preventive maintenance is shown in Table 6. In consideration of the preventive maintenance strategies when component 1 is repaired, the interval is selected when the cost budget is between 50 RMB and 65 RMB. According to data in Table 6, components 10 and 13 could be updated when the cost budget increases from 50 RMB to 65 RMB.

Table 6. Selection strategy of component 1 for preventive maintenance

Cost	Component													
	2	3	4	5	6	8	9	10	11	12	13	14	15	16
50	0	0	0	0	0	0	0	1	0	0	1	0	0	0
65	0	0	0	0	1	0	0	1	0	0	0	0	0	0

Component 10 has two types, and component 13 has three types. The costs of different types of components are shown in Table 7. The failure distribution parameters of different types of components are shown in Table 8. Type 1 means original components, which are selected to be replaced.

Table 7. The cost of different types of components

Component	Price (RMB)		
	Type 1(origin)	Type 2	Type 3
10	30	35	
13	20	23	25

The strategy when the lower limit of the cost budget is 50 RMB is shown in Table 9. When the cost budget is 55 RMB, the optimal update strategy is to select type 2 of component 10 and type 1 of component 13. When the cost budget is 55 RMB, type 1 of component 10 and type 3 of component 13 are selected. Since the update strategy is based on the selection strategy, the lower limit of the cost budget is 50 RMB. The number of SPM components is always 2, and components 10 and 13 are updated.

Table 8. Parameters of components in hydraulic system

Component	θ_1	β_1	θ_2	β_2
10	3657	1.8530	4657	1.3530

Component	$\lambda_1\left(10^{-6}\right)$	$\lambda_2\left(10^{-6}\right)$	$\lambda_3\left(10^{-6}\right)$
13	0.2283	0.11	0.07

Table 9. Strategies under different cost budgets

Cost	Number of SPM components	Component	
		10	13
50	2	Type 1	Type 1
53	2	Type 1	Type 2
55	2	Type 2	Type 1
58	2	Type 2	Type 2
60	2	Type 2	Type 3

5. Conclusions

In this paper, a preventive maintenance model for multiple components was applied to a hydraulic tension system. According to the model analysis, the pump in this system is the most important component. When the cost budget increases, there are three different variations in the number of components for SPM. When the cost budget is equal to 50 RMB, components 10 and 13 are selected. When the cost budget increases from 50 RMB to 65 RMB, different types of components 10 and 13 are selected to replace the original type to improve the system performance. Different components have different repair times. Therefore, it is necessary to add component repair time research to the model in future work.

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