

Joint optimization of repair and ordering of centrifugal compressor key performance spare parts based on gas supply reliability

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Abstract. The development of efficient and economical centrifugal compressor key performance spare parts ordering program is very important to improve the maintenance management efficiency of the equipment and reduce costs, this paper proposes a centrifugal compressor based on the reliability of gas supply key performance spare parts maintenance and ordering joint optimization. First of all, based on the average failure rate of compressor unit and the average time between failures to establish unit reliability mathematical model; secondly, based on the unit reliability mathematical model, the establishment of the compressor key components unit preventive maintenance cost model; finally, based on the ordering of spare parts at various moments of the cost function, the working time of the components to establish the compressor key performance parts ordering optimization model, the use of genetic algorithms to get the optimal ordering of the key performance of the spare parts time and optimal replacement of the components time.

Keywords: Compressor parts; spare parts; reliability-based preventive maintenance.

1. Introduction

Centrifugal compressors, as the "heart" of natural gas pipeline transportation, are critical to ensuring the safety of gas supply to the pipeline system in terms of operational stability and reliability. On the one hand, centrifugal compressor unit failures and downtimes have a serious impact on the reliability of natural gas pipeline systems[1]. On the other hand, spare parts replacement and spare parts redundancy bring high cost, according to statistics, in the past ten years, the gas pressure station field within the pipeline network cumulative replacement of more than 300 pieces of dry gas seals. The price of each dry gas seal is about 500,000 RMB, totaling about 150 million RMB. Therefore, it is necessary to reduce management costs and improve the reliability of natural gas pipeline supply through the development of a scientific and rational spare parts optimization program[2].

Spare parts management has a number of special characteristics that make the optimization of spare parts management particularly difficult[3, 4]. Due to the complexity and uniqueness of spare parts management, many researchers have studied it. Niu et al. gave a multi-stage inventory control optimization method under the assumption of random demand for spare parts[5]. In their research, Xie Mix, Liu Kai et al. found that the accuracy of spare parts demand forecasting and the way of setting up safety stock are the key factors to control the inventory risk[6]. Fang et al. confirmed through research that the joint inventory approach is more suitable for spare parts with low demand and high value[7]. Wildeman RE et al. proposed an algorithm that can approximate the optimal value with arbitrarily small deviation based on the research foundation of the previous research, which further improves the inventory modeling in the multi-product environment[8]. Qiang Wang

et al. provide a computational model and methodology for determining the reserve quantity of maintenance spare parts for machinery and equipment for a given operating time and reliability of use[9].

Although the spare parts optimization method can improve the system reliability and reduce the management cost to some extent, it is less combined with the maintenance plan. The maintenance management efficiency of the equipment not only depends on the number of spare parts, but also the maintenance content, maintenance method and maintenance time will affect the maintenance efficiency and increase the management cost. Therefore, it is necessary to formulate a scientific and reasonable spare parts program, seek the optimal ordering time and optimal replacement time of spare parts, and consider the maintenance decision and spare parts inventory at the same time, in order to improve the efficiency of system management and reduce costs[10, 11].

2. Unit Reliability Modeling of Compressor Key Components

This paper proposes a centrifugal compressor key performance spare parts ordering decision optimization method based on the reliability of gas supply. The method mainly consists of three parts: the establishment of compressor key component unit reliability mathematical model, reliability-based preventive maintenance cost model and compressor key performance spare parts ordering decision optimization model. The overall idea of the study is shown in Fig. 1.

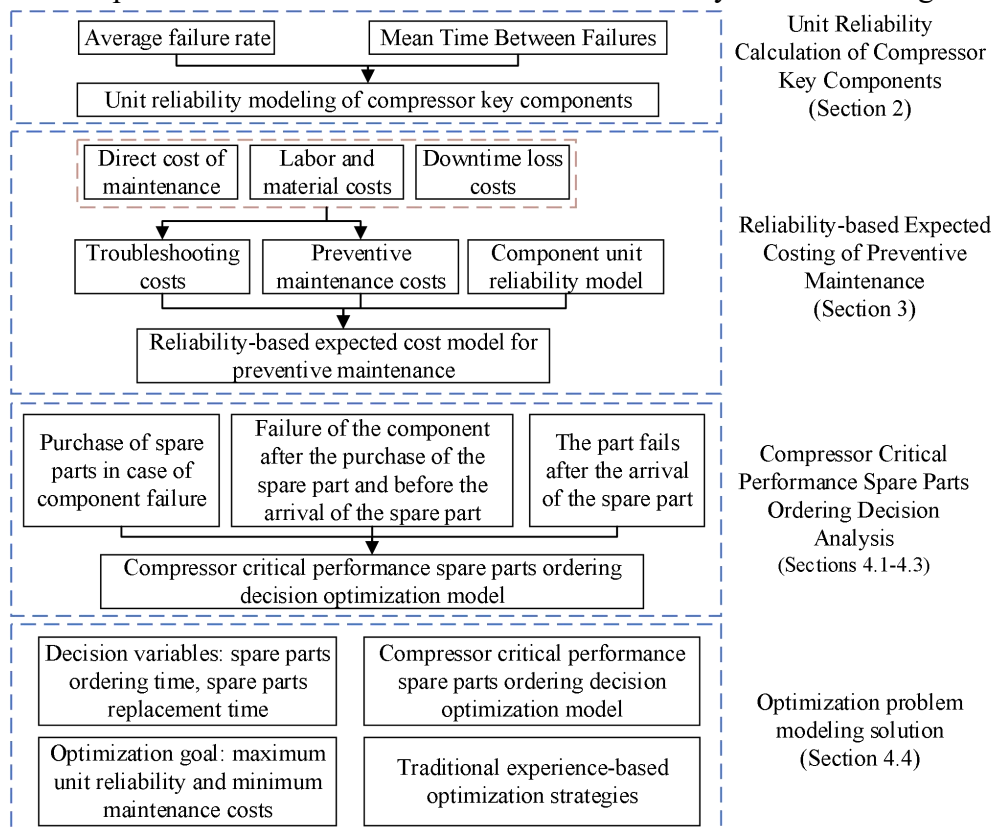


Fig. 1 Optimization of centrifugal compressors based on the reliability of gas supply, key performance spare parts ordering decision-making ideas block diagram

Compressor failures can be caused by a variety of reasons. Dry gas seal failure is the main cause of compressor performance degradation, so optimizing dry gas seal testing intervals and spare parts ordering times can improve compressor reliability[12, 13]. In addition, dry gas seals are expensive single components, so it is assumed that dry gas seals belong to the (0,1) type of spare parts, and a zero inventory strategy is adopted, i.e., only one spare part is ordered or warehoused at the same time, and only one spare part is consumed in any one maintenance activity.

The working condition of the centrifugal compressor is determined by the sealing system. Assuming that the life variable X of the dry gas seal obeys an exponential distribution, the reliability model of the dry gas seal is as follows[14].

$$R(t) = e^{-\lambda t} \tag{1}$$

Where: $R(t)$ is the reliability of the compressor at moment t ; λ is the average failure rate.

When the product life obeys an exponential distribution, the mean failure rate (λ) and the mean time between failures (MTBF) are the inverse of each other:

$$\lambda = \frac{1}{MTBF} \tag{2}$$

Where: λ is the average failure rate, 1/h; MTBF is the mean time between failures, h.

3. Reliability-based preventive maintenance cost model

Based on the unit reliability mathematical model of compressor key components established in Section I, a reliability-based preventive maintenance cost model of compressor key components is established in this section. First, a failure repair model for compressor key components is established; second, a preventive maintenance model for compressor key components is established; and finally, a reliability-based preventive maintenance cost model is established based on the unit reliability mathematical model for compressor key components established in the first section.

3.1 Troubleshooting and repair costs

Fault repair, also known as corrective maintenance, is based on equipment failures. It involves repairing the equipment to restore its normal functionality after a failure occurs during operation. The cost of fault repair includes direct costs associated with the repair, labor and material costs incurred during the repair process, and the cost of downtime resulting from the fault repair. The cost model for the repair of a critical component, such as the dry gas seal, in a centrifugal compressor is as follows.

$$C_F = C_{FS} + C_{FP} + C_{FM} + C_L \cdot t_F \tag{3}$$

Where: C_F is the total cost of component failure repairs, 10^4 RMB; C_{FS} is the direct cost of component failure repairs, 10^4 RMB; C_{FP} is the total labor cost of component failure repairs, 10^4 RMB; C_{FM} is the total material cost of component failure repairs, 10^4 RMB; C_{FL} is the cost of component failure repairs resulting in downtime losses, 10^4 RMB; C_L is the cost per unit time of failure downtime loss, 10^4 RMB/h; t_F is the time generated by the component to carry out failure repairs, h.

3.2 Preventive maintenance costs

Preventive maintenance, refers to the time-based maintenance, according to experience in accordance with the specified time interval for downtime inspection in order to prevent damage, this maintenance method is also commonly used in the current maintenance method. Preventive maintenance costs include the direct costs of preventive maintenance, preventive maintenance of human and material costs and preventive maintenance of the cost of downtime losses[15]. The cost model for preventive maintenance of dry gas seals, a key performance component of centrifugal compressors, is as follows.

$$C_P = C_{PS} + C_{PP} + C_{PM} + C_L \cdot t_P \tag{4}$$

Where: C_P is the total cost of performing preventive maintenance on the component, 10^4 RMB; C_{PS} is the direct cost incurred by performing preventive maintenance on the component, 10^4 RMB; C_{PP} is the total cost of labor incurred by performing preventive maintenance on the component, 10^4 RMB; C_{PM} is the total cost of material resources incurred by performing preventive maintenance on the component, 10^4 RMB; C_{PL} is the cost of downtime loss due to performing preventive

maintenance on the component, 10^4 RMB; C_L is the cost per unit time of failure and downtime loss, 10^4 RMB /h; t_p is the time generated by the component to carry out failure repairs, h.

3.3 Reliability-based preventive maintenance costs

In most cases, regular preventive maintenance management of equipment lacks economy and safety, and it is difficult to effectively carry out "preventive" maintenance management. Therefore, equipment preventive maintenance should be combined with reliability to carry out reliability-based preventive maintenance. The reliability-based preventive maintenance cost model established in this section is mainly composed of preventive maintenance costs and potential risk costs. The unreliability is taken as the potential risk of failure of the compressor's key performance components.

$$C_{RP}(t) = C_P \cdot R(t) + C_F \cdot F(t) \tag{5}$$

Where: $F(t)$ is the unreliability function of the component, $F(t)=1-R(t)$; $C_{RP}(t)$ is the total cost of reliability-based preventive maintenance of the component, 10^4 RMB.

4. Optimization Model for Ordering Performance Spare Parts for Compressors

When a compressor fails, it is necessary to replace the failed part with a spare part to bring the compressor back to normal. It is assumed here that the dry gas seals have a zero inventory strategy, i.e., there is only one spare part in the inventory to carry out maintenance activities. Assuming that the compressor is in normal operating condition at time $t=0$, after time t_0 has elapsed, dry gas seal spares are ordered. After elapsing the spare parts delivery time L , the spare parts were delivered to the site and the site personnel replaced the spare parts to bring the equipment back to normal condition.

The three typical scenarios for spare parts replacement and ordering are: (1) Purchase of spare parts in case of component failure. It indicates that the spare parts are ordered when the equipment fails and replaced after the arrival of the spare parts, at which time the cost of spare parts shortage and failure repair costs are incurred. (2) Component failure within spare parts delivery time. It means that the spare parts are ordered in advance before the failure of the parts, the equipment fails while waiting for the delivery of spare parts, and the spare parts are replaced after the arrival of the spare parts, which generates the cost of shortage of spare parts and the cost of fault repair. (3) The part fails after the arrival of the spare part. It means that the spare parts are ordered in advance and the spare parts have arrived, and the equipment is replaced after the arrival of the spare parts, which generates the inventory holding cost and the preventive maintenance cost based on reliability. The specific analysis is as follows.

4.1 Purchase of spare parts in case of component failure

Suppose that a component fails at time t_w , and in order to minimize equipment downtime, spare parts need to be ordered immediately. The spare parts are ordered at time $t_0=t_w$. The purchased spare parts arrive after time L , and they need to be repaired immediately after their arrival. Fig. 2 illustrates the schematic of purchasing spare parts in case of component failure.

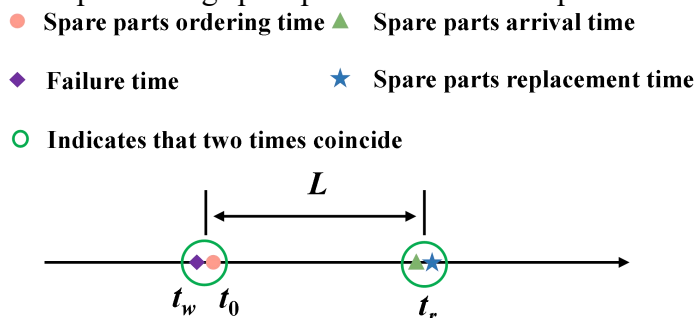


Fig. 2 Diagram for purchasing spare parts in case of component failure

Based on the component reliability function, the probability of the situation occurring is obtained:

$$P_1 = F(t_w) = F(t_0) \tag{6}$$

Where: t_w is the time of component failure, h; t_0 is the time of spare parts purchase, h; P_1 denotes the probability of occurrence at $t_0=t_w$.

Based on the Fig. 2, it can be concluded that the operating time of the component before failure is $t_1=t_0=t_w$. Spare parts are ordered when a component fails and repairs are carried out as soon as the spare part arrives, so the downtime after a component fails is the delivery time of the spare part.

$$t_1' = t_r - t_0 = L \tag{7}$$

Where: L is the time between the start of the spare parts order and the arrival of the spare parts, also known as the spare parts delivery time, h; t_r is the spare parts replacement time, h; t_1' is the component failure downtime, h.

Since the spare parts are used to repair the failure immediately upon arrival, the holding time of spare parts inventory is zero in this case, and the cost of this spare parts ordering decision model includes the cost of purchasing the spare parts, the downtime loss of the component failure, and the cost of repairing the failure.

$$C_1 = C_M + C_L \cdot t_1' + C_{FM} \tag{8}$$

Where: C_1 is the cost required by the spare parts ordering decision model for case (1), 10^4 RMB; C_M is the unit price of spare parts, 10^4 RMB.

4.2 Component failure within spare parts delivery time

Spare parts are purchased at moment t_0 , when the component has not yet failed. Suppose the component fails at moment t_w , when the purchased spare parts have not yet arrived, incurring a cost of downtime loss with $t_0 < t_w < t_r$. After the purchased spare part arrives at elapsed time L , the failure needs to be repaired immediately in order to minimize equipment downtime. Fig. 3 illustrates a schematic diagram of a component failing before the arrival of spare parts.

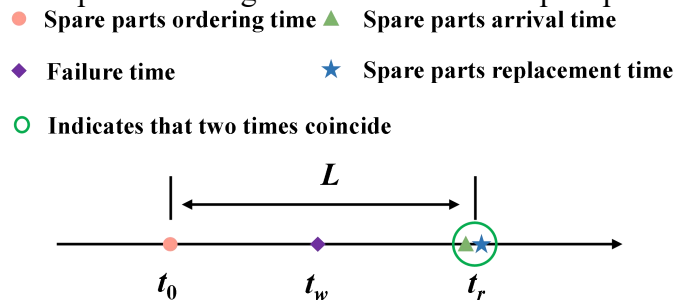


Fig. 3 Diagram of component failure before arrival of spare parts

Based on the component reliability function, the probability of the situation occurring is obtained:

$$P_2 = F(t_r) - F(t_0) \tag{9}$$

Where: P_2 denotes the probability that a component will fail within the delivery time of the spare part.

Using the integral form of the reliability function to describe the component's operating time, the component's operating time before failure at time t_w can be obtained as:

$$t_2 = t_0 + \int_{t_0}^{t_r} R(t)dt \tag{10}$$

The component has not yet failed when the spare part is purchased, and the component fails before the spare part arrives, so the downtime of the component after the failure is the time between the failure of the component and the replacement of the spare part.

$$t_2' = t_r - t_2 \tag{11}$$

Where: t_2 is the operating time before component failure, h ; t_2' is the downtime after component failure, h .

As in case (1), the costs required in case (2) include the cost of purchasing spare parts, the loss of downtime due to component failure and the cost of repairing the failure.

$$C_2 = C_M + C_L \cdot t_2' + C_{FM} \tag{12}$$

4.3 The part fails after the arrival of the spare part

Spare parts are purchased at moment t_0 and arrive after a delivery time L . The spare parts arrive ready to meet the repair needs of the component and will incur inventory holding costs. After the arrival of the spare part, the component fails. Fig. 4 illustrates the schematic of component failure after the arrival of spare parts.

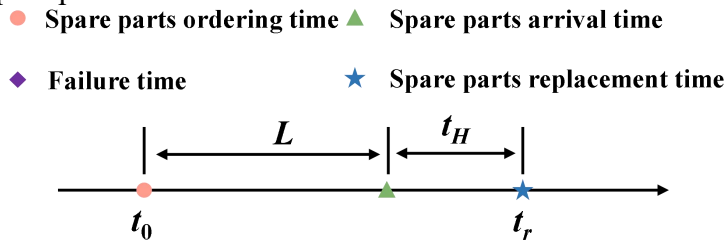


Fig. 4 Diagram of component failure after arrival of spare parts

The probability of occurrence of case (3) is:

$$P_3 = 1 - P_1 - P_2 \tag{13}$$

In this case, the time until the replacement of the spare part is the working time of the component, $t_3=t_r$. The component fails after the arrival of the spare part, at this time if the component fails, the ordered spare part can be put into use immediately, so there is no cost of downtime loss due to the lack of spare parts. Inventory holding costs will be incurred after the spare part arrives and before the spare part is replaced, and the holding time for the spare part in inventory is as follows.

$$t_h = \int_{t_0+L}^{t_r} R(t)dt \tag{14}$$

Where: t_h is the holding time of the spare parts in storage, h .

There is a certain holding cost and risk cost for holding spare parts in storage [16]. For the dry gas seal, a key component of the compressor, it is only under actual operating conditions that the failure of the dry gas seal can be truly evaluated. It is assumed that if, after the reliability-based preventive maintenance, the replacement part is found to have deteriorated, then the spare part is ordered and replaced as soon as it arrives (Fig. 5); if it is found to be in a normal condition, then nothing is done with it. This does not take into account the case where the spare part is in a degraded state.

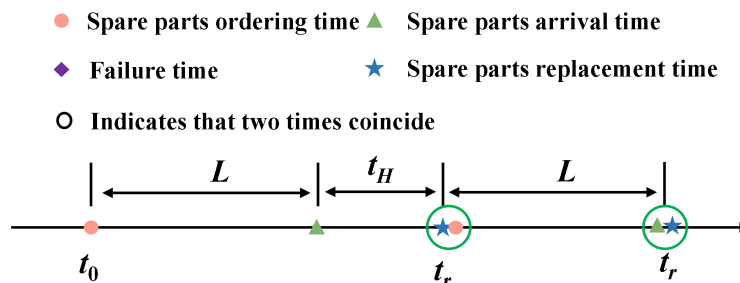


Fig. 5 Schematic diagram of the damaged condition of the replaced spare parts

Found that the replacement spare parts have been damaged directly after ordering spare parts, and wait for the arrival of spare parts immediately after the replacement of spare parts, at this time the lack of spare parts downtime that is the delivery time of spare parts, such a situation is similar to the case (1), so the required cost is as follows.

$$C_{risk}' = C_M + C_L \cdot L + C_{FM} \tag{15}$$

The cost of the risk of holding spare parts in storage is as follows.

$$C_{risk} = C_{risk} \cdot P_H = C_{risk} \cdot F(t_h) \tag{16}$$

From the above analysis, it can be concluded that the cost of such a spare parts ordering decision model includes the cost of purchasing spare parts, the cost of holding spare parts in stock (which includes a certain amount of holding costs and risk costs), and the cost of preventive maintenance based on reliability.

$$C_3 = C_M + C_H \cdot t_H + C_{risk} + C_{RP}(t_r) \tag{17}$$

Where: C_3 is the cost required by the spare parts ordering decision model for case (3), 10^4 RMB; C_H is the inventory holding cost per unit of time, 10^4 RMB.

4.4 Optimization Models

Based on the above analysis, it can be seen that there are multiple ordering scenarios for parts and each has a corresponding probability of occurrence. The total expected cost and the average working time incurred by ordering spare parts at each moment of the part can be obtained as follows.

$$\begin{cases} C = \sum_{i=1}^3 P_i \cdot C_i \\ t = \sum_{i=1}^3 P_i \cdot t_i \end{cases} \tag{18}$$

Where: C is the total expected cost incurred by ordering spare parts at each moment of the part, 10^4 RMB; t is the average working time of the part, h.

The objective function of the spare parts ordering decision optimization model established in this paper is the lowest expected cost per unit of time generated by ordering spare parts at each moment of the part, and the optimization objectives and constraints are as follows:

$$\begin{cases} \min \bar{C} = \frac{C}{t} \\ t_r \geq t_0 + L \\ R(t_r) \geq R_s \end{cases} \tag{19}$$

Where: R_s is the target reliability of the part.

During the decision optimization, it should be ensured that the reliability of the component is higher than the target reliability of the component. The optimization problem is solved using NSGA-II (Nondominated Sorting Genetic Algorithm II) programmed in Python language to obtain the optimal spare parts ordering time and optimal spare parts replacement time.

4.5 Optimization problem solving

NSGA-II (Nondominated Sorting Genetic Algorithm II) is a classical multi-objective genetic algorithm for solving complex multi-objective optimization problems[17, 18]. By simulating the genetic, selection and mutation operations of natural evolution, NSGA-II is able to search for a set of high-quality nondominated solution sets that are optimal under multiple objective functions, providing effective multi-objective decision-making solutions. NSGA-II has good performance and robustness in multi-objective optimization problems, and has been widely used in the fields of engineering design, resource allocation, and so on, which provides valuable decision support for decision makers to provide valuable decision support. The flowchart (Fig. 6) for solving the model using NSGA-II is shown below.

(1) Initialize the population: a group of individuals is randomly generated to constitute the initial population, and the set of the reliability of each pressurized gas station in this paper is the initial population.

(2) Evaluating adaptability: evaluate the adaptability of each individual, and calculate the adaptability value of each individual under each objective according to the objective function of the problem.

(3) Non-dominated sorting: according to the fitness value of individuals under multiple objectives, non-dominated sorting is carried out. Non-dominated sorting categorizes individuals into different levels, with higher levels indicating better individuals.

(4) Calculation of crowding: In order to maintain population diversity, the crowding of each individual needs to be calculated. Crowding degree indicates the density around an individual and is used to measure the distribution of individuals.

(5) Selection, crossover, and mutation operations: Based on the non-dominated sorting and crowding degree calculation, a portion of the individuals are selected as the parents for generating the next generation of the population. Crossover operation is performed on the selected individuals to generate new individuals. The mutation operation is performed on the newly generated individuals to introduce a certain degree of randomness, and the mutation operation can be used to generate new individuals by changing certain gene values of the individuals.

(6) Update population: merge the newly generated individuals with the parent population to form a new population.

(7) Repeat iteration: Repeat the execution of steps (2) to (6) until the stopping condition is satisfied. Common stop conditions include reaching the maximum number of iterations or finding a satisfactory solution set.

(8) Output results: The final output of the algorithm is the results of the algorithm, these solution sets are optimal under multiple objectives.

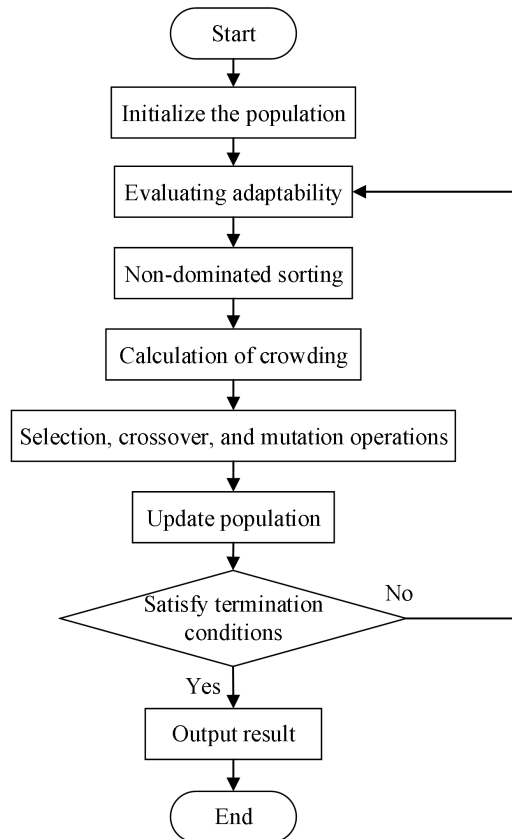


Fig. 6 Flowchart of the NSGA-II

5. Case Studies

5.1 Basic parameters

In this paper, based on the reliability of dry gas seals, which is a key component of a certain compressor model, the proposed spare parts ordering decision-making optimization model is used to determine the optimal purchase time and the optimal replacement time of dry gas seals. Through data collection, the average time between failures of the compressor dry gas seals is 9196 h. The data related to failure maintenance are shown in Table 1, the data related to preventive maintenance are shown in Table 2.

Table 1. Repair costs for compressor key component failures

| Direct cost of breakdown maintenance C_{FS} (10^4 RMB) | Total labor costs C_{FP} (10^4 RMB) | Total cost of material resources C_{FM} (10^4 RMB) | Downtime loss costs C_L (10^4 RMB /h) | Breakdown repair time t_F (h) |
|--|---|--|---|------------------------------------|
| 5.6 | 0.3 | 0.1 | 20 | 3 |

Table 2. Preventive maintenance costs for key compressor components

| Direct cost of preventive maintenance C_{PS} (10^4 RMB) | Total labor costs C_{PP} (10^4 RMB) | Total cost of material resources C_{PM} (10^4 RMB) | Downtime loss costs C_L (10^4 RMB /h) | Breakdown repair time t_P (h) |
|---|---|--|---|------------------------------------|
| 3.7 | 0.2 | 0.05 | 20 | 2 |

5.2 Reliability-based preventive maintenance costs

The reliability function and unreliability function of the dry gas seal can be obtained from the mean time between failures of the compressor dry gas seal is 9196h, respectively:

$$R(t) = e^{-0.0001t} \tag{20}$$

$$F(t) = 1 - e^{-0.0001t} \tag{21}$$

Based on the above data, the expected cost of reliability-based preventive maintenance for dry gas seals is as follows.

$$C_{RP}(t) = 43.95 \cdot R(t) + 66 \cdot F(t) \tag{22}$$

Fig. 7 shows the reliability-based preventive maintenance cost of a component. The initial moment of component operation reliability is 1, the cost of maintenance is preventive maintenance costs; with the increase in operating time, the reliability is gradually reduced, the proportion of potential risk costs gradually increase; when the reliability drops to 0, the component fails, the cost of maintenance at this time for the failure of the cost of maintenance.

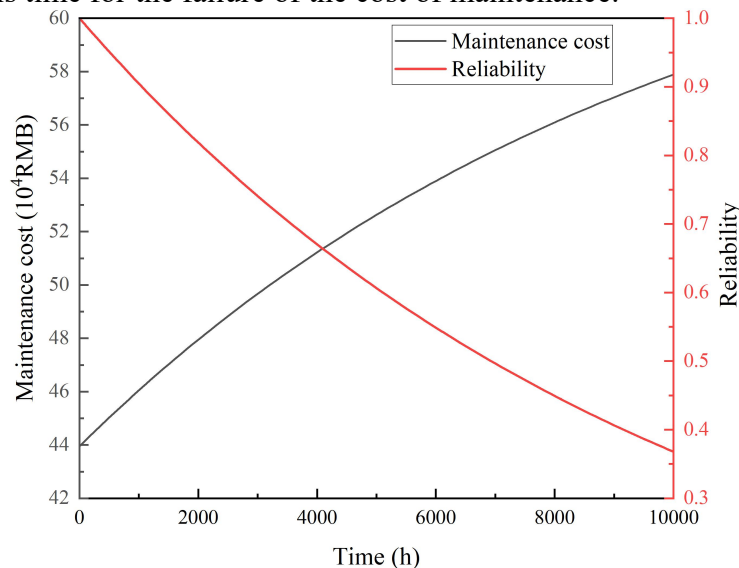


Fig. 7 Reliability-based preventive maintenance costs

5.3 Optimization strategy

In order to verify the effectiveness of the proposed decision optimization model for spare parts ordering, it is compared with the traditional empirical-based optimization strategy, and the two strategies are illustrated as follows:

(1) Spare parts ordering decision optimization model: Considering the case of spare parts being damaged in the inventory, the replacement time of parts and the purchase time of spare parts are used as decision variables to optimize the expected cost per unit of time generated by ordering spare parts at each moment.

(2) Traditional experience-based optimization strategy: Based on the actual production of the enterprise and the experience of experts, a fixed spare parts replacement cycle is adopted. The default replacement time for spare parts is 90 days; order spare parts in advance 7 days before replacement.

Fig. 8 depicts the results of the spare parts ordering decision optimization, corresponding to the optimal replacement time and spare parts ordering time in the horizontal and vertical coordinates, respectively.

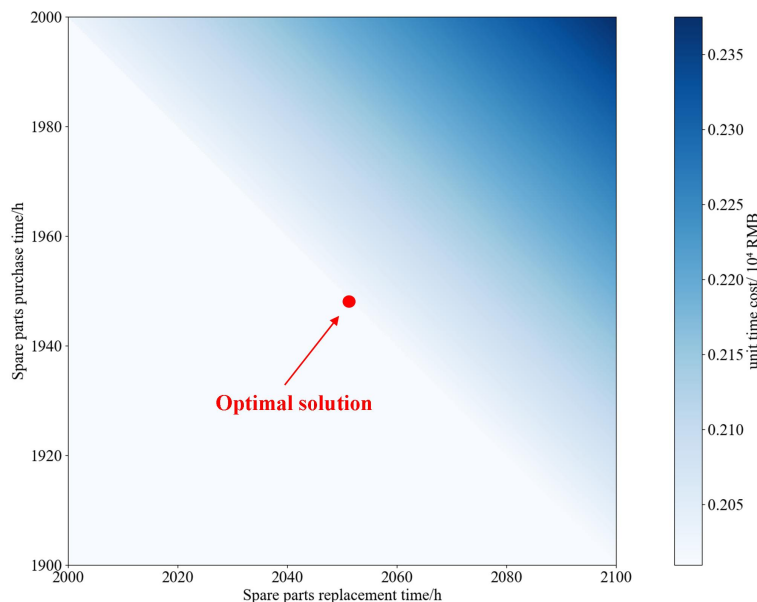


Fig. 8 Optimized projection results for spare parts ordering decisions

Table 4. Comparison of different optimization strategies

| Model | Optimal ordering time | Optimal replacement time | Expected cost per unit of time |
|--|-----------------------|--------------------------|--------------------------------|
| Spare parts ordering decision optimization model | 1948 | 2048 | 0.2020 |
| Traditional experience-based optimization strategies | 1922 | 2096 | 0.3251 |

Table 4 summarizes the optimal replacement time and optimal ordering time for the two maintenance strategies. The results show that the optimal ordering time under the spare parts ordering decision optimization model is 1,941h, the optimal spare parts replacement time is 2,041h, and the expected cost per unit of time is 0.2020 million yuan. The traditional empirical-based optimization strategy has a unit time expected cost of 0.3251; the proposed optimization model achieves the smallest average cost rate.

6. Conclusions

A joint optimization model of repair and ordering of critical performance spare parts for centrifugal compressors based on gas supply reliability is established, which combines the component repair strategy, takes into account the failure of spare parts within the inventory, determines the optimal spare parts ordering time and spare parts replacement time, and realizes the optimization of spare parts ordering decision.

(1) Compared with the traditional empirical-based optimization strategy, the proposed centrifugal compressor key performance spare parts ordering decision optimization method based on gas supply reliability achieves the lowest cost.

(2) In summer, the optimal ordering time under the spare parts ordering decision optimization model is 1,941h, the optimal spare parts replacement time is 2,041h, and the expected cost per unit of time is 0.2020 million yuan. The traditional empirical-based optimization strategy has an expected cost per unit time of 0.3251; the proposed optimization model achieves the smallest average cost rate.

(3) In winter, the optimal spare parts ordering time under the spare parts ordering decision optimization model is 1569 h, and the optimal spare parts replacement time is 1699 h, with an expected cost per unit of time of 0.2962 million yuan, while the traditional empirical optimization strategy has an expected cost per unit of time of 0.3551 million yuan; moreover, the optimal spare parts ordering time is about 130h earlier than the optimal spare parts replacement time. The proposed spare parts ordering decision optimization model achieves the lowest cost.

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