Preventive maintenance strategy for detection and buffer optimization in series production system

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Abstract. The equipment for series production line as the research object, a preventive maintenance model of joint equipment shutdown detection and equipment buffer optimization is proposed, in which the operation rate change and precision reduce of line production equipment caused by the bottleneck factor of production equipment are considered. The equipment shutdown detection and the size of the device buffer are optimized at the same time in the model. The deterioration state of the equipment is detected by stopping test, and the preventive maintenance plan is adjusted in time. By setting the buffer to reduce downtime of production shutdown process, reduce the equipment failure probability change, reduce the loss caused by the emergence of a series of equipment after shutdown. Finally, the effectiveness of the strategy is verified by the analysis of the two equipment series production system with the production bottleneck characteristics.

1. Introduction

In the series production system of modern production and manufacture, because the economic and structural correlation of the production system, once any equipment in the system is shut down due to failure, it will cause a great loss of the enterprise. In order to reduce the losses caused by the unplanned downtime of the equipment, a buffer is set up between the devices, making the serial production system change from "stop to stop" to "stop without stopping", and reduce the dependency between devices, which provides buffer time for downstream equipment to continue production. Therefore, many scholars have studied the non planned downtime in the production process, and put forward a number of preventive maintenance models with buffer zones.

Xi [1] combined with the age reduction factor and failure rate increase factor, the deterioration of single equipment's hybrid evolution, and equipment maintenance cycle with increasing service life gradually decreased by simulation. Jin and Jiang [2] in order to reduce the effect of equipment failure on production, considering the single equipment maintenance plan and production scheduling and optimization, and the introduction of buffer, the maintenance cost, the total completion time, total weighted completion time and the total weighted delay time as the multiple objective functions is obtained. But it does not take into account the impact of the number of buffers. Nahas [3] optimizes the buffer and preventive maintenance of equipment in the unreliable production system, and reduces the unplanned downtime losses in the whole production process. Nahas [4] considers the system's optimal selection of equipment maintenance under the condition of given output. Taking into account the optimization of the buffer area, the total cost of the two parts is optimized jointly. Zhou [5] considers the dynamic combination optimization of the buffer zone, but does not consider the size of
the buffer stock and the size of the impact on the maintenance activity. Yu and Zhou [6] studied the existence of the buffer zone, aiming at minimizing the overall maintenance cost, and optimizing the preventive maintenance plan. Wang [7] put forward a joint optimization model of buffer and maintenance based on the research of non Markovian serial production system. Considering the system to meet the demand output rate, we optimized the cost of the system operation process. Lu [8] study the impact of buffer on system production process, and use fuzzy weighted average algorithm to calculate the optimal maintenance plan and the optimal buffer size under the current plan. TAMBE [9] in order to stable operation of the production system, through the opportunity adjustment strategy adjustment, reduce the unplanned downtime, simulate the real data, consider a series of cost combination problems, and use three different algorithms to simulate. Cheng and Guo [10] consider the continuous deterioration system to detect the situation, describe the change of the system in the Levy process, and use the updated reward theory to optimize the detection time and maintenance threshold, and get the best maintenance strategy. KHATAB [11] consider the evaluation of some important industrial tasks, balancing the production line with the maximum probability and the minimum cost to complete the task. DO[12] discusses the perfect and imperfect maintenance effect based on equipment condition, and will affect the equipment inspection of equipment into account, in the maintenance of model will also take into account the detection interval, determined by the current detection results of current equipment maintenance type. DANIEL [13] make the royal Australian navy was used as the research object, and some defects in maintenance management were found by questionnaire survey. By enhancing the maintenance knowledge of the fleet maintenance personnel, the overall production and maintenance management of the fleet is considered, and the maintenance plan is optimized. Of course, it will take a long time to achieve certain results from the cultural Angle of the document [14]. Sensor technology was applied to monitoring were studied on the wind turbine running condition, and will get the sensor data in the database, respectively, three different function model is established for the analysis of the sensor in the input parameters have an impact on equipment failure, according to the parameters obtained from the analysis can predict to some extent the failure time of equipment. The main point of this paper is to propose different analysis methods to get the output parameters that have influence on the equipment.

However, the production process of the above literature is produced at a constant rate, without considering the production bottleneck, the equipment will change the production rate. When the equipment runs at different rates for a long time, it will accelerate the deterioration rate of the equipment, so the time based preventive maintenance strategy is insufficient to meet the maintenance requirements. In this paper, the deterioration state of the equipment is determined by stopping the equipment, and the optimal buffer number is set up to do the joint model.

2. Problem description
In serial production, the production process is carried out immediately after the product completes the process on the current equipment. When any equipment fails, the whole production system will enter the downtime maintenance or maintenance state. However, in the actual production process, between each equipment and equipment will set up a buffer zone, even if there is a sudden failure of the whole production equipment, the system can still run for a period of time, while the running time depends on the cache in the number of products after the equipment failure. The deterioration state of the equipment is determined by stopping the equipment, and the optimal buffer number is set up to do the joint modelling in the paper.

To make a clearer study of the problem, the following assumptions are made:
(1) When any device reaches its threshold $R$, the preventive maintenance is stopped. The preventive maintenance time is greater than the maximum buffer time of the buffer.
(2) The minor repair of unplanned downtime is used in the maintenance period $T$. The minor repairs only make to repair the equipment back to the state before the failure, the failure rate of the equipment does not be changed.
(3) The failure rate function of each device is known and deteriorates with the increase of use time.
(4) After the preventive maintenance of the equipment, the state of the equipment is between the "restore the old" and the "restore as the new". 
(5) The mean time of inspection of the equipment is \( t_{MTOR \text{const}} \) constant.

The bottleneck production equipments is known in this paper. The product is processed from the first device, and then passes through all the devices and their buffers until the last process is completed. It is necessary to consider different conditions when a certain device in the system stops. For the upstream equipments, when the downstream equipment failure occurs the upstream equipment to continue production for a while, when the maximum production reached its buffer value, the upstream equipment to stop produce into the shutdown state, when the upstream equipment failure rate to maintain the threshold at the same time for maintenance. For the downstream equipment group, when the breakdown equipment up stream, downstream equipment can continue production, when the equipment within the buffer zone after production is shut down, the downstream equipment group may have reached the threshold of failure rate of equipment, so it can be with the upstream equipment for maintenance, can reduce the downtime cost, shortage cost and delay cost of maintenance process.

The equipment deteriorates with the use of time, so the failure rate of each device obeys the two parameter Weibull distribution \( W(\eta, \xi) \), \( c_p \) is preventive maintenance cost per unit time, \( c_i \) is a minor repair cost per unit time, \( c_i \) is detection cost of each time, \( c_i \) is the compensation cost rate of inspection process, \( c_b \) is inventory cost per unit time, \( c_s \) is the shortage cost per unit time, Preventive maintenance time obeys density function \( f_i(t) \). In the actual production process, due to human or manufacturing defects and changes in speed, the device is in use, or the failure rate may change, for manufacturing enterprises, any change will affect the entire system given equipment maintenance plan, and they also consume a certain period of time for maintenance decision. In this paper, the failure rate of change based on the consideration, so the detection and buffer optimization of production system.

The equipment failure rate after I preventive maintenance is 
\[
\lambda_{i+1} = \rho \lambda_i (t + \sigma T_i)
\]

Where, \( \rho \) and \( \sigma \) is failure increase factor and age reduction factor, respectively. The equipment reliability expression is
\[
R = \exp \left[ -\int_0^T \lambda_i (t) \, dt \right] = \exp \left[ -\int_0^T \lambda_i (t) \, dt \right] = \exp \left[ -\int_0^T \lambda_i (t) \, dt \right] \quad (2)
\]

\( T_i \) is the \( i \)th maintenance cycle.

3. Model establishment

The particularity of series production line was considered, the output rate of equipment depends on the lowest rate of production rate in normal production process, assuming that the production rate per unit time of bottleneck production equipment Mb is b. The unit time production rate of the Mb upstream device Ma is a, and a>b. In normal production, every unit time will increase the number of a-b products in the buffer area of two devices. When the upper limit of the buffer reaches the limitation, the production rate of Ma will change from a to b due to production bottlenecks.

In order to build a model, \( N(t) \) is used to represent the number of expectations of a device failure in the preventive maintenance cycle \( T_i \). So there is
\[
N(t) = \int_0^T \lambda_j (t) \, dt \quad (3)
\]
\( \lambda_j (t) \) is the failure rate of the \( j \)th equipment with the enlistment age \( t \)

The overall expected maintenance cost of the system in the maintenance cycle \( T_i \)
\[
C_M = C_p \int_0^T \tau f_p (t) \, dt + C_i f_{MTOR} \cdot N(t) + C_f f_{MTOR} \cdot cN(t) \quad (4)
\]
where \( c \) is the detection coefficient. The expected inventory cost \( C_{M} \) can be obtained as following:
\[ C_{ha} = \frac{c_{b}}{2} \left( \frac{B^2}{a-b} + c_{x}N_{a}(t) \frac{2B-bt_{\text{MTOR}}}{a-b} + c_{x} h_{a}(t) \frac{2B-bt_{\text{MTOL}}}{a-b} \right) \]  

(5)

\[ c_{h} \left[ T_{j} - \frac{B}{a-b} - N_{a}(t) \frac{at_{\text{MTOR}}}{a-b} + \varepsilon N_{a}(t) \frac{at_{\text{MTOL}}}{a-b} \right] B \]

\[ C_{hb} = c_{b} h_{j}(t) I_{\text{MTOR}} \times B \]  

(6)

\[ C_{H} = C_{ha} + C_{hb} \]  

(7)

The \( C_{ha} \) is inventory cost due to the equipment \( M_{a} \) failure or maintenance, \( C_{hb} \) is inventory cost due to the equipment \( M_{b} \) failure or maintenance.

The shutdown time caused by system maintenance is

\[ D(\psi) = \begin{cases} 0 & \tau < \frac{B}{b} \\ \tau - \frac{B}{b} & \tau \geq \frac{B}{b} \end{cases} \]  

(8)

The expected cost of the system's downtime maintenance is \( C_{S} \):

\[ C_{S} = c_{b} h_{j} \int_{0}^{\psi} D(\psi) f(\tau) d\tau \]  

(9)

Found sudden deterioration of the reward cost \( C_{C} \) in advance:

\[ C_{C} = N(t)\varepsilon \times 0.2e_{c} \]  

(10)

So the total cost of the system is \( C_{T} \):

\[ C_{T} = C_{M} + C_{H} + C_{S} + C_{C} \]  

(11)

Objective optimization function obtained from the theory of renewal reward

\[ C = \frac{E(C)}{E(T)} = \frac{C_{T}}{\sum_{i=0}^{\infty} (T_{i} + \int_{0}^{\infty} \tau f(\tau) d\tau) \int_{0}^{T_{i}} \tau f(\tau) d\tau} \]  

(12)

The detection equipment is put forward in this paper, compared to the non detection of the pipeline can advance detection equipment whether change occurred in the operation process, so as to advance the maintenance, therefore in the detection process, the product after the completion of the delayed delivery cost without considering the cost model, added in advance that balance deterioration of equipment cost reward, this study in figure 1. When the device is in a given maintenance period, the detection time is considered in a given period of time, when the equipment is found after the sudden change of the current detection equipment reliability is obtained, and then re optimization of the entire production system maintenance plan, in the objective function, to ensure the total cost rate under the condition of small optimal buffer allocation in series the bottleneck of production line equipment.

**Figure 1.** Operation diagram in cycle.
4. Example analysis

In this paper, a series production system of two devices is used to simulate the production bottlenecks of production system, and the following parameters are used for numerical analysis. The shape parameters and scale parameters of the device are respectively \((5, 3)\) and \((90, 100)\). The probability density of the preventive maintenance time of the equipment obeys an exponential distribution of 0.05. \(\rho = 1.05\), \(\sigma = 0.15\), productivity per unit time \(a=2500\), \(b=2000\), detection coefficient \(\varepsilon=0.3\). Part of the cost parameters of table 1 from the literature [7].

| type | \(c_P\) | \(c_I\) | \(c_r\) | \(c_h\) | \(c_s\) | \(c_C\) |
|------|--------|--------|--------|--------|--------|--------|
| cost | 200    | 30     | 50     | 5      | 50     | -700   |

The relationship between the maintenance period and the minimum cost rate is considered. By maintaining the number of maintenance cycles as variables, we calculate the minimum cost rate of the current plan, and get the relation curve between the number of maintenance cycles and the minimum cost rate under this model, as shown in figure 2.

![Figure 2](image)

We can see that the minimum cost rate of series production lines is increasing with the number of maintenance cycles increasing from figure 2. Therefore, in order to avoid the upper limit of maintenance, the upper limit of maintenance period is eight. When the number of maintenance cycles is determined, in order to consider the opportunity maintenance, the minimum cost rate is obtained when the time window \(T_w=8\) in the maintenance process through the data iteration. In the above data, the optimal maintenance plan is obtained through MATLAB data processing, such as table 2.

| cycle | \(T_1\) | \(T_2\) | \(T_3\) | \(T_4\) | \(T_5\) | \(T_6\) | \(T_7\) | \(T_8\) |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|
| The shutdown of time point | 61     | 60     | 59     | 58     | 57     | 56     | 56     | 55     |
| Maintenance | 16.16 | 16.01 | 15.86 | 15.70 | 15.54 | 15.38 | 15.38 | 15.20 |

Under this maintenance plan, the optimal cost rate is \(C=24302.57\), and the optimal slow stock is \(B=1345\). When only considering the literature [1] preventative maintenance and increase the chance of maintenance, do not use the equipment deterioration detection and do not consider the buffer optimization, once any downtime will be "one stop stop" phenomenon, only to carry out preventive maintenance and maintenance opportunities obtained by calculation when the pipeline equipment reliability in \(R=0.8\), get the minimum production cost rate is \(C=25222.50\), compared to the traditional maintenance strategy, maintenance plan total cost rate higher than 3%, greater than the rate of the proposed optimization model of equipment failure and the production line.
Table 3. Effect of inventory cost on total cost and inventory size.

| $C_h$ | $C_s$ | $C_c$ | $C$   | $B$ |
|-------|-------|-------|-------|-----|
| 5     | 50    | -700  | 24302.58 | 1345 |
| 6     | 50    | -700  | 23845.70 | 614  |
| 7     | 50    | -700  | 23317.90 | 100  |

From table 3, with the increase of inventory cost and other cost under the same conditions, the total cost was decreased gradually, the cache size is greatly reduced, when the inventory cost $C_h=7$, cache size $B=100$, because the cache size of the initial iteration limit is 100, the cache limit reached stop, change inventory variables. while the inventory cost increase, the buffer size at the same condition, it will cause system total cost increase, so it is necessary to decrease the buffer size to optimization total cost.

Table 4. Impact of out of stock cost on total cost ratio and cache size.

| $C_h$ | $C_s$ | $C_c$ | $C$   | $B$ |
|-------|-------|-------|-------|-----|
| 5     | 50    | -700  | 24302.58 | 1345 |
| 5     | 55    | -700  | 26922.93 | 1772 |
| 5     | 60    | -700  | 29515.73 | 2191 |
| 5     | 65    | -700  | 32081.81 | 2601 |
| 5     | 70    | -700  | 34621.92 | 3004 |

As shown in table 4, when other costs remain unchanged and the cost of the shortage is gradually increased, the total cost rate of the pipeline is rise, and the size of the cache is also increasing. It needs rise buffer size to decrease the pipeline down time, due to buffer area can storage product, it will make the downstream equipments of the failure equipment keep working until run out of all buffer product. So while the shortage cost increase, it need to rise buffer size to decrease downtime to optimization total cost.

This maintenance strategy was based on the time the main maintenance and state maintenance strategy based on the comprehensive consideration, each time the equipment shutdown detection results may change the original maintenance plan, because the initial maintenance plan was based on the time of the maintenance, sudden deterioration in equipment, taking into account the deterioration the equipment in the production process is not in accordance with the deterioration law on time, so we need to detect equipment deterioration condition, based on the adjustment of the whole system dynamic deterioration of equipment condition maintenance plan. When the mere introduction of equipment testing content, while improving the reliability of the production system, but in the process of detection equipment downtime increases the equipment downtime losses, so this paper also introduces buffer optimization, and solve the detection equipment downtime caused by the loss, reduce the loss caused by the maintenance process.

5. Conclusions

The equipment inspection and buffer was introduced to preventive maintenance plan in the paper, so to optimization the maintenance plan, which obey to deterioration rule of production equipment, and the period of each maintenance decreases with using. At the same time, planning for other buffer allocation can be considered. The model studied in this paper is only suitable for the production line with high reliability. For the production line with low reliability, the demand for equipment inspection is low. At the same time, there have some views not discussed in the paper, when the equipment with different degradation rate of deterioration, the deviation of reliability the actual equipment deterioration and the reliability of the model is in the range considered, as well as in the multi device hybrid system, limited resources down the chance of detecting detection and detection equipment personnel.
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