Reliability analysis and optimization of production system for production scheduling

Weiwei Duan, Wei Dai*, Yue Wang and Jiahuan Sun
School of Reliability and Systems Engineering, Beihang University, Beijing, China
E-mail:16141017@buaa.edu.cn.

Abstract. Production planning and scheduling mainly solve the problems of multi-process, multi-resource scheduling and sequence optimization in the workshop. Existing production scheduling methods focus on how to minimize the production period, but production system reliability is seldom considered in the actual production scheduling strategy. Production system reliability is closely related to the state change of equipment in production system, the production stability and efficiency. Therefore, in order to ensure the reliability of the production system when planning production tasks, this paper proposes a new strategy for production scheduling. Firstly, the model of production system is conducted to analyses its reliability. Secondly, a reliability evaluation method is proposed by analysing the status of equipment in the production system. Moreover, the optimization goal of production system reliability is added to the original production scheduling goal. Finally, the optimization method is put forward and verified by an example.

1. Introduction
In the history of human industrial production, how to reasonably arrange the production task has always been an important issue. Production scheduling has gradually developed from manual to digital, and then to intelligent. According to the constraints of production system capacity and process logic, production planning and scheduling is to allocate production resources to each production task in some optimization rule so that it can meet the demands of production tasks. The optimization rules include the shortest production period, the lowest production cost, the most balanced equipment load, etc. Based on this, researchers have made many theoretical explorations and innovations on the optimization of production scheduling methods.

It should be noted that the state of the equipment will change in the actual production, which will also affect production system reliability. Production system reliability is a significant part of the performance of production system, also the key to ensure the product quality. So it is necessary to optimize the reliability of production system when planning production task. Availability and effective productivity of production system can be the reliability index of production system [1-2]. Secondly, establishing a production system reliability model can better analyze the system reliability in actual production, such as reliability block diagram [3], fault tree analysis [7], etc. After the reliability analysis of the production system, the reliability optimization indexes which need to be considered in the actual production scheduling process can be obtained. This kind of multi-objective optimal scheduling problem can be solved by many methods, mainly including optimal scheduling method and heuristic scheduling method [8-9]. Genetic algorithm, which belongs to heuristic scheduling method, is the most widely used. There are also many improved genetic algorithms.
proposed for it: those based on immune principle, those using coevolution mechanism, those based on game theory, etc.

In this paper, the necessity of optimizing the reliability of production system is put forward, and the modeling and reliability analysis methods of production system are introduced in Section 2. In Section 3, we discuss how to optimize the reliability of production system in production scheduling. The multi-objective optimization method is briefly introduced. In Section 4, the optimized production scheduling method is verified by a case.

2. Production system modelling and reliability analysis
The production system is composed of production equipment (machine) and material storage and transportation equipment (buffer). As shown in Figure 1, the circle represents machine, and the square represents buffer. The production line in Figure 1 consists of $M$ machines and $M-1$ buffers.

![Figure 1. Standard serial production line](image)

Before modeling analysis, we must understand the following concepts and parameter definitions. 

- **Hunger**: machine runs out of workpieces in the previous buffer.
- **Block**: machine processed workpieces fill the last buffer.
- **Operation-related failures**: machines do not fail when blocked or hungry.
- **Time-related failures**: machines can still fail if they are blocked or hungry.
- **Availability**: the probability that the machine can work normally in unit time. In this article we use $A$ to represent it.
- **Effective productivity**: when the system or machine is running in a steady state, the average number of workpieces produced in a unit time. In this paper we use $W$ to represent it.

- $\omega_i$: productivity of machine $m_i$
- $\lambda_i$: failure rate of machine $m_i$
- $\mu_i$: repair rate of machine $m_i$
- $k_i$: capacity of buffer $b_i$
- $B_i$: impact factor of buffer on machine $m_i$

Based on the above, we make the following assumptions:

1. The primary machine $m_1$ will not be hungry, the final machine $m_M$ will not block.
2. The workpiece processing cycle, fault interval and fault repair time of machine $m_i$ obey the exponential distribution of the parameters of $\omega_i$, $\lambda_i$ and $\mu_i$ respectively.
3. Machines fail only during normal operation, and do not fail when hungry or blocked.

According to these three assumptions, we respectively model the buffer and the machine and analyze their states, then obtain the general formula of the availability and effective productivity of the production system.

2.1 State analysis of buffer
Given that $k_i$ is the capacity of the buffer $b_i$, it has $k_i + 1$ states. Its state transitions are shown in Figure 2, where $p_i$ represents the probability when the stock of buffer $b_i$ is equal to $l$. 

![Figure 2. State transitions of buffer](image)
**Figure 2.** State transition probability of buffer

From Figure 2, the state probability equation of buffer $b_i$ is obtained:

$$
\begin{align*}
\dot{p}_0 &= -\omega_0 p_0 + \omega_{i+1} p_i \\
\dot{p}_i &= \omega_i p_0 - (\omega_i + \omega_{i+1}) p_i + \omega_{i+1} p_2 \\
&\vdots \\
\dot{p}_{k_i} &= \omega_i p_{k_i-1} - \omega_{i+1} p_{k_i} \\
\sum_j p_j &= 1
\end{align*}
$$

In equations (1), $\dot{p}_j$ represents the state change of the buffer $b_i$ after $\delta t$. When the buffer stock is in steady state, $\dot{p}_j$ is equal to 0. Then the steady-state solution of the equations (1) can be obtained:

$$
\begin{align*}
p_j &= r_j' \frac{1 - r_i}{1 - r_{i+1}} \\
r_i &= \omega_i / \omega_{i+1}
\end{align*}
$$

Further, the steady-state solutions of the two typical states of buffer $b_i$ are as follows:

When the buffer $b_i$ is not full, its probability is

$$
\alpha_i = 1 - p_{k_i} = \frac{1 - r_i}{1 - r_{i+1}}
$$

When the buffer $b_i$ is not empty, its probability is

$$
\beta_i = 1 - p_0 = \frac{r_i - r_{i+1}}{1 - r_{i+1}}
$$

In a serial production line, in addition to its failure-free conditions, the necessary conditions for the normal operation of the machine $m_i$ also require that the former buffer is not empty and the latter buffer is not full. Therefore, given the influence factor of the buffer on the availability of the machine $m_i$:

$$
B_i = \begin{cases} 
\alpha_i = 1 - p_{k_i} & i = 1 \\
\alpha_i \beta_{i-1} = (1 - p_{k_i})(1 - p_{(i-1)0}) & 1 < i < M \\
\beta_{i-1} = 1 - p_{(i-1)0} & i = M
\end{cases}
$$

**2.2 State analysis of the machine**

(1) When the impact of the buffer on the machine is not considered, the machine $m_i$ has two states of failure and work. Let $P_{ij}$ be the probability that machine $m_i$ is in state $j$, $j = 0$ represents that the machine $m_i$ has failed, $j = 1$ represents that the machine $m_i$ has not failed.

**Figure 3.** State transition probability of independent machines

From Figure 3, the state probability equation of machine $m_i$ is obtained:
In equations (6), $\dot{P}_j$ represents the state change of the machine $m_i$ after $\delta t$. When the machine $m_i$ is in steady state, $\dot{P}_j$ is equal to 0. Then the steady-state solution of the equations (6) can be obtained:

$$P_\omega = \frac{\lambda_j}{(\mu_i + \lambda_4)}$$

Then the availability and effective productivity of the machine $m_i$ are

$$A_i = P_\omega = \frac{\mu_i}{(\mu_i + \lambda_4)}$$

$$W_i = A_i \omega_i = \frac{\mu_i \omega_i}{(\mu_i + \lambda_4)}$$

When considering the impact of the buffer on the machine, we call this kind of machine an dependent machine, the dependent machine $m_i$ (with the exception of the primary machine $m_1$ and the final machine $m_M$) has five states:

**Table 1. Five states of dependent machine**

| $j$ | State of dependent machine |
|-----|----------------------------|
| 0   | machine $m_i$ is in a fault state |
| 1   | machine $m_i$ is in normal working condition |
| 2   | machine $m_i$ is in a hunger state |
| 3   | machine $m_i$ is in a block state |
| 4   | machine $m_i$ is both in hunger and block states |

And the state transition of an independent machine is shown in Figure 4:

**Figure 4. State transition probability of machines considering the impact of buffer**

Let $P'_u$ be the probability of machine non-fault state, which means $P'_u = P_{2u} + P_{3u} + P_{4u} + P_{5u}$, a set of equations can be obtained by combining the influence factor of buffer on machine $m_i$ in section 2.1:

$$\begin{cases}
    P_{2u} = P_{1u} \alpha_i \beta_{i-1} \\
    P_{3u} = P_{1u} (1 - \alpha_i) \beta_{i-1} \\
    P_{4u} = P_{1u} \alpha_i (1 - \beta_{i-1}) \\
    P_{5u} = P_{1u} (1 - \alpha_i) (1 - \beta_{i-1}) \\
    P_0 + P'_u = 1 \\
    P_0 = P_{1u} \lambda_i - P_{0u} \mu_i
\end{cases}$$

(10)
Similar to the previous subsection, when the machine $m_i$ is in steady state, $P_{ji}$ is equal to 0. Then the steady-state solution of the equations (10) can be obtained:

$$P_{ji} = B, \lambda_i \mu / (\mu_i + B, \lambda_i)$$  
$$P_{ji} = B, \mu / (\mu_i + B, \lambda_i)$$  

Then the availability and effective productivity of the machine $m_i$ considering the impact of buffer are

$$A_i = P_{ji} = B, \mu / (\mu_i + B, \lambda_i)$$  
$$W_i = A_i \omega_i = B, \mu \omega_i / (\mu_i + B, \lambda_i)$$  

2.3 Reliability analysis of production system

In the actual serial production line, a process may be composed of multiple machines. When the processing capacity of a single machine is insufficient, multiple machines need to be connected in parallel, as shown in Figure 5. When a process requires several synchronous operations to complete, a serial connection occurs, and the failure of any one of these operations will cause the entire process to fail, as shown in Figure 6.

For $s$ with parallel machines  $m$ with synchronous related machines  $s$ in a process. Correspondingly, we should merge their parameters with the following formula.

**Table 2. Equivalent formula for multiple machines**

|                      | failure rate | repair rate | productivity |
|----------------------|--------------|-------------|--------------|
| with synchronous related machines | $\lambda_{si} = \max \lambda_{ij}$ | $\mu_{si} = \min \mu_{ij}$ | $\omega_{si} = \min \omega_{ij}$ |
| with parallel machines | $\lambda_{si} = \lambda_i \sum_{j=1}^{n} 1/j$ | $\mu_{si} = \mu_i$ | $\omega_{si} = n \omega_i$ |

*a This table shows that there are $n$ machines in the $i$th process.

After simplifying the original production line into a standard serial production line, we then consider the impact of the buffer on the machine and calculate the respective availability $A_i$ and effective productivity $W_i$ of the machine. The following formula can be used to calculate the availability and effective productivity of the entire production system, which is also the reliability index of the production system.

$$A_i = A_M$$  
$$W_i = min W_j$$

The availability and effective productivity mentioned above combine system parameters such as $\lambda_i$, $\mu_i$, $\omega_i$ and $k_i$, so they can be effectively used as indicators for evaluating the reliability of a production system.

3. Multi-objective optimization in production scheduling
3.1 Introduction to multi-objective optimization methods

In the multi-objective production scheduling problem, most of the optimization objectives appear in the form of minimization, but there are also forms of maximization. In this paper, the availability and effective productivity of the production system are the maximization problems. The minimization and maximization problems are interchangeable. Therefore, the MOP (multi-objective optimization problem) with availability and effective productivity as the objective function can be described as follows:

\[
\begin{align*}
\text{min} & \quad y = f(x) = (f_1(x), f_2(x), \ldots, f_k(x)) \\
\text{subject to} & \quad e(x) = (c_1(x), c_2(x), \ldots, c_m(x)) \\
\text{Where} & \quad x = (x_1, x_2, \ldots, x_n) \in X \\
& \quad y = (y_1, y_2, \ldots, y_k) \in Y
\end{align*}
\]

Among them, \( x \) represents a decision vector composed of \( n \) decision variables, and \( X \) represents a decision space formed by \( x \). \( y \) is the target vector composed of \( k \) optimization goals, and \( f(x) \) is composed of the corresponding \( k \) objective functions. It is worth noting that these optimization goals may conflict. \( Y \) represents the target space formed by \( y \) . \( e(x) \) is a constraint space composed of \( m \) constraint functions, which determines the feasible value range of \( x \).

There are many ways to solve such a target optimization problem, mainly including the optimization scheduling method and the heuristic scheduling method. The optimization scheduling method can generally obtain the optimal solution of the problem by accurately solving the analytical model, or the sub-optimal solution of the problem, which mainly includes the mathematical programming method, branch boundary method, and enumeration method. The optimization scheduling method is more effective for simple optimization problems. When faced with the multi-objective optimization scheduling problem of more complex production systems, as the number of machines and targets increases, the difficulty of solving will also increase significantly.

The heuristic method is a solution method that can balance the scheduling effect and the calculation time to obtain a suboptimal solution or a satisfactory solution of the problem with less calculation time. It is more suitable for complex multi-objective optimization problems. When faced with the multi-objective optimization scheduling problem of more complex production systems, as the number of machines and targets increases, the difficulty of solving will also increase significantly.

The heuristic method is a solution method that can balance the scheduling effect and the calculation time to obtain a suboptimal solution or a satisfactory solution of the problem with less calculation time. It is more suitable for complex multi-objective optimization problems. Heuristic methods are divided into rule scheduling method, artificial intelligence method, simulation-based method and domain search method. Among them, the neighborhood search method generally has universal applicability and less experience complexity, so it has become the main optimization method for solving multi-objectives in recent years. It mainly includes simulated annealing algorithm, Particle swarm algorithm and genetic algorithm.

3.2 Introduction to genetic algorithm

Genetic Algorithm (GA) is a computational model that simulates the natural selection and genetic mechanism of Darwinian biological evolution. It is a method to find the optimal solution by simulating the natural evolution process. GA has characteristics of simplicity, generality, and strong robustness, so it is widely used in many fields such as combinatorial optimization production scheduling problems, function optimization, and automatic control. The principle genetic algorithm are introduced below.

GA starts with the initial population. This population corresponds to a solution set consisting of several feasible solutions in practical problems, and each individual corresponds to a feasible solution. The individual phenotype corresponds to the specific description of the feasible solution, and its genotype is the necessary mapping of the feasible solution in the algorithm. Many operations in genetic algorithms cannot directly act on feasible solutions, so certain rules need to be used to map feasible solutions into the algorithm domain. We usually call this mapping work as coding, and return from the algorithm space to the problem domain. The opposite operation is decoding.
After the first-generation population is produced, each individual will adapt to the rules of nature and strive to survive. This natural rule corresponds to the optimization goal in the actual problem. In each generation, individuals are selected according to their fitness, and then a new population is generated by combining crossover and variation of the original individuals. Therefore, in accordance with the natural law of survival of the fittest, the initial population will evolve into a better population from generation to generation. Finally, the optimal individual in the last-generation population is decoded to obtain the optimal solution of the problem.

In summary, we can get the general steps and basic flowchart of GA, as shown in Figure 7:

1. Randomly generate populations.
2. Determine the fitness of the individual according to the strategy and whether it meets the optimal termination criterion. The termination criterion can be the set number of iterations or the fitness threshold. If it matches, output the best individual and its optimal solution and end; otherwise, proceed to the next step.
3. The parent is selected according to the individual's fitness level. The higher the fitness level, the greater the probability of being selected, and the lower fitness individual is more likely to be eliminated.
4. Cross the chromosomes of the parents in a certain way to produce offspring.
5. Perform variation operations on offspring chromosomes.

![Figure 7. The basic flowchart of GA](image)

3.3 Establish a multi-objective optimization problem model in production scheduling
The main optimization goals of existing scheduling methods are to minimize delivery cycles, production costs, and balance equipment loads, but the optimization of reliability indicators for production systems is seldom. Therefore, the scheduling strategy proposed in this paper indicates that we need to take reliability, that is, effective productivity, as a new optimization goal. Although it may conflict with other optimization goals, such as production costs.

In addition, we also need to determine the decision variables \( x \) and constraints \( c(x) \) in the multi-objective optimization problem. Combined with the actual production, we get \( x \) and \( c(x) \) in the scheduling as follows:
In actual production scheduling, the buffer available for allocation in a production system is limited. In the sense of the model, the total buffer capacity is limited. According to the reliability model of the production system, the buffer capacity will affect the reliability of the production system. Therefore, it is necessary to consider how to allocate the capacity of each buffer reasonably.

Since the tasks of the same process can be assigned to several identical machines, this means that the number of parallel machines in a process can be allocated. Noted that the number of machines is also limited. From Table 7, we know that changing the number of parallel machines can be regarded as changing $\lambda$ and $\omega$ of the machine in the $i$th process. These parameters will affect the reliability of the production system, so we also should determine how to allocate the number of parallel machines in each process in production scheduling.

In addition, it is necessary to arrange manual maintenance during production scheduling. Assigning maintenance personnel to a certain process is equivalent to increasing $\mu$ of the machine in that process. However, due to various restrictions, it is difficult for maintenance personnel to conduct a comprehensive overhaul of all processes. Therefore, how to arrange maintenance personnel's inspection points is also a consideration in scheduling.

The above lists several decision variables, constraints and optimization goals in the scheduling problem model. In actual production, there are more variables and constraints, and this article will not elaborate too much here. Later in this article, the case will be analyzed and calculated based on these model parameters.

4. Case verification

4.1 Case introduction

Take a bridge bearing production line of an enterprise as an example. The production line is simplified to a standard serial production line consisting of 5 processes and 4 buffers. According to the equipment information and work records, we get the working parameters of the machine and resource constraints, as shown in Table 3.

| No. | $\lambda_i$ (h^{-1}) | $\mu_i$ (h^{-1}) | $\omega_i$ (Pieces/d) | $N_i$ | $C_i$ (¥/d) |
|-----|---------------------|------------------|----------------------|------|-------------|
| 1   | 0.005               | 0.02             | 16                   | 2    | 300         |
| 2   | 0.001               | 0.02             | 30                   | 2    | 500         |
| 3   | 0.001               | 0.02             | 23                   | 3    | 200         |
| 4   | 0.005               | 0.02             | 30                   | 3    | 500         |
| 5   | 0.005               | 0.02             | 18                   | 3    | 200         |

$N_i$: Maximum number of parallel machines in process $i$.

$C_i$: Operating cost per machine.

$C_B$: Consumption cost per capacity of buffer, that is, the consumption cost of $b_i$ is $k_iC_B$.

$k_i$: The maximum buffer capacity the production line can provide.

$\mu_m$: Repair rate provided by maintenance personnel, that is, if a maintenance person is assigned to a certain process, the repair rate of the machine in this process can be increased by 0.1 h^{-1}.

In the scheduling task of this case, we need to allocate the number of parallel machines in each process, the capacity of the buffer at all levels, and the maintenance personnel. Our production scheduling goal is to make the production system reliability higher and the cost lower.

4.2 Establish a multi-objective optimization model

4.2.1 Decision variables.
The decision variables in this case are: \( x = (k_1, k_2, k_3, k_4, n_1, n_2, n_3, n_4, n_5, h) \). In this case, these variables are all positive integers. \( k_1 \sim k_4 \) are the actual capacity of the 4 buffers allocated respectively. \( n_1 \sim n_5 \) are the number of parallel machines called by each process. The value of \( h \) is in the range of 1~5, and its value represents that the maintenance personnel is assigned to \( h \)th process for maintenance, which means machines of \( h \)th process can improve the repair rate of \( \mu_h \).

4.2.2 Constraints.
(1) The total buffer capacity actually allocated shall not be more than 70, and the capacity of each buffer shall not be less than 10. The mathematical expression is

\[
c_1(x): k_1 + k_2 + k_3 + k_4 \leq 70
\]

\[
c_2(x): k_1, k_2, k_3, k_4 \geq 10
\]

(2) The number of parallel machines allocated for each process shall not exceed the corresponding maximum number of parallel machines. The mathematical expression is

\[
c_3(x): i \leq n_i \leq N_i
\]

(3) There is only one maintenance person, and the maintenance personnel can only choose one of the five processes for maintenance. The mathematical expression is

\[
c_4(x): h \leq 5
\]

4.2.3 Objective function
(1) In the production cycle of a serial production system, operating costs are incurred once the machine is turned on. The availability of the machine represents the probability of the machine working normally. So the operating cost during the normal working period is used for product manufacturing, while the operating cost during the abnormal working period is essentially the cost of loss, which has not been converted into actual product output. Therefore, the calculation formula of loss cost \((C_l)\) and the total cost of system operation \((C_s)\) are

\[
C_l = \sum_i n_i C_i (1 - A_i)
\]

\[
C_s = \sum_i n_i C_i + C_p \sum_i k_i
\]

We define the ratio of \( C_l \) and \( C_s \) as the cost-loss ratio \((R_l)\), that is

\[
R_l = C_l / C_s
\]

Then the objective function is described as

\[
f_1(x): \min R_l \text{ or } \max 1 / R_l
\]

(2) Take system effective productivity as an indicator of production system reliability, then the objective function is described as

\[
f_2(x): \max W_i
\]

4.3 Solve with genetic algorithm

4.3.1 Coding.
In this case, the optimization problem involves 10 decision variables, and each variable has different constraints, it is not suitable for binary coding. So real number coding is used here, and each individual has 10 gene loci, corresponding to 10 decision variables. For example, an individual code is \([10, 20, 10, 20, 1, 1, 2, 3, 1, 3]\).

4.3.2 Fitness function.
Since there are two objective functions and their optimization goals are opposite, the two objective functions need to be converted and weighted. Combining the production needs of the enterprise, we choose 0.6 and 0.4 as the weighting factors for the two goals.
Fitness = 0.6 \text{WR} + 0.4 / R_i \quad (25)

4.3.3 Set genetic algorithm parameters

| Table 4. genetic algorithm parameters |
|---------------------------------------|
| Population size | Number of iterations | Select rate | Crossover rate | Variation rate |
| 50              | 20                    | 0.5         | 0.5            | 0.02           |

We use MATLAB to run the code of GA, and finally calculate the optimal solution as \((k_1, k_2, k_3, k_4, n_1, n_2, n_3, n_4, n_5, h) = (20, 27, 12, 11, 2, 2, 3, 2, 3, 1)\). And the corresponding objective function value is

\[ R_i = 0.242, \quad W_S = 31.135 \]

4.4 Result analysis

In theory, the maximum value of \(W_s\) in this case should be \(\min \{N_i \omega_i\} = 2 \times 16 = 32\), it is very close to the required effective productivity. In addition, 300 sets of feasible solutions are randomly generated to calculate \(W_s\) and \(R_i\). The average value of \(W_s\) is 17.86, and the average value of \(R_i\) is 34.4%. It can be seen that this method has a good optimization effect.

Although this example is only a serial production line with 5 processes, this paper proposes an optimization solution, and it fully validates the effectiveness of considering the reliability of the production system in scheduling. When scheduling production for more complex production systems, as long as more advanced algorithms and technologies are combined, this optimization idea can still be applied in deeper and wider applications.

5. Conclusion

This article focuses on the reliability issues ignored in production system scheduling. Through the reliability modelling and analysis of the production system, reliability indicators such as availability and effective productivity can be obtained. The optimization objective of reliability is added to the original scheduling optimization objective. It also introduces typical methods for solving multi-objective optimization problems. And it provides ideas for optimizing the reliability of the production system in the production scheduling process. At present, the manufacturing industry is required to develop in a high-quality direction. This scheduling optimization method will provide a more healthy and reasonable solution for the production plan, ensuring efficient and stable production process. Thereby it can help enterprises to reduce the waste of resources and inefficient production. What’s more, this scheduling optimization method can also be combined with technologies such as dynamic monitoring of equipment status in the future, which will create the possibility for dynamically formulating a reasonable scheduling strategy.

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