Flexible Flow Shop Scheduling and Energy Saving Optimization Strategy under Low Carbon Target

Ruixue Yin*, Chaowen Li, Xuqing Feng, Qingbin Yang
College of Mechanical Engineering, Guizhou University, Guiyang, China
yinruixue@sina.com

Abstract. In order to reduce the carbon emissions of the flow shop which consists of unrelated parallel machine, a kind of scheduling mathematical mode with low carbon emission target is built by analyzing the carbon emissions of the machine tools under different running conditions. Not only the carbon emissions produced in the handling process which is rarely discussed in the previous studies, but also the carbon emissions produced during the start-up and shutdown process of the selected machine tools are considered in the model. Based on this model, a multi-state alternation energy saving optimization strategy is proposed to reduce carbon emissions during the idle waiting period of machine tools. An improved genetic algorithm is employed to solve this optimization problem. In the end, the t cases are studied to validate the strategy.

1. Introduction
At present, the issue of global warming has become a topic of widespread concern. The manufacturing industries, as the main energy consumer produce a huge amount of carbon dioxide. Therefore, reducing carbon emissions from manufacturing industries is the primary task. It is necessary to implement low-carbon and energy-saving optimization policy in the production workshop, which is the main energy consumption link in the manufacturing industry.

Regarding the problem of energy consumption in the flow workshop, Liu Xinyue [1] uses an ultra-low standby state based on CNC machine tools to schedule the workshop. Ren Caile [2] established a mixed-integer linear programming model and optimized it with the goal of minimizing energy consumption based on the analysis of the energy consumption composition of the flexible flow shop with unrelated parallel machines. Li Bing [3] considered the constraints related to adjustment time and sequence. He analyzed and modeled energy consumption problems and conducts scheduling research with the goal of minimizing total energy consumption. Ai Ziyi [4] established a mathematical model in the flexible flow shop with the goal of carbon emissions and added a variety of speed options to this model for low-carbon optimal scheduling.

Wang et al. [5] analyzed a variety of states during the operation of the machine tool and pointed out that during the machining process, some energy-consuming parts of the machine tool were turned off to change the machine tool operation state. This method can save 26% of energy consumption. In the first part of the Environmental evaluation of machine tools [6] analyzed the energy consumption status of each unit of the machine tool the relationship between the operating status of the machine tool and the operating status of each unit was established. The above-mentioned literatures mainly focus on the energy consumption and proportion of a single machine tool operating state. He Yan [7] basing on the analysis of the machine's operating status, the energy saving operation of a single machine tool was studied by the random arrival of the workpiece. Liu Xinyue [1] combined the state of the machine tool with workshop scheduling to study and actively control the operating state of the machine tool. However,
it only considered the flow shop situation without parallel machine. The unrelated parallel machine environment was studied in the article of Ren Caile [2] the energy consumption of loading, unloading, transportation and switching process of machine tool still was ignored in the study. Above almost of the current researches are focused on the energy consumption ratio of single machine tool operation state, only a few studies combine it with workshop scheduling to actively control the running state of machine tool. In addition, the influence of the energy consumption and its carbon emissions of loading, unloading and transportation workshop are often ignored. The value of carbon emissions is employed as the evaluation index of machine tool energy consumption, and the calculation model of carbon emissions for the machine tool in several different operating states during the process from the beginning to the shutdown are built in this paper. Firstly, the strategy of multi-state switching and active adjustment is adopted by the machine tool. This strategy takes into account the influence of the workpiece loading and unloading process on the workshop process planning sequence. Secondly, combined with workshop scheduling, the mathematical model of scheduling optimization is established with the goal of minimizing carbon emissions under the background of flow workshops with unrelated parallel machines and use improved genetic algorithm to solve it. Finally, through relevant examples, the impact of the above factors on the carbon emissions of the workshop and the effectiveness of the adjustment strategy are analyzed.

2. Problem description and mathematical model

2.1. Problem description

In this paper, the scheduling problem is described as follows: there are \( n \) pieces of workpieces processed on an assembly line which includes \( k \) processing stages. \( m_s \) is the number of the machines in \( s \)th stage (where \( s = 1, 2, \ldots, k \)). \( M \) is the sum of the machine tools of all stages. There is at least one machine tool available in each stage. At any time, each workpiece can only be processed by one machine at most and each machine tool can only process one workpiece at most. In each stage, at least one stage has more than one parallel machine. In a stage, the time for processing the same workpiece on each device in this stage is different, and the power of processing different workpieces on the same device is also different. Workpiece transportation is completed by loading and unloading handling equipment. The optimization goal is to reduce the total carbon emissions by determining the suitable machine for machining the workpiece in each stage and the optimal sequence of processing in each machine.

2.2. Categories of carbon emissions during machine tool operation

During the operation of the machine tool, its operating state can be divided into processing state, preparation processing state, standby and shutdown state [7]. During the operation of the machine tool, the energy consumption and carbon emissions are different conditions. The specific analysis is as follows.

2.2.1. Processing carbon emissions. Processing carbon emissions refer to the carbon emissions generated by the machine tool in the processing state. The total carbon emissions calculation of the processing state is shown in formula (1):

\[
C^w = \sum_{s=1}^{n} \sum_{w=1}^{k} \sum_{h=1}^{m_s} P_{h,w}^{w} t_{h,w}^{w} \alpha_e X_{i,s,h}^{w}
\]

\( P_{h,w}^{w} \) is the average power of the \( h \)th machine tool in the machining state when the \( i \)th workpiece is processed on it (kW); \( t_{h,w}^{w} \) is the time of the \( h \)th machine tool in the processing state when the \( i \)th workpiece is processed on it (min); \( \alpha_e \) is the carbon emissions factor of electric energy (kgCO2e/kWh); \( X_{i,s,h}^{w} \) represents decision variable, which is shown in formula (2):

\[
X_{i,s,h}^{w} = \begin{cases} 
1, & \text{workpiece } i \text{ is arranged to be processed on the machine in } s \text{th stage} \\
0, & \text{otherwise}
\end{cases}
\]
2.2.2. Carbon emissions generated by machine tool switch. Start-up and shutdown are necessary parts of the machine tool. The calculation of the total carbon emissions during one start-up and shutdown process is shown in formula (4):

\[ C^\text{be}_h = C^b_h + C^e_h = P^b_h t^b_a + P^e_h t^e_a \]

Where \( C^\text{be}_h \) is the sum of the carbon emissions of the \( h \)th machine tool when it is turned on and off once (kgCO2e); \( P^b_h \) is the average power of the machine tool from turning on to preparing for processing (kW); \( P^e_h \) is the average power of the \( h \)th machine tool during shutdown (kW); \( t^b_a \) is the time when the \( h \)th machine tool is turned on to the state of preparing for processing (min); \( t^e_a \) is the time which is taken to turn off all energy-consuming components after finishing processing the workpiece of the \( h \)th machine tool (min).

The flow shop studied in this paper contains unrelated parallel machines. At least one machine must work at each stage. The working machine must be turned on before use, and it must be turned off after processing all the workpieces arranged on it. Therefore, the total carbon emissions calculation of the switch machine is shown in formula (4):

\[ C^\text{be}= \sum_{h=1}^{M} C^\text{be}_h X^\text{be}_h = \sum_{h=1}^{M} (P^b_h t^b_a + P^e_h t^e_a) X^\text{be}_h \]

Where \( X^\text{be}_h \) represents decision variable, its meaning is shown in formula (5):

\[ X^\text{be}_h = \begin{cases} 1, \text{workpiece processing is arrabged on the } h \text{th machine tool} \\ 0, \text{otherwise} \end{cases} \]

2.2.3. Idle carbon emissions. Above all, the idle carbon emissions calculation of \( h \)th machine tool at \( t \)th position is shown in equation (6):

\[ C^i_h = \begin{cases} C^i_h X^i_h + C^\text{be}_h X^\text{be}_h B^i_h - F^i_h \geq T^i_h \\ P^i_h (B^i_h - F^i_h) a^i_e, \text{otherwise} \end{cases} \]

The value of \( X^i_h \) is 1 when the idle waiting time of the \( h \)th machine tool at positions \( t \to t+1 \) is greater than the state switching threshold \( T^i_h \), and the carbon emissions \( C^\text{be}_h \) which produced in standby stage is less than the carbon emissions \( C^\text{be}_h \) which produced by a shutdown and restart (kgCO2e). This means that in this time interval, the \( h \)th machine tool must keep in the standby state with low energy consumption, otherwise the value of \( X^i_h \) is 0. The value of \( X^\text{be}_h \) is 1 when the idle time of the \( h \)th machine tool at the position \( t \to t+1 \) is greater than the state switching threshold \( T^i_h \) (min); and the carbon emissions situation is opposite to the above situation. This means that in this time interval, the \( h \)th machine tool will perform shutdown and restart to wait for the arrival of the next workpiece, otherwise the value of \( X^\text{be}_h \) is 0. The value of \( T^i_h \) is smaller of \( T^s_h \) and \( T^r_h \).

The calculation of total idle carbon emissions is shown in equation (7):

\[ C^i = \sum_{h=1}^{M} \sum_{t=1}^{T} C^i_h \]

2.3. Low-carbon optimization scheduling model

Considering the energy consumption of transportation process and the machine tool in the different operating states, an FFSP mathematical model with irrelevant parallel machines with the goal of minimizing carbon emissions is established, which is shown in equation (8):

\[ \min C = C^o + C^\text{be} + C^i + C^c \]

Where \( C^c \) is transportation carbon emissions, which is the product of the power of the transportation equipments and the transportation time (kgCO2e).

The equation (9) indicates that the workpiece must go through \( h \)th stages of processing, and at each stage, a workpiece can only be processed on one machine. The equation (10) indicates that the \( h \)th
workpiece is the \(r\)th processed workpiece on the \(h\)th machine tool, and its completion end time is the sum of the start processing time and the processing time. The equation (11) indicates that on any machine tool, the machining of the next workpiece must be performed after the machining of the previous workpiece finished.

\[
\sum_{s=1}^{m_h} X_{i,s,h}^w = 1, i = 1, 2, \ldots, n, s = 1, 2, \ldots, k
\]

\[
F_{h,i} = B_{h,i} + t_{i,h}^w X_{i,h,i}^w, h = 1, 2, \ldots, M
\]

\[
B_{h,i+1} \geq B_{h,i} + t_{i,h}^w X_{i,h,i}^w, h = 1, 2, \ldots, M
\]

3. Simulation case analysis

In order to verify the effectiveness of the proposed model and energy-saving optimization strategy in the processing environment, the test case data in the literature [2] is utilized. And on the basis of its calculation examples, the imitating method of generating calculation examples comes from literature [4] and [14].

The initial population size is set as 300, and number of iterations is set as 150. According to the literature [15], the parameters are set as follows: \(k_1 = 0.9, k_2 = 0.6, k_3 = 0.8, k_4 = 0.5\). Each type of problem runs 20 times, and the optimal solution is selected. The strategy of switching to standby mode will be adopted during the idle waiting period. At the same time, the situation is recorded as state A when the handling process and the power consumption boundary of the selected machine tool are ignored. The case is denoted as state B when the above boundary is considered. The situation is marked as state C when the energy-saving optimization strategy is adopted, meanwhile the above-mentioned energy consumption boundary is considered. The results of optimized energy consumption in each state are shown in Table 1. The index marked as \(R_{MN}\) is used to represent the contrast deviation of the energy consumption results of state M and state N, which can be calculated as \(R_{MN} = \frac{\text{the difference of energy consumption under state M and N}}{\text{energy consumption of state N}} \times 100\%\).

Table 1. Comparison of Optimized Energy Consumption Results in Various States

| Problem model | Total energy consumption \(\times 10^{-3}\text{kWh}\) | State A | State B | State C | \(R_{AB}\) | \(R_{AC}\) |
|---------------|---------------------------------|--------|--------|--------|----------|----------|
| 4x4x0         | 2388.6                          | 2331.8 | 2316.7 | 2.43%  | 3.10%    |
| 6x4x0         | 3484.7                          | 3448.3 | 3443.6 | 1.06%  | 1.20%    |
| 8x4x0         | 4558.2                          | 4496.7 | 4496.7 | 1.37%  | 1.37%    |
| 10x4x0        | 5618.6                          | 5568.3 | 5562.3 | 0.90%  | 1.01%    |
| 12x4x0        | 6667.8                          | 6641.9 | 6640.9 | 0.39%  | 0.41%    |
| 4x4x1         | 5301.7                          | 5157.4 | 5126  | 2.80%  | 3.43%    |
| 6x4x1         | 7863.8                          | 7708.1 | 7675.4 | 2.02%  | 2.45%    |
| 8x4x1         | 10428.3                         | 10195.9| 10185.8| 2.28%  | 2.38%    |
| 10x4x1        | 13048.8                         | 12678.1| 12674.3| 2.92%  | 2.95%    |
| 12x4x1        | 15709.7                         | 15263.1| 15263.1| 2.93%  | 2.93%    |

According to Table 1, state B effectively reduced the energy consumption by considering the power consumption boundary of the handling process and the switch machine of the selected machine tool, which is compared with state A. The lowest percentage deviation is 0.39%, and the highest deviation is 2.93%. The highest energy consumption reduction value is 446.6\(\times 10^{-3}\text{kWh}\). It shows that expanding the accounting boundary in the optimization target model can further reduce energy consumption, and
also proves the feasibility of the established optimal scheduling model. State C is the addition of energy-saving optimization strategy on the basis of state B, because the effective range of energy-saving optimization strategy is the idle waiting period of the machine tool, and the optimization effect is affected by the energy consumption during the idle waiting period. The maximum idle waiting energy consumption in state B is 36, and in state C it is reduced to 31.4 after optimization. The difference between before and after optimization accounts for 87.2% of the idle waiting energy consumption before optimization, indicating that the energy saving strategy acting on the idle waiting period of the machine tool has obvious effect. At the same time, it can be found that the value of $R_{AC}$ in each case is higher than that of $R_{AB}$, the highest $R_{AC}$ value is 3.43%, indicating that on the basis of expanding the accounting boundary, continuing to add energy-saving optimization strategies can further reduce energy consumption, which further illustrates the effectiveness of the energy-saving optimization strategy.

4. Conclusions

This paper proposes a relatively comprehensive low-carbon optimal scheduling model based on the carbon emissions of workpiece processing, machine tool and handling process for the flexible flow shop scheduling problem with unrelated parallel machines. The model fully considers the carbon emissions estimation problem in each working state of the machine tool. It proposes to optimize the energy saving by changing the waiting state of the machine tool during the idle period of the machine tool, and designs an improved genetic algorithm to analyze and solve the problem. With case illustrate the feasibility and effectiveness of the model, which provides a way for enterprises to further the implementation of energy conservation. How to combine the low-carbon optimal scheduling model with the existing scheduling software for actual production will be one of the tasks of the next research work.

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