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An improved multi-objective firefly algorithm for integrated scheduling approach in manufacturing and assembly considering time-sharing step tariff

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ABSTRACT

Today, energy conservation and reduction of consumption are crucial concerns for manufacturing companies. Current research on integrated scheduling of processing and assembly typically focuses only on equipment resources and processing and assembly processes. A new method for energy-saving integrated scheduling in workshops has been proposed, which incorporates the recently introduced time-of-use tiered electricity prices into the scheduling optimization model. This method also introduces an operation strategy of turning equipment on and off during idle periods. A multi-objective mathematical model was developed to minimize energy consumption and assembly delay time in the processing and assembly processes. Due to the complexity of the model, the standard firefly algorithm was improved when used to solve the model. This involved designing a three-layer encoding method and two decoding methods, and providing detailed steps of the algorithm. Using a mixed flow production line as an example, the final scheduling solutions were obtained through model construction and algorithm solving, taking into account the tiered electricity price. The results of the example demonstrate that parallel processing and assembly effectively reduce assembly delay costs, and the implementation of the on/off strategy reduces power consumption during the machining process.

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1. Introduction

As the main energy of manufacturing industry, how to save energy has become a problem that manufacturing industry has to consider [1-4]. To solve the above problems, the key is whether through the product manufacturing and assembly process management, to achieve energy-saving cooperative manufacturing of parts manufacturing and assembly. Therefore, it is of great practical significance for energy saving and consumption reduction of manufacturing and assembly manufacturing enterprises to study the energy saving integrated scheduling optimization problem of manufacturing and assembly links [5].

The production process of manufacturing and assembly enterprises includes many links such as process planning before production, workshop scheduling and final assembly molding after workpiece processing. Scholars at home and abroad have studied the workshop scheduling of single link or the integrated scheduling of multiple links. The research on the integrated scheduling of the two stages of manufacturing and assembly in the production process can reduce the high cost and low efficiency caused by separate scheduling, which has also attracted wide attention of scholars.

Peng and Zheng [6] developed an improved wild horse optimization (IWHO) algorithm to simultaneously optimize three objectives: makespan, maximum machine workload, and total machine workload. Huo and Wang [7] proposed a hybrid dynamic scheduling method with Digital Twin and improved bacterial foraging algorithm (IBFOA) to minimize the maximum completion time and machine load. The results show that the scheduling scheme using the IBFOA can optimize the system performance as a whole and effectively deal with the problem of extended production time caused by disruption. Komaki and Kayvanfar [8] proposed an improved Grey Wolf Optimizer (GWO) to minimize the maximum completion time of two-stage flow shop scheduling with delivery time. Sun *et al.* [9] proposed a dynamic shop scheduling method integrating deep reinforcement learning and convolutional neural network (CNN), and could adaptively select appropriate dispatching rules based on the state features of the production system.

Ren *et al.* [10] tackled Distributed Permutation Flow-shop Scheduling Problems (DPFSPs), aiming to minimize the maximum completion time of workpieces. The authors proposed a NASH Q-Learning algorithm based on Mean Field (MF), employing a two-layer online learning mode within a multi-agent Reinforcement Learning framework, and demonstrated its superior efficiency over similar algorithms. Tian and Zhang [11] focused on the dynamic job-shop scheduling problem (JSP) with the goal of reducing manpower and material costs. They proposed a dynamic job-shop scheduling model using deep learning, specifically employing a long short-term memory network (LSTM) with Dropout technology and adaptive moment estimation (ADAM) to enhance prediction. The optimization was targeted at three objective functions, and the multi-objective problem was solved using an improved multi-objective genetic algorithm (MOGA), with experimental results proving the algorithm's effectiveness. Zhao and Yuan [12] addressed the integrated scheduling of production and maintenance in a parallel machine job-shop environment, considering stochastic machine breakdowns. They developed an integrated model utilizing minimal and preventive maintenance strategies and designed a genetic algorithm to solve the problem. The model and algorithm were verified through an instance, proving their effectiveness. Wang [13] investigated the quality management and control of multi-variety small-batch production (MVSBP) manufacturing logistics, analyzing factors and optimizing elements like site selection, path design, and warehousing. A real case simulation in a porcelain blank processing workshop demonstrated the effectiveness of their approach in aligning with the shift from traditional mass production to MVSBP. Belmahdi *et al.* [14] conducted a comprehensive review of the various scheduling methods and algorithms utilized in Fog Computing, a paradigm that extends the capacities of Cloud and improves performance and QoS for applications. They analyzed, compared, and classified these scheduling approaches according to the algorithm's nature, the optimized QoS, and application types such as critical IoT (CIOT), massive IoT (MIOT), and Industry IoT (IIOT), and provided a comparison of different simulation tools to guide developers and researchers in the field of fog computing. Ren *et al.* [15] developed a two-stage optimization algorithm for the JSP, considering job transport, that combines the improved fast elitist nondominated sorting genetic algorithm II (INSGA-II) with a local search strategy, and an ant colony algorithm based on reinforcement learning (RL-ACA), to minimize makespan, tardiness, and energy consumption, demonstrating superiority over other algorithms in similar problems. Bedhief and Dridi [16] tackled the three-stage hybrid flow shop scheduling problem with two dedicated machines in stage 3, aiming to minimize the maximum completion time (makespan), and proposed an improved genetic algorithm (IGA) that incorporates more than one crossover operator and a 2-opt local search method, demonstrating effectiveness and efficiency in comparison to an existing heuristic approach. Zhao and Yuan [17] developed a multi-objective optimization model for integrating job-shop production scheduling and predictive maintenance, considering constraints like product delivery time and changing machine failure rate, and used an enhanced non-dominated sorting genetic algorithm (NSGA)-II with simulated binary crossover (SBX) to minimize processing cost and time, validating the approach with a case study.

Deng *et al.* [18] research aimed at minimizing the total completion time, including the three-stage integrated scheduling problem of workpiece processing, transportation and assembly, and proposed a hybrid distribution estimation algorithm integrating multiple rules. Aiming at the integrated optimization scheduling problem of mixed-flow assembly line and machining line with parallel machine, Guo and Ryan [19] addresses a real-life uncertainty factor identified in a manufacturer of large vehicles, by modelling unreliable part delivery and quality. Stochastic optimization is applied to find sequencing policies that improve the on-time performance of its mixed-model assembly lines. Wei *et al.* [20] adopts colored Petri nets (CPN) and a minimal spanning tree (MST) to address the type I problems for two-sided assembly line balancing problem (TALBP). Aiming at the integrated optimization problem of manufacturing and assembly workshop, Liang *et al.* [21] establishes a multi-objective mathematical model for integrated scheduling of manufacturing and assembly workshops with the goal of minimizing the completion time of manufacturing and assembly stages, and designs a genetic algorithm to solve the model. The feasibility of the model and the effectiveness of the algorithm are verified by examples.

Current research indicates that the combined scheduling problem of manufacturing and assembly continues to prioritize minimizing completion time and delay, with limited focus on energy conservation. Specifically, there is a lack of studies addressing the impact of time-sharing step tariffs on energy usage. Nevertheless, energy consumption is a crucial factor in scheduling. Therefore, it is essential to investigate integrated scheduling for energy efficiency. In particular, integrating machining and assembly with time-sharing step tariffs holds significant theoretical and practical value.

Therefore, this paper focuses on the processing and assembling manufacturing enterprises, integrating the scheduling issues of manufacturing and assembly links for the processing-assembling mixed-flow production line. It systematically examines the integrated scheduling problems of manufacturing and assembly with a focus on energy conservation, considering time-sharing step tariffs and aiming to reduce assembly delay time and power costs. The paper is structured as follows: Section 2 outlines the energy-saving integrated scheduling problem under time-sharing step tariffs, develops the integrated scheduling mathematical model, and presents the model's objective function and constraint conditions. Section 3 enhances the multi-objective firefly algorithm to address the scheduling model from Section 2. Finally, Section 4 validates the correctness of the model from Section 2 and the effectiveness of the algorithm from Section 3 through an example.

2. Construction of energy-saving integrated scheduling model

In the mixed workshop of production and assembly considering the time-sharing step tariff, the processing equipment completes the processing of the workpiece according to the product requirements, and the assembly equipment completes the product assembly according to the equipment process. In the process of processing, there are many kinds of workpieces, different kinds of workpieces need to be processed by different process routes; In the assembly process, each assembly equipment corresponds to an assembly node. Before assembly, the corresponding workpiece to be assembled needs to be processed. Therefore, in the workshop, the processing sequence of the workpiece to be processed needs to be sorted, and the starting time of the assembly needs to be determined to reduce the waiting time of the assembly process and ensure the timely delivery of the product. To minimize the power cost and delay time of manufacturing and assembly process, the integrated scheduling of manufacturing and assembly process is carried out.

For the integrated optimization scheduling problem of manufacturing and assembly, the following assumptions are made: (1) At the same time, each processing equipment can only process one work piece; (2) The processing route of the workpiece, the processing time of each processing procedure and the assembly time of each assembly procedure are known and determined in advance; (3) Once each processing or assembly process starts to complete the processing task, it cannot be interrupted; (4) The preparation time of tool change and clamping is included in the processing or assembly time of each process; (5) Each processing procedure of the workpiece must be completed before the subsequent processing procedure is completed; (6) The workpiece needed at the beginning of the assembly process has been processed.

To establish a mathematical model for integrated scheduling optimization of machining and assembly, the following symbols are defined:

i Workpiece number, $i \in [1, \dots, I]$;
j identification number, $j \in [1, \dots, J]$;
k Electricity price period, $k \in [1, \dots, K]$;
v Electricity price ladder, $v \in [1, \dots, V]$;
a Assembly node number, $a \in [1, \dots, A]$;
w_i Number of processes of workpiece i, $w \in [1, \dots, w_i]$;
u_j Number of locations of machine j, $u \in [1, \dots, u_j]$;
ST Planned start time;
ET Planned finish time;
O_{iwju} Boolean variable, the w-way program for the job i is processed at the u position on machine j, then the value is 1, otherwise 0;
SM_{iwju} The starting time of w-channel process of workpiece i at u position on machine j;
EM_{iwju} The completion time of w-channel procedure of workpiece i at u position on machine j;
SA_{ai} Assembly node a Requirement time for artifacts i;
EA_{ai} Workpiece i completion time at assembly node a;
RT_j The time consumed when machine j shuts down once;
W_j^{re} The energy consumption of machine j shutdown once;
x_{ju} Boolean variable, machine j takes the switch policy after finishing the machining position u, then the value is 1, otherwise it is 0;
AT_{ai} Boolean variable, whether the assembly node a needs workpiece i, if so, the value is 1, otherwise the value is 0;
$h_{ai'I}$ Boolean variable, if assembly node a requires that workpiece i after work piece i ', then the value is 1, otherwise it is 0;
$t^{idle}{}_{jk}$ The idle time of machine j in period k;
$p^{idle}{}_j$ The standby power of machine j;
$p^{asse}{}_a$ Average power of assembly node a;
$t^{asse}{}_{ai}$ The installation time of workpiece i on assembly node a;
$t^{mach}{}_{iwj}$ The processing time of process w of workpiece i on machine j;
$p^{mach}{}_{iwj}$ The power requirement of process w of workpiece i when machining on machine j;
p^{pub} Power of public equipment;
PS_k Start time of period k;
PE_k Finish time of period k;
PCS_{kv} Electricity consumption standard for v-th price of period k;
y_{kv} Boolean variable, whether the power consumption of period k meets the standard of v, if so, the value is 1, otherwise, it is 0;
P_{kv} The v-th price of period k;
z_{iwjk} Boolean variable, whether machine j processes w operations of workpiece i in K period. If so, the value is 1; otherwise it is 0;
az_{ak} Boolean variable, if assembly node a is assembled in period k, the value is 1, otherwise it is 0;
at_{ak} Assembly time of assembly node a in time k;
t_{iwjk} The processing time of w-channel sequence of machine j processing workpiece i in period k;
R_{jk} The number of times that machine j adopts switch strategy in period k.

2.1 Objective functions

The processing period is divided into machine tool processing energy consumption and idle standby energy consumption. The assembly period has assembly energy consumption, and then the public energy consumption such as lighting is considered.

(1) Machine tool processing energy consumption

Processing energy consumption of machine j in period k:

$$W_{jk}^{mach} = \sum_{i \in I} \sum_{w \in w_i} t_{iwjk} p_{iwj}^{mach} \tag{1}$$

where

$$t_{iwjk} = \begin{cases} t_{iwj}^{mach}, & \sum_{k \in K} z_{iwjk} = 1 \\ EM_{iwju} - PS_k, & SM_{iwju} \le PS_k \le EM_{iwju} \\ PE_k - SM_{iwju}, & SM_{iwju} \le PE_k \le EM_{iwju} \end{cases} \tag{2}$$

(2) Standby power consumption

The standby energy consumption of machine j period k:

$$W_{jk}^{idle} = t_{jk}^{idle} p_j^{idle} + R_{jk} W_j^{re} \tag{3}$$

The machine standby time t_{jk}^{idle}:

$$t_{jk}^{idle} = PS_k - PE_k - \sum_{i \in I} \sum_{w \in w_i} t_{iwjk} - \sum_{i \in I} \sum_{w \in w_i} \sum_{u \in u_j} \left[(S_{i'w'j,u+1} - E_{iwju}) x_{ju} z_{iwjk} \right] \tag{4}$$

(3) Assembly energy consumption

Assembly energy consumption of assembly node a at period k:

$$W_{ak}^{asse} = at_{ak} \times p_a \tag{5}$$

among them:

$$at_{ak} = \begin{cases} t_{ai}^{asse}, & \sum_{k=1}^{K} az_{ak} = 1 \\ EA_{ai} - PS_k, & SA_{ai} \le PS_k \le EA_{ai} \\ PE_k - SA_{ai}, & SA_{ai} \le PE_k \le EA_{ai} \end{cases} \tag{6}$$

(4) Public energy consumption of public equipment including lighting equipment

Public energy consumption for period k:

$$W_k^{pub} = (PS_k - PE_k) p^{pub} \tag{7}$$

In summary, the total energy consumption of workshop in period k is:

$$W_k = \sum_{j \in J} \left(W_{jk}^{mach} + W_{jk}^{idle} \right) + W_k^{pub} + \sum_{a \in A} W_{ak}^{asse} \tag{8}$$

Energy consumption minimization objective function:

$$min \left\{ \sum_{k=1}^{K} \left[P_{k1} W_k + \sum_{v=2}^{V} \left(y_{kv} (W_k - PCS_{kv})(P_{kv} - P_{k,v-1}) \right) \right] \right\} \tag{9}$$

At the same time, the delay time of manufacturing and assembly caused by workpiece processing should be considered. Therefore, the processing time and assembly time of workpiece should be comprehensively considered to establish the second optimization objective:

$$min\left\{\begin{array}{c}\sum_{a\in A}\sum_{i\in I}\left[SA_{ai}-max\left(AT_{ai}\times EM_{iwju}\right)\right]\\+\sum_{a=1}^{A-1}\left[\min\left(SA_{a+1,i}\right)-max\left(EA_{a,i'}\right)\right]+\sum_{i\in I}\sum_{w\in w_i}\left(EM_{iwju}-SM_{i,w-1,j'u'}\right)\end{array}\right\} \tag{10}$$

In summary, the objective function is established as follows:

$$\left\{\begin{array}{l}min\left\{\sum_{k=1}^{K}\left[P_{k1}W_k+\sum_{v=2}^{V}\left(y_{kv}(W_k-PCS_{kv})(P_{kv}-P_{k,v-1})\right)\right]\right\}\\ min\left\{\begin{array}{l}\sum_{a\in A}\sum_{i\in I}\left[SA_{ai}-max\left(AT_{ai}\times EM_{iwju}\right)\right]+\\ \sum_{a=1}^{A-1}\left[\min\left(SA_{a+1,i}\right)-max\left(EA_{a,i'}\right)\right]\\ +\sum_{i\in I}\sum_{w\in w_i}\left(EM_{iwju}-SM_{i,w-1,j'u'}\right)\end{array}\right\}\end{array}\right. \tag{11}$$

2.2 Constraint conditions

Consider the following constraints.

Uniqueness constraint of machines:

$$SM_{i'w'j,u+1}\geq EM_{iwju}+RT_j\times x_{ju} \tag{12}$$

Uniqueness constraint of workpiece:

$$SM_{i,w+1,j'u'}\geq EM_{iwju}+RT_j\times x_{ju} \tag{13}$$

Ensure the continuity of the machining process, once the process begins to process, uninterruptible before completion:

$$SM_{iwju}+t_{iwj}^{mach}=EM_{iwju} \tag{14}$$

$$\sum_{k=1}^{K}t_{iwjk}=t_{iwj}^{mach} \tag{15}$$

Start processing and complete processing tasks within the specified period of time:

$$SM_{iwju}\geq ST \tag{16}$$

$$EM_{iwju}\leq ET \tag{17}$$

Constraints on the number of switching strategies adopted by processing equipment:

$$\sum_{k=1}^{K}R_{jk}=\sum_{u=1}^{u_j}x_{ju} \tag{18}$$

One process for the same workpiece can only select one machine:

$$\sum_{i\in I}\sum_{w\in w_i}o_{iwju}=1 \tag{19}$$

When the processing equipment adopts the switch strategy, the free time meets the minimum time requirement of the processing equipment shutdown once:

$$(SM_{i'w'j,u+1}-EM_{iwju})x_{ju}\geq RT_j \tag{20}$$

When processing equipment adopts switch strategy, standby energy consumption of idle time is greater than that of shutdown once:

$$(SM_{i'w'j,u+1} - EM_{iwju})x_{ju}p_j^{idle} \geq W_j^{re} \tag{21}$$

Start time and finish time of assembly within specified time period:

$$SA_{ai} \geq ST \tag{22}$$

$$EA_{ai} \leq ET \tag{23}$$

Workpiece i completes machining before assembly node needs workpiece i:

$$SA_{ai} \geq max\left(AT_{ai} \times EM_{iwju}\right) \tag{24}$$

The start time of the next assembly node $a + 1$ is less than the end time of the current assembly node a:

$$SA_{a+1,i} \geq EA_{a,i} \tag{25}$$

Ensure the order of assembly requirements on assembly nodes:

$$\left(SA_{a,i'} - EA_{ai}\right)h_{ai'i} \geq 0 \tag{26}$$

Continuity of assembly, that is, once the assembly process begins, it cannot be interrupted before the assembly process is completed:

$$SA_{ai} + t_{ai}^{asse} = EA_{ai} \tag{27}$$

3. Improved multi-objective firefly algorithm

We strive to reduce the energy expenses and production time during the manufacturing and assembly process, which is a common multi-objective optimization challenge. Currently, there are numerous algorithms available for addressing multi-objective scheduling issues, including Genetic algorithm [22, 23], particle swarm optimization [24], migratory bird optimization [25], and firefly algorithm [26]. The firefly algorithm, as a novel swarm intelligence optimization approach, offers benefits such as a straightforward model, fewer adjustable parameters, simple parallel processing, and rapid convergence, and has been successfully applied in various domains.

Considering the complexity of the problem, the standard multi-objective firefly algorithm cannot completely solve the energy-saving integrated scheduling mathematical model established in Section 2, and several important parts of the algorithm need to be redesigned and improved.

3.1 Encoded mode

In this paper, the combined scheduling optimization issue of manufacturing and assembly under the time-based step tariff can be broken down into four sub-problems. The initial sub-problem involves establishing the processing sequence for the workpiece. The second sub-problem is to determine the start time for each process of the workpiece. The third sub-problem is to ensure the completion of workpiece processing and the start time for assembly at the assembly node. The fourth sub-problem occurs during the processing stage, where the machine decides whether to implement a switch strategy after completing the current processing task, based on specific criteria.

According to the four sub-problems, the three-layer coding is designed as follows: The first layer is based on the workpiece sequence coding, including two parts of the workpiece manufacturing and assembly, the assembly process is regarded as a workpiece, considering the precedence constraints of the assembly workpiece; The second layer coding is the starting time of the workpiece, which corresponds to the first layer coding, and also includes the manufacturing and assembly of the workpiece, respectively corresponding to the processing starting time or assembly starting time of the workpiece in the first layer coding. The third layer code is the code whether to adopt the switch strategy, which is whether the current machine adopts the switch restart operation after the workpiece is processed.

It is presumed that there are three pieces of work to be completed, requiring three processing steps and two assembly steps to finish assembly after processing. The viable design solution is depicted in Figure 1. In the first layer, 1, 2, and 3 represent the three workpieces, while 4 and 5 represent the assembly process. The processing sequence is indicated in the first layer's coding sequence. The second layer shows the corresponding start times, and the third layer indicates whether a shutdown restart operation is necessary.

the first layer:	1	2	3	1	3	2	1	3	2	4	5
the second layer:	0	4	4	3	9	8	9	14	18	25	30
the third layer:	0	0	0	1	0	0	0	1	0	0	0

Fig. 1 Schematic diagram of three-layer coding

3.2 Decoding method

In accordance with the specifications of this issue, a single decoding method is not entirely suitable for this problem, which differs from the typical job-shop scheduling problem by taking energy consumption into account. As a result, this study proposes two decoding methods: one based on workpiece sequence and the other based on start time.

(1) Decoding based on workpiece sequence

Decoding based on workpiece sequence is one of the common decoding methods. Decoding for the first layer of coding, the sequence of the workpiece corresponds to the processing sequence of the workpiece. The starting time of the workpiece is determined by the idle time of the workpiece, the idle time of the processing equipment and the processing time of the workpiece, that is, the workpiece and the machine can start processing when they are idle at the same time. After decoding by this decoding method, the maximum completion time of the workpiece can be obtained, and then whether the workpiece can complete the processing task within the specified time can be judged. If the maximum completion time of the workpiece is within the specified time, this solution meets the requirements and can enter the next operation. Otherwise, this solution does not meet the requirements and cannot carry out the next operation. It needs to be iterated again in order to enter the next step.

(2) Decoding based on start time

The decoding based on the start time is to determine the processing sequence of the workpiece according to the coding based on the workpiece sequence in the first layer of the coding, determine the start time of the workpiece according to the coding based on the start time in the second layer, and determine whether the machine performs the shutdown restart operation after finishing the current workpiece according to the coding based on the switch strategy in the third layer. From the decoding operation, it can be seen that in the final feasible solution, the decoding operation based on the start time is adopted.

3.3 Key link

(1) Location update

The location update formula when the firefly *i* is attracted by the brighter firefly *j* and moves to *j* is:

$$x_i = x_i + \beta(d)\left(x_j - x_i\right) + \alpha(rand - \frac{1}{2}) \tag{28}$$

In Eq. 28, x_i and x_j are the spatial positions of individual *i* and individual *j* of firefly ; α is a step factor, which is a constant between 0-1; ‘rand’ is a random number with uniform distribution between 0-1; $\alpha(rand - \frac{1}{2})$ is a random disturbance term to avoid falling into local optimum too early in the population iteration process.

In the multi-objective firefly algorithm, in order to maintain the diversity of Pareto solution set, Yang [27] added a random moving method, that is, a new method of position updating, as shown in Eq. 29:

$$x_i = g^* + \alpha\left(rand - \frac{1}{2}\right) \tag{29}$$

where g^* is the optimal solution in the current population solution space obtained by weighting multiple objective function values according to the random weight (the sum of random weights is 1).

Therefore, in the multi-objective firefly algorithm, the firefly individual has two ways of position updating. When the firefly individual x_i exists in the current population, the position updating operation is carried out according to the Eq. 28. When the firefly individual x_i does not exist in the current solution space, the position is updated according to Eq. 29.

For the discrete domain space encoded by the first layer, when the individual firefly is dominated, the Precedence preserving order-based crossover (POX), which is commonly used in workshop scheduling, is used for crossover operation. This operator can well retain the excellent characteristics of the parent generation, inherit the processing order of the parent generation, and ensure the feasibility of the offspring [28]. If individual fireflies are not dominated, swap (SWAP) operation is adopted.

For the continuous domain space of the second layer coding, the position update operation in the multi-objective firefly algorithm is adopted. If the firefly individual is dominated, the position update is carried out according to Eq. 28. If the firefly individuals are not dominated, they are randomly moved according to Eq. 29 to increase the diversity of Pareto solution set.

(2) Judgement and repair of feasible solution

There are two types of infeasible solutions. The first is the infeasible solution caused by the sequence of the assembly process does not meet the constraints, and the second is the infeasible solution caused by the conflict of the starting time of the workpiece.

The initial solution is not possible due to an infeasible assembly sequence resulting from the interchange operation of the first layer code in the firefly individual. This is caused by constraints in the assembly sequence between the workpiece assembly processes. Therefore, for this kind of infeasible solution, the following feasible solution judgment and repair operation should be implemented.

Step 1: Find the correct assembly sequence constraint;
Step 2: Find the assembly process in the first layer of code by traversal and record the location;
Step 3: Compare the assembly process and assembly sequence constraints in the code, if so, do step 4, otherwise, insert the correct assembly process in turn according to the assembly process location in the code, and return step 2;
Step 4: Output the feasible solution of the first layer encoding.

The second layer coding has an impractical solution due to the requirement that the workpiece's starting time must align with the unique constraints of the processing equipment and the workpiece when they are both idle. In such cases of infeasible solutions, the following determination and repair operations are implemented.

Step 1: Determine whether the second layer code is planned after the start time, if so, the next step; otherwise, the coding that is not within the specified time is set as the planned start time before the next step;
Step 2: The first layer coding is traversed one by one, and the next idle time of the workpiece and the processing equipment is determined according to the current processing status of the workpiece and the processing equipment and the processing time of the workpiece. And determine the feasibility of the second layer encoding corresponding coding, if feasible, the next step, otherwise, with the workpiece and processing equipment at

the next time the idle time to replace the corresponding coding, and then to the next step;

Step 3: Determine whether the second layer code is before the completion time of the plan, if so, go to step 5, otherwise, the code that is not within the specified time range is set as the completion time of the plan, and continue the next step;

Step 4: Inversely traverse the first layer encoding to determine the last idle time of the workpiece and the processing device according to the processing time of the workpiece and the current processing state of the workpiece and the processing device. Determine whether the second layer encoding is feasible, if feasible, take the next step, if not, replace the corresponding encoding with the last free time of the workpiece and processing equipment, and then go to step 1;

Step 5: Output the feasible solution of the second layer encoding.

3.4 Algorithm procedure

The algorithm procedure is designed as follows:

Step 1: Setting initial parameters. m: the number of fireflies, also known as population size, γ : light absorption coefficient, β_0: maximum attraction, α: step size factor, T : population iteration number, and initializing the location of fireflies;

Step 2: Calculate and sort the dominance level and crowding distance for each firefly individual;

Step 3: The individual firefly x_j is selected to update the position of the first layer coding. If the individual x_j is not dominated, SWAP switching operation is performed on the first layer coding. If the individual x_j is dominated, POX crossover operation is performed on the first layer coding;

Step 4: Judge and repair the feasibility of the first layer coding;

Step 5: The maximum completion time of the work piece is obtained by decoding based on the work piece sequence. If the completion time is within the specified time, the next step is continued, otherwise step 3 is returned;

Step 6: Select the firefly individual x_j to update the location for the second layer code: If the individual x_j is not dominated, then move randomly according to Eq. 29; If the individual x_j is dominated, then update the location according to Eq. 28;

Step 7: The feasibility of the second layer coding is judged and repaired, and then the third layer coding is calculated according to the switch strategy requirements, and a firefly individual is obtained;

Step 8: If all firefly individuals have a location update operation, continue the next step, otherwise, return step 3;

Step 9: Implement elite strategy, merge father and son generation to select elite, keep good individual;

Step 10: Determines whether the number of iterations satisfies the population iteration number T, and if so, continues the next step, otherwise returns step 2;

Step 11: Calculate and output Pareto front solution set.

The procedure of the algorithm is shown in the Fig. 2.

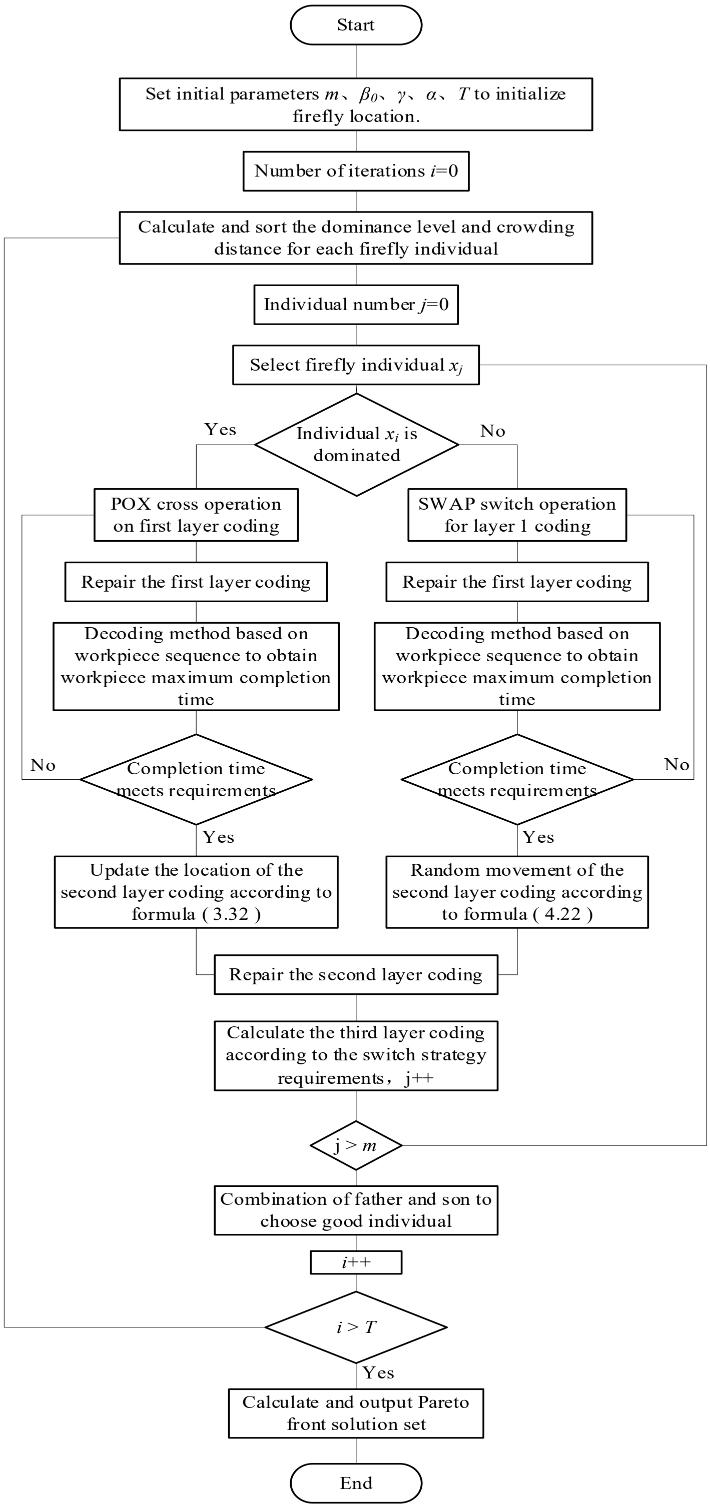

Fig. 2 Flowchart of integrated scheduling algorithm for machining and assembly

4. Results and discussion of case study

4.1 Case study results

The processing-assembly manufacturing enterprise has a mixed-flow production line for processing and assembling, taking into account the time-sharing step price. After creating standard parts in other processing workshops, the personalized core parts are produced and the products are assembled on the mixed-flow production line. For an existing product A, the product structure, as depicted in Figure 3, consists of 8 parts and 6 assembly tasks.

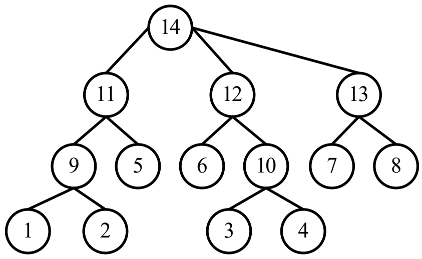

Fig. 3 Product structure diagram

Each workpiece undergoes five processing steps, requiring passage through five processing machines. The processing equipment and time required for each processing step of the workpiece are detailed in Table 1. Six assembly tasks are carried out using three assembly machines. The assembly equipment and time required for each assembly task are outlined in Table 2. Table 3 provides information on the standby power, processing power, shutdown restart power, and time for both the processing and assembly equipment, with the public equipment having a power rating of 5. Assembly tasks must commence after the corresponding processing steps are completed, and assembly and processing tasks can be conducted concurrently.

Table 1 Corresponding processing equipment and processing time for workpiece processing

Workpiece serial number	(Equipment sequence, processing time /min)				
1	(3,73)	(5,68)	(2,64)	(1,64)	(4,79)
2	(3,76)	(2,78)	(5,64)	(1,63)	(4,77)
3	(2,74)	(1,66)	(4,61)	(3,66)	(5,81)
4	(1,75)	(4,62)	(2,69)	(3,61)	(5,79)
5	(2,73)	(1,65)	(5,64)	(3,63)	(4,79)
6	(1,79)	(4,65)	(2,68)	(5,68)	(3,84)
7	(1,76)	(3,67)	(5,69)	(2,72)	(4,75)
8	(2,78)	(1,68)	(3,73)	(4,65)	(5,76)

Table 2 Assembly equipment and assembly time corresponding to the assembly process

Assembly task	9	10	11	12	13	14
Equipment sequence	6	6	7	7	7	8
Length of assembly /min	119	109	119	128	111	115

Table 3 Some parameters of processing and assembly equipment

	Equipment 1	Equipment 2	Equipment 3	Equipment 4
Processing power (kW)	25	28	27	31
Standby power (kW)	4	5	4	3
Shutdown restart time (min)	20	25	30	38
Shutdown restart energy consumption (kWh)	6	9	6	5
	Equipment 5	Equipment 6	Equipment 7	Equipment 8
Processing power (kW)	30	40	45	42
Standby power (kW)	4	5	6	5
Shutdown restart time(min)	40	45	48	55
Shutdown restart energy consumption (kWh)	6	10	14	10

Referring to the current time-sharing electricity price and residential ladder electricity price in Shaanxi Province, assuming that there are two electricity prices in each period, this paper constructs the time-sharing ladder electricity price model. The first stage is normal electricity consumption, and the second stage is high standard electricity consumption. It is concluded that the time-sharing electricity price is shown in Table 4 below. The cut-off point of the step price is 60 kWh per hour, starting at 7 a.m. and requiring completion within one day.

Table 4 Time-sharing tier electricity price period and price list

	Time periods	First-grade electricity price	Second-grade electricity price
Peak hours	8:00-11:00 18:00-23:00	0.9831	1.3131
Normal period	7:00-8:00 11:00-18:00	0.6712	1.0012
Low valley period	23:00-7:00	0.3594	0.6894

According to the model established in section 2 of this paper, the MATLAB algorithm is written, and the program is run on the MATLAB R2014 b version. The population size is 100, the light intensity absorption coefficient γ is 0.5, the maximum attraction β_0 is 1, the step factor α is 0.5, and the number of iterations is 500. The Pareto solution set is obtained, as shown in Figure 4. Statistics were conducted on the target values corresponding to the solutions in the Pareto set, and the results are shown in Table 5.

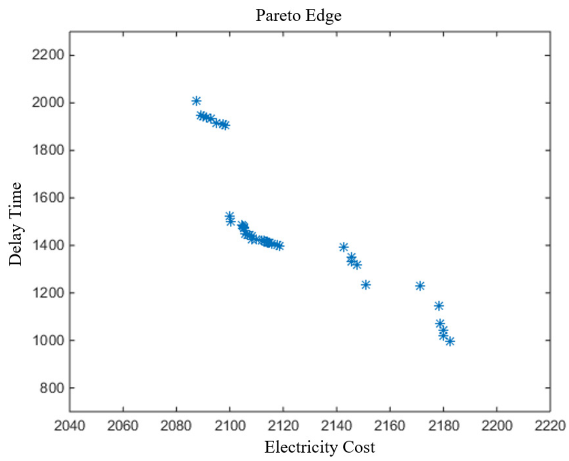

Fig. 4 Pareto Frontier

Table 5 Pareto solution set statistical results corresponding to each target value

Electricity cost (Yuan)			Delay time (min)		
Maximum value	Minimum value	Average value	Maximum value	Minimum value	Average value
2182.4	2087.6	2121.2	2008	997	1472.5

The Gantt chart for the single best solution is depicted in Figures 5 and 6 within the Pareto solution set.

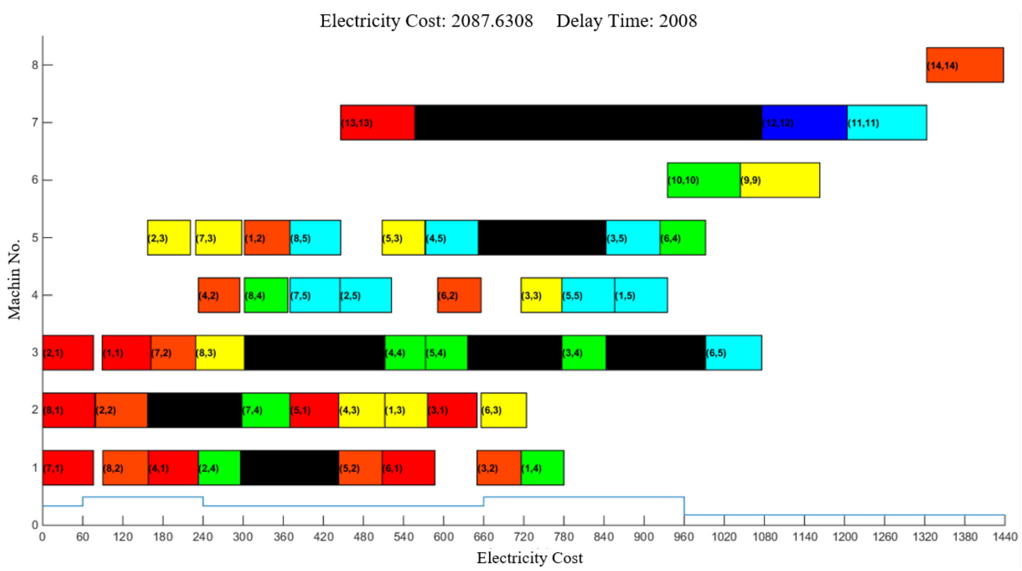

Fig. 5 Pareto solution to the concentrated Gantt chart for optimal power cost

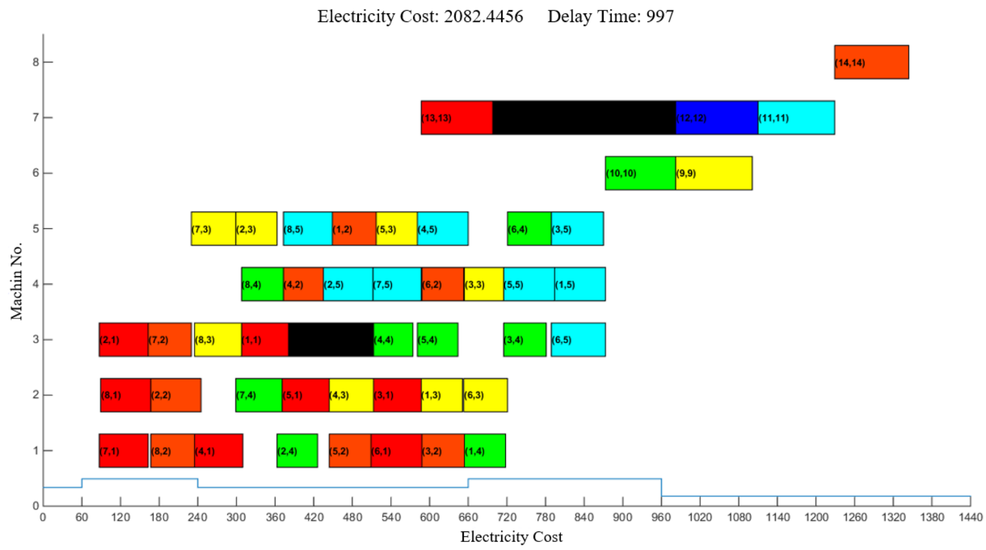

Fig. 6 Pareto solution to the concentrated Gantt chart for optimal delay time

It can be seen from Table 5 and Fig. 4 that the single pursuit of the optimal power cost or the optimal delay time of processing and assembly will lead to another goal too high. When the optimal power cost is 2087, the delay time reaches the high value of 2008, and when the minimum delay time is 997, the power cost reaches the high value of 2182. Therefore, multi-objective integrated scheduling is necessary. From the results of the algorithm, a set of scheduling schemes is obtained for this instance. The scheme set is non-dominated, and the decision makers can select the most suitable implementation scheme according to certain subjective preferences.

As shown in the Gantt chart, the implementation of the switch strategy reduces the power cost in the processing process, and the parallel processing and assembly effectively reduces the waiting time of the components, and completes the assembly task in time in the idle time of the equipment. So as to improve production efficiency and achieve the purpose of energy saving and punctual production.

4.2. Discussion

In the 21st century, manufacturing enterprises cannot overlook the issue of energy-efficient production. The scheduling problem, which takes energy consumption into account, is more intricate and involves a wider range of influencing factors compared to traditional production planning and scheduling. This study focuses on the integrated scheduling problem of machining and assembly in manufacturing enterprises. While this is a conventional issue in production and manufacturing, the study incorporates the time-sharing ladder price and switch strategy to establish a new optimization goal and a comprehensive scheduling model for machining and assembly with the aim of conserving energy. The firefly algorithm is chosen to solve the model, and by adjusting certain aspects, the results are quickly obtained. The example results demonstrate that this method, which considers the parallelism of processing and assembly processes, can effectively utilize equipment resources and reduce power loss during idle equipment, ultimately achieving punctual production and energy savings.

5. Conclusion

This paper considers time-of-use tiered electricity pricing and focuses on integrated scheduling of processing and assembly for mixed flow production lines in processing assembly firms. Establish a mathematical model for this problem and introduce shutdown and restart procedures when the device is idle with the optimization goal of minimizing power consumption costs and delay time during the machining and assembly process. A multi-objective firefly technique based on three-layer encoding was created for the ease of solving the model. Lastly, examples were used to confirm the accuracy of the solving method and the efficacy of the constructed mathematical model. Empirical evidence indicates that the approach put forward in this work yields certain advantages over conventional scheduling techniques for mixed flow production lines that combine processing and assembly. In addition, during peak and off peak hours, the on/off strategy adopted based on the time of use tiered electricity price reduces standby time of equipment, lowers power costs, and achieves the goal of on-time production and energy conservation for enterprises. On the one hand, it reduces waiting delays for components during processing and assembly, and improves production efficiency.

Owing to space constraints, this article ignores the comparison of various techniques and instead concentrates on solving model solving problems. To confirm their superiority, the solution algorithms will be compared and examined in further studies.

Acknowledgments

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