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Optimization for energy-efficient flexible flow shop scheduling under time of use electricity tariffs

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Abstract

With the development of society and economy, the global energy problem has become increasingly critical. Methods for time of use electricity tariffs have been introduced to balance the demand for resource and increase the energy efficiency in manufacturing industry. The scheduling problem for flexible flow shop in the environment of TOU is studied in this paper. An energy consumption model of machine tools is established which involves the processing energy, standby energy and set-up energy for a detailed description of electricity cost in shop-floor. The Improved Strength Pareto Evolutionary Algorithm is employed in which a novel gene encoding considering processing sequence, machine tool and processing time simultaneously is proposed to obtain the Pareto Front of the makespan and electricity cost. A case study is presented and the result shows that the proposed method is applicable for trade-off of electricity cost and delivery time for the purpose of enhanced energy efficiency.

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Keywords: energy efficiency; time of use electricity tariffs; flexible flow shop; electricity cost.

1. Introduction

With the development of sustainable manufacturing, it has been one of the global focuses that reducing energy consumption and improving its efficiency [1]. According to the report of international energy agency, energy cost by industry accounts for about one-third of the total global energy supplied [2]. The energy consumed by manufacturing industry is mainly in the form of electricity [3]. Due to the spikes and dives of the demand for electricity throughout the day, meanwhile the fact that no economically feasible method for its storage, excess equipment such as generators has to be built to meet the peak demand [4, 5]. The unstable capacity utilization decreases the energy efficiency and causes more greenhouse gas emission. Besides curbing the electricity demand, flexible pricing mechanisms have been introduced by many governments to depress the peak consumption, one of which is time of use (TOU) pricing scheme [6].

Existing studies have proved the effectiveness of TOU electricity tariff for reducing energy usage and shifting consumption applied in the field of household and buildings management [7]. However, this pricing method also has a noticeable impact on the electricity cost and energy efficiency in manufacturing. The time when to start the processing and its duration affect the cost of electricity, then the production.

Computerized Numerical Control (CNC) machine tools are the basic equipment of modern manufacturing units for workpieces processing. Product quality and production efficiency are improved a lot with the assistance of perception and automation involved. A significant portion of energy in the workshop is consumed by CNC and its auxiliaries. Therefore, energy consumed by CNC machine tools should be analyzed precisely and they need to be arranged dynamically considering the varying price of electricity for reducing the electricity cost and improving the energy efficiency.

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Multi-objective scheduling models have been proposed to optimize both the time cost of production, known as makespan and electricity cost in shop-floor [8]. Fang et al. [9] studied the single-machine scheduling problem under TOU electricity price. Both the uniform-speed and speed-scaling of processing were considered. These cases are solved in polynomial time. Shrouf et al. [10] studied the single-machine scheduling problem by proposing a mathematical model describing the production processes. Genetic algorithm and heuristic solutions were implemented to obtain a near-optimal solution. The research shows that shifting workload from peak period to off-period is able to significantly reduce electricity cost under the TOU electricity tariff. Furthermore, in the shop level, Lin et al. [3] aimed at minimizing the total electricity consumption and cost under the constraint of production target in a typical manufacturing system containing N-1 buffers and N machines. The binary Particle Swarm Optimization algorithm was applied to obtain a suitable production scheduling plan. The binary coding was applied to describe that the machine is running or not. Another case was given by Luo et al [11]. They proposed a new ant colony optimization meta-heuristic to solve the scheduling problem that considering both the production efficiency and electric power cost in the hybrid flow shop.

Most workshop scheduling problems under TOU electricity price consider the processing order of workpieces with different processing sequences and the selection of corresponding machine tools. In fact, when the delivery constraints are comparatively loose, there are reasons for managers to avoid the peak period and halt the processing until the off-peak period. Besides, the model of electricity cost of the machine tool is not described precisely since the energy consumption in the stand-by period of the machine tool is seldom considered. The process of machine tool operation can be divided into several states including warm-up, stand-by and so on. Changes in machine operation result in the fluctuation of machine tool energy consumption. Therefore, this work addresses these problems for the case of hybrid flow shop by constructing overall models of electricity cost describing the processing energy, standby energy, and set-up energy. A novel gene encoding is proposed to describe the relationship among processing sequence, machine tool, and processing time, which is utilized to trade off the electricity cost and makespan.

2. Modeling of electricity cost for flexible flow shop

2.1. Scheduling problem formulation

The scheduling problem in hybrid flow shop which consists multi-stages and each stage is made up of more than one machine can be described as follows: Total $n\ (1 \le i \le n)$ different jobs with the same processing sequence need to be processed on $s\ (1 \le j \le s)$ serial stages. Each stage in the shop consists of $d_k\,(d_k > 1, k \in \{1,2,\dots m\})$ parallel machines. The energy consumption and processing time of each job on different machine tool are not the same. The work patterns of machine tools are expressed as follows. Each job should be processed on one machine tool no more than once. Whereas each machine should not be interrupted while processing and no more than one job are executed at any time on it. The start time of machine tool operation is when the first job arrives and the end time is when all jobs assigned are finished, during which is running, stand-by or set-up stage. Besides, the cost time of delivering parts from one machine tool to the other is ignored in this paper. The sequence of jobs and their corresponding machine tools should be scheduled simultaneously to meet objectives that the production specifies.

Generally, the indicator for evaluating the performance of shop-floor scheduling is the order tardiness which is the difference between the expected delivery time and the actual one. The following notations are used in this paper:

- i' denotes the job before job i processed on the same machine tool, also known as pre-job of job i.
- j' denotes the stage before stage j processed on the same machine tool, also known as pre-stage of stage j.
- $T_k^{i,j}$ denotes the time cost of the stage j of job i processed on machine tool k which is determined.
- $T_{\max}$ denotes the time when all jobs are finished in the shop.
- $Ft_k^{i,j}$ denotes the time when the stage j of job i is finished on machine k.
- JRt_i denotes the time when the first stage of job i could be processed.
- MRt_k denotes the moment when the machine k is prepared for processing.
- $MFt_k^{i',j'}$ denotes the finished time of one job after which is stage j of job i on machine k.
- It_k denotes the stand-by time of machine tool k.

As one of the efficient indicators, the maximum completion time of jobs, $T_{\max}$, represents the efficiency of operation directly. $T_{\max}$ is calculated by Eq. (1).

$$T_{\max} = \max(Ft_k^{i,j}) \tag{1}$$

In the actual environment of production, the finished time of a job is decided by its starting time and duration on the assigned machine tool. Whereas, the starting time is decided by when the job arrives at the machine tool, when the machine tool is accessible or when the former job is finished. The constraints are as follows:

1) Starting time of the job processed

When there are no pre-process of job and pre-job for machine tool, the starting time $St_k^{i,j}$ is described as follows:

$$St_k^{i,1} = \max(JRt_i, MRt_k), (1 \le i \le n, 1 \le k \le m) \tag{2}$$

When there is the pre-job for the machine tool and no pre-process of job, the starting time is denoted as follows:

$$St_k^{i,1} = \max(JRt_i, MFt_k^{i',j'}), \\ (i \ne i', 1 \le i / i' \le n, 1 \le j' \le s, 1 \le k \le m) \tag{3}$$

When there are the pre-process of job and no pre-job for the machine tool, the starting time is calculated as follows:

$$St_k^{i,j} = \max(Ft_h^{i,(j-1)}, MRt_k), \quad (k \neq h, i = 1,2,\ldots,n, 1 \le j \le s, 1 \le k \le m, 1 \le h \le m) \tag{4}$$

When there are the pre-process of job and the pre-job for the machine tool, the starting time is calculated as follows:

$$St_k^{i,j} = \max(Ft_h^{i,(j-1)}, MFt_k^{i',j'}), \quad (i \neq i', k \neq h, 1 \le i / i' \le n, 1 \le j' \le s, 1 \le k / h \le m) \tag{5}$$

2) Finished time of the job processing

$$Ft_k^{i,j} = St_k^{i,j} + T_k^{i,j}, (1 \le i \le n, 1 \le j \le s, 1 \le k \le m) \tag{6}$$

3) Stand-by time of machine tool

$$It_k = \sum_i (St_k^{i,j} - Ft_k^{i',j}), (1 < i \le n, 1 \le j \le s, 1 \le k \le m) \tag{7}$$

2.2. Electricity cost model in shop floor

In this section, an electricity cost model for hybrid flow shop is presented. Consumed energy in the workshop can be mainly categorized into several parts [12], namely the energy consumption of machine tool, the energy consumption of transportation and overhead. The time cost of transportation is not considered in this paper, and the corresponding cost of electricity is not described in this model. Meanwhile, overhead energy is defined as the energy consumed by auxiliary equipment and supporting facilities, like air conditioning, lighting, and heating. Running conditions of this equipment are affected by the environment and the impact caused by changeable electricity tariffs on the scheduling of these facilities is limited. Therefore, this paper focuses on the scheduling problem of machine tool under TOU electricity tariffs in a hybrid flow shop.

A typical power profile of cutting processes is shown in our previous research [13]. The profile illustrates that a machine tool is at several different states, which are power-on, warm-up, stand-by, set-up and processing. The first four states are fixed for each machine tool and can be obtained by off-line experiments. The energy consumption of workpieces processing is proven to be influenced by the cutting parameters. Concerning the short period and just one time of power-on, the energy consumption of power-on and warm-up state are rationally neglected.

2.2.1. Electricity cost of processing

Electricity cost of processing (C_P) represents electricity cost during machining processes, in which the cost of idle cutting and the material removal cutting are considered. C_P can be calculated by Eq. (8).

$$C_P = \sum_{i=1}\sum_{j=1}\sum_{k=1}\left\{PE_k^{i,j} \bullet \left[\int_{t=0}^{t=T_{\max}} x_k^{i,j}(t) \bullet \alpha(t) \bullet dt\right]\right\} \tag{8}$$

$$x_k^{i,j}(t) = \begin{cases} 1, \text{ the stage } j \text{ of job } i \text{ is processed on} \\ \quad \text{machine } k \text{ at } t \text{ moment} \\ 0, \text{ else} \end{cases} \tag{9}$$

$$\alpha(t) = \begin{cases} p_1 \; t_1 \le t \le t_2 \\ p_2 \; t_2 \le t \le t_3 \\ \cdots \\ p_w \; t_w \le t \le t_{w+1} \end{cases} \tag{10}$$

where, $PE_k^{i,j}$ is the energy consumption per unit time while processing, $t = 0$, $t = T_{\max}$ are the start time and the finished time of processing respectively. $\alpha(t)$ is the function that represents the relationship between the time t and varied electricity price p_w .

2.2.2. Electricity cost of set-up

Electricity cost of set-up (C_U) represents electricity cost during set-up which involves the cost of clamping, positioning, and tool change. It can be calculated by Eq. (11).

$$C_U = \sum_i \sum_p \sum_j \sum_k \{ SE_k^{(i',j),(i,j)} \bullet [\int_{t=0}^{t=T_{\max}} y_k^{(i',j),(i,j)}(t) \bullet \alpha(t) \bullet dt]\} \tag{11}$$

$$y_k^{(i',j),(i,j)}(t) = \begin{cases} 1, \text{ the adjustment from job } i' \text{ to job } i \\ \quad \text{for stage } j \text{ on machine } k \text{ at moment } t \\ 0, \text{ else} \end{cases} \tag{12}$$

where, $SE_k^{(i',j),(i,j)}$ is energy consumption per unit time for adjusting from job i to job j on machine k .

2.2.3. Electricity cost of stand-by

Electricity cost of stand-by (C_B) defines the cost when a machine waits for the next job and it can be calculated by Eq. (13).

$$C_B = \sum_k \left\{WE_k \bullet \left[\int_{t=0}^{t=T_{\max}} z_k(t) \bullet \alpha(t) \bullet dt\right]\right\} \tag{13}$$

$$z_k(t) = \begin{cases} 1, \text{ machine } k \text{ is standing by at moment } t \\ 0, \text{ else} \end{cases} \tag{14}$$

where WE_k is energy consumption per unit time when machine k is waiting.

2.3. Objective functions

For a given schedule, the total electricity cost can be calculated as:

$$C_{Total} = C_P + C_U + C_B \tag{15}$$

where C_{Total} stands for the total electricity cost of hybrid flow shop. On the basis of models for electricity cost and makespan, the multi-objective optimization problem for energy-efficient scheduling is described in the form:

$$\begin{cases}\min(T_{\max}) = \min(\max(Ft_k^{i,j})) \\ \min(C_{Total}) = \min(C_P + C_U + C_B)\end{cases} \tag{16}$$

subject to

$$T_{\max} \le DT \tag{17}$$

$$Ft_k^{i,j} = St_k^{i,j} + T_k^{i,j},\ 1 \le i \le n; 1 \le j \le s; 1 \le k \le m \tag{18}$$

$$Ft_k^{i,j} \le St_k^{i,(j+1)},\ 1 \le i \le n, 1 \le j \le s, 1 \le k \le m \tag{19}$$

$$\sum_i X_k^{i,j} \le 1,\ j = 1,2,\ldots,s,\ k = 1,2,\ldots m \tag{20}$$

$$\sum_k Y_k^{i,j} \le 1,\ \ i = 1,2,\ldots n,\ j = 1,2,\ldots,s \tag{21}$$

where, $X_k^{i,j} \in \{0,\ 1\}$, $X_k^{i,j} = 1$ means that job i at stage j begins to be processed on machine k , while $Y_k^{i,j} \in \{0,\ 1\}$, $Y_k^{i,j} = 1$ means that the stage j of job i is processing on machine k .

The objective function (16) describes the multi-objective as makespan and the electricity cost. Constraint (17) ensures that the makespan of the whole processing is less than delivery time. Constraint (18) defines that the processing cannot be interrupted and (19) imposes that one job cannot be processed at the next stage before finished at the current stage. Constraints (20) and (21) ensure that each job only can be processed on one machine tool at each stage.

3. SPEA2 based multi-objective optimization

To handle with the complexity of dimension processing and subjectivity of weight setting for multi-objective, the improved strength Pareto evolutionary algorithm (SPEA2) is chosen. As one of the typical evolutionary algorithms, SPEA2 is based on the concept of Pareto to search the set of non-dominated solutions in which each solution is not better than others in this set [14]. There are some disadvantages of SPEA. On the one hand, all the individuals in each generation have the same fitness, which cannot be used to describe the superiority or inferiority of each individual, let alone guarantee the dispersion and representativeness of solutions; on the other hand, typical solutions are often ignored when the representative solutions are filtered through clustering. In view of these disadvantages above, the way of assigning fitness is improved formulating the SPEA2. The overall procedure of SPEA2 is shown in Fig. 1.

A novel gene encoding is proposed to describe the relationship among processing sequence, machine tool and processing time. Considering the fact that processing in different periods of time has a great different impact on electricity cost under TOU environment, this paper has taken the starting time of each stage along with the processing sequence and machine tool into consideration. Assuming that the operation of processing is uninterruptible, once the start time of the process is determined and the corresponding electricity tariff period can be immediately determined. Therefore, based on the hybrid two-level gene encoding which combines the processing sequence and the machine tool, the third level referring to starting time is added to form a hybrid three-level structure of the chromosome.

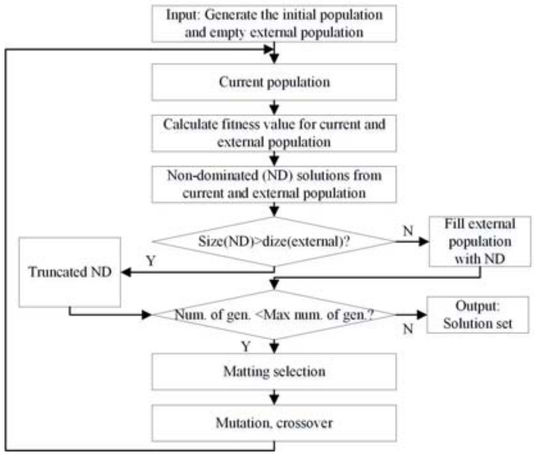

Fig. 1. Flow chart of SPEA2 algorithm.

As shown in Fig. 2, the first level of the chromosome encodes processing sequence of each job. The second level specifies the selected machine tool. The third level denotes the starting time of each stage which is arranged from small to large according to the sequence of the job. Code 201 in the first level of the chromosome means stage 1 of job 2. Machine tool 2, 3, 5 and starting time 0, 8, 18 for job 1 represents that the stage 1, 2, 3 of job 1 are processed on machine 2, 3, 5 at the moment 0, 8, 18 respectively. These three levels of encoding are combined together to determine the starting time of job with a unique processing sequence and machine tool.

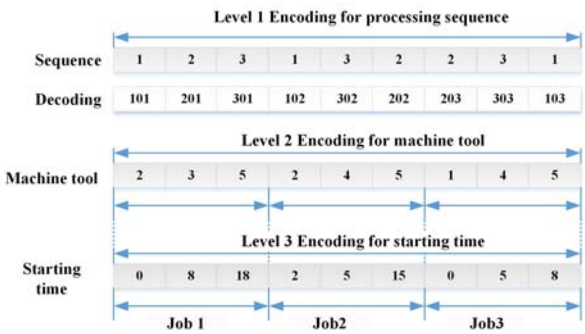

Fig. 2. Structure for three-level chromosome encoding.

4. Experiments and analysis

In order to validate the proposed electricity cost model and chromosome encoding, the scheduling of 6 jobs in a hybrid flow shop containing 4 stages was examined. For each stage, there are 2 machine tools respectively. The average processing time and power demanded each job on each machine tool are listed in Table 2 whose data are measured from Hass and Hoch machine tools while processing different workpieces. Here the set-up time is ignored for the similarity of each job. Meanwhile, the power of stand-by for each machine tool are listed in Table 1.

Table 1. Power of Stand-by for each machine tool.

Machine tool	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
Power (kW)	0.40	0.51	0.41	1.02	0.40	0.51	0.40	0.51

Table 3 shows the electricity cost of unit energy (kW) consumed per hour referring to the actual pricing mechanism of electricity of Beijing and the period each price lasts. Considering the makespan of our experiments, the duration of each period in Table 3 only represents the relationship between each stage, which is different from the actual one.

The SPEA2 was employed to find the Pareto front of makespan and electricity cost. The relevant parameters of the algorithm are set as follows: the population size is 200, the number of iterations is 200, the crossover rate is 0.95, and the initial mutation rate is 0.1. The algorithm is coded in MATLAB software. A Core i5-8400 2.8GHz computer with 8GB RAM was used to do the experiment.

Table 2. Average processing time and power demand for each job.

Jobs	Average processing time (min) / Average power demanded (kW)							
	Stage 1		Stage 2		Stage3		Stage4	
	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
1	5/1.25	4/1.75	4/2.51	3/3.48	3/1.15	2/1.60	2/1.19	1/1.98
2	7/1.45	5/1.80	4/2.45	3/3.52	7/1.32	5/1.75	3/1.29	2/1.87
3	9/1.40	6/1.78	6/2.65	4/3.72	5/1.28	41.72	3/1.29	2/1.86
4	10/1.35	8/1.82	6/2.25	4/3.86	8/1.25	6/1.76	3/1.29	2/1.85
5	12/1.37	7/1.85	5/2.02	3/3.78	9/1.20	7/1.68	4/1.32	3/1.68
6	18/1.48	12/1.95	8/2.35	6/3.45	15/1.30	12/1.85	5/1.35	4/1.72

Table 3. The TOU pricing profile.

Period	Electricity price period	Electricity price duration (min)	Electricity price (￥/kW·h)
1	Off-peak	30	0.3784
2	On-peak	10	1.4002
3	Mid-peak	30	0.8745
4	On-peak	20	1.4002
5	Off-peak	30	0.3784

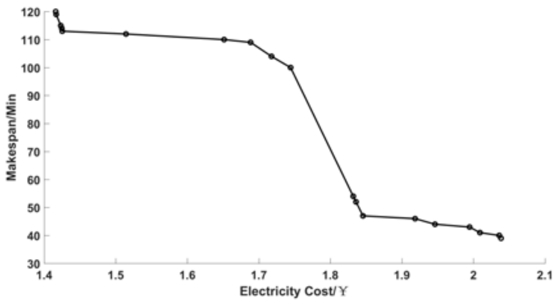

Fig. 3. The Pareto Front of makespan and electricity trade-off.

A total of 19 schemes were obtained based on the mentioned algorithms and these schemes formed the Pareto Front of makespan and electricity cost which is shown in Fig. 3. Results of these schemes are shown in Table 4. Three schemes 1, 10 and 19 among 19 scenarios were chosen for comparison to reveal impacts caused by electricity tariff and time which represents the consideration of the electricity price only, both the electricity price and makespan, and the makespan only. The identifier of each block is consistent with the chromosome mentioned above. Lines at the top of the Gantt denotes the varying electricity price.

According to the Gantt charts, in order to ensure the minimum electricity cost, all the processes are preferentially arranged in the off-peak period, meanwhile, machine tools whose energy consumption are comparatively lower are chosen. With the shortening of delivery time, processing only in the off-peak period no longer satisfies specifications and the mid-peak period is selected. When jobs must be processed in the on-peak period to meet the delivery time constraint, jobs are placed on low-energy machines during high-price periods. All the results are consistent with the rule of scheduling priority that the job is arranged on the machine tool whose energy consumption is comparatively lower in the off-peak period with the makespan constraint considered.

Table 4. Results of 19 schemes on energy and electricity cost.

Schemes	C_{max}(min)	SE (kJ)	Increase in SE (%)	EC (￥)	Increase in EC (%)
1	120	14161.2	-	1.42	-
2	119	14167.8	0.05	1.42	0.00
3	115	14232.0	0.50	1.42	0.00
4	114	14246.4	0.60	1.42	0.00
5	113	14253.0	0.65	1.43	0.70
6	112	15143.4	6.94	1.51	6.34
7	110	14319.6	1.12	1.65	16.62
8	109	14689.8	3.73	1.69	19.01
9	104	14410.2	1.76	1.72	21.12
10	100	14776.2	4.34	1.74	22.53
11	54	14454.6	2.07	1.83	28.87
12	52	14724.0	3.97	1.84	29.56
13	47	14724.0	3.97	1.85	30.28
14	46	15142.8	6.93	1.92	35.21
15	44	14788.2	4.43	1.95	37.32
16	43	14536.2	2.65	1.99	40.14
17	41	14496.6	2.37	2.01	41.55
18	40	14584.2	2.99	2.04	43.66
19	39	14590.8	3.03	2.05	44.37

As shown in Fig. 4, the on-peak and mid-peak periods are all avoided when the constraint of makespan is comparatively loosed. Results of Scheme 19 indicate that the minimum time is 39min and electricity cost of this scheme is 44.3% higher than Scheme 1 whose makespan is 120min. In Fig. 4, all jobs are processed during off-peak period to decrease the electricity cost. There is a tendency that more jobs are arranged during on-peak or mid-peak period from Figs. 4 to 6. It is shown that the existence of high electricity price has a great impact on the electricity cost. Therefore, under the TOU environment, managers are able to reasonably arrange production schedule according to the delivery time while satisfying specification customers, minimizing total electricity costs, and obtaining economic benefits.

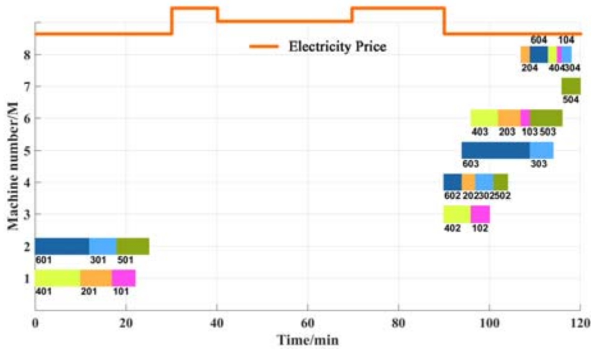

Fig. 4. The Gantt chart of S.1 with makespan of 120 minutes.

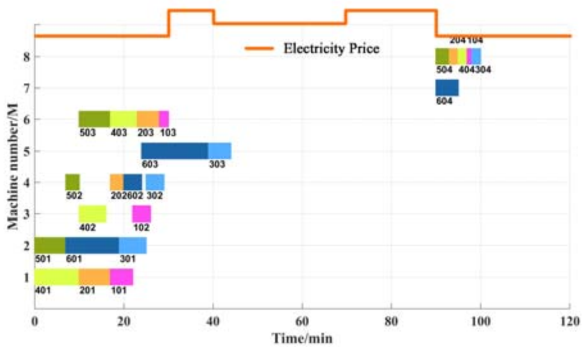

Fig. 5. The Gantt chart of s.10 with makespan of 100 minutes.

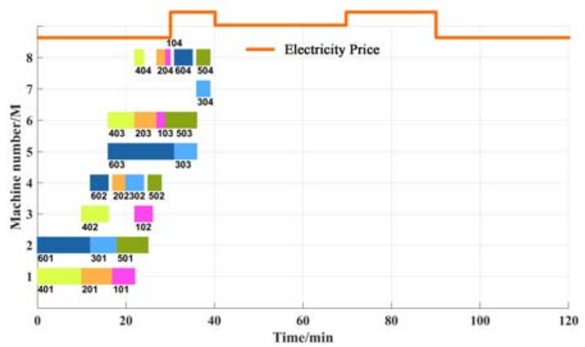

Fig. 6. The Gantt chart of S.19 with makespan of 39 minutes.

5. Conclusions

The optimization problem for energy-efficient flexible flow shop under TOU environment was discussed in this paper. Electricity model of shop-floor which was more detailed and precise considering the set-up, stand-by and processing state of the machine tool was established. The improved three-level chromosome encoding was presented to denote the processing sequence, machine tool and starting time of processing which enabled them to be scheduled simultaneously. The Pareto Front of makespan and electricity cost was generated through SPEA2. The proposed method is able to make a trade-off between the electricity cost and delivery time. It is also indicated that transferring production activity from the on-peak period to off-peak or mid-peak is able to reduce the electricity cost which enhances the energy efficiency. This transformation relieves the pressure of power supply for a more sustainable environment.

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