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Integrated Production and Maintenance Scheduling using Memetic algorithm under Time-of-use Electricity tariffs

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Abstract: *In response to the actual needs of manufacturing enterprises for energy reduction, energy-efficient scheduling has received more and more attentions. Most research on energy-efficient scheduling in literature only consider scheduling jobs on machines. This paper investigates an integrated production and maintenance scheduling problem under time-of-use electricity tariffs to minimize total energy consumption. We consider the flexible periodic maintenance strategy and model the integrated scheduling problem as a mixed integer program model. A memetic algorithm is proposed based on genetic algorithm with a parallel local search structure enabled by simulated annealing and tabu search. The parallel local search structure achieves high-quality exploitation ability in jumping out local optimum. A two-segment coding operator is proposed taking into account both job and maintenance scheduling decisions. Besides, a novel stacking adjustment strategy is presented to improve the search efficiency of the MA. By comparing to the optimal solutions by CPLEX, the performance of the MA is verified.*

Keywords: *Time-of-use electricity tariffs, memetic algorithm, production scheduling, preventive maintenance*

1 Introduction

Energy shortages have become a bottleneck restricting the economic development of many countries. Manufacturing industry is facing unprecedented resource and environmental pressure due to its energy consumption characteristics such as high energy consumption and low energy efficiency. In recent years, the concept of Green manufacturing (GM) has gradually emerged and become an important paradigm in the transformation and upgrading of manufacturing.

The time-of-use electricity tariffs (TOU) is a demand-side power load management method that guides users to achieve a balanced output of power loads by formulating different power price ranges. In this mechanism, there are multiple electricity tariffs slots with different unit electricity prices in one day. Generally, the electricity tariffs during peak periods can reach two to three times compared to that during low peak periods. Electricity suppliers use the TOU to stimulate consumers to adjust their peak hours of electricity demand to other periods with lower prices, thereby reducing the peak-to-average ratio (PAR) of the demand load curve.

Under the TOU, how a company reasonably schedules production tasks have a huge impact on the company's power consumption. In the context of time-of-use electricity tariffs.(Moon & Park, 2014) studied the mixed processing shop scheduling problem under the TOU, and established two discrete-time mathematical models to minimize the weighted sum of the maximum completion time and the total electricity cost. (Luo et al., 2013)proposed a multi-objective ant colony optimization meta-heuristic algorithm for the mixed flow shop scheduling problem of TOU to minimize the weighted sum of total completion time and total electricity cost. (Sharma et al., 2015) studied the variable processing speed scheduling problem under the TOU and used a multi-objective meta-heuristic optimization algorithm to minimize the total electricity cost and environmental impact. (Fang et al., 2013)studied the single-machine scheduling problem considering the TOU under the assumptions of constant processing speed and variable processing speed, and proved that the problem is a strong NP-hard problem. (Che et al., 2016) investigated a single machine scheduling problem under TOU tariffs to minimize the total electricity cost. A new continuous-time MILP model was developed. Based on the property analysis of the problem, an efficient greedy insertion heuristic was proposed. (H. Zhang et al., 2014)studied the flow shop scheduling problem under the time-of-use electricity price model, and established a discrete-time integer programming model to simultaneously minimize the total electricity cost and carbon dioxide emissions.

Obviously, most of the energy-saving scheduling research under the TOU does not consider machine failures and machine maintenance. However, machine failures and machine maintenance are common in actual production and are closely related to production scheduling. In order to reduce the impact of machine failures on production, most companies will adopt preventive maintenance strategies(Allaoui et al., 2008). Preventive maintenance aims to prevent failures. Through the inspection and detection of equipment, the signs of failure are discovered in advance, and preventive equipment maintenance is performed to keep the equipment in the specified functional state and avoid shutdown maintenance that seriously affects production.

Therefore, this paper integrates production scheduling and maintenance scheduling. For the single machine-type shop, under the TOU, we adopt the flexible periodic maintenance strategy, and use the delivery date as a hard constraint to study the integrated scheduling problem of production and machine maintenance to minimize the objective of power consumption.

First, we establish a mixed integer program (MIP) model for the integrated scheduling problem. Considering the complexity of the problem, we propose a memetic algorithm (MA) based on the population-based search of genetic algorithm (GA). We propose a two-segment coding operator to realize the integrated decision-making of job sequence and processing interval. A parallel local search enabled by simulated annealing (SA) and tabu search (TS) is embedded in the GA, which improves the algorithm's exploration and exploitation capabilities(Q. Zhang et al., 2012).

2 An integrated Model for production and maintenance scheduling under TOU

2.1 Problem description

Assume that an order has n independent jobs, the processing time of job i is t_i, and the power consumption per unit time of job i is c_i ,. The due date of the order is $d_{\max}$, that is, the completion time of all jobs of the order must be less than $d_{\max}$.

All the jobs are processed in a single machine. In order to avoid accidental failures of machine, a strategy of flexible periodic maintenance is adopted. The flexible periodic maintenance strategy stipulates the shortest continuous running time and the longest continuous running time of the machine; that is, the time interval between two consecutive maintenance must be not less than v and not greater than u.

Consider order production under the time-of-use electricity tariffs mechanism. This paper adopts the piecewise TOU pricing mechanism. For example, the electricity tariff cycle is 24 hours, and there are 4 electricity tariffs intervals in the cycle, and the length of each interval may not be equal. Based on this mechanism, jobs arrangement in different electricity tariffs intervals have different processing costs. Assume that the start time of the k electricity tariffs interval is b_k , the end time is b_{k+1} , and the corresponding electricity tariffs is p_k . If the processing time of the job in the k electricity tariffs interval is t_i , the power cost of the job is $t_i p_k$.

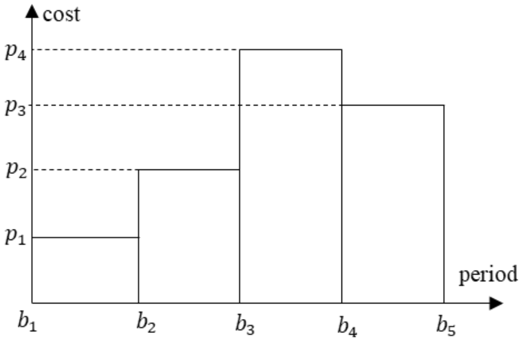


Figure 1: Schematic diagram of TOU mechanism.

In addition, the problem also satisfies the following assumptions.

(1) Jobs processing and machine maintenance cannot be interrupted.

(2) The machine can process at most one job at any time.

(3) The job is allowed to be produced across the electricity tariffs interval, but it must be processed continuously without interruption.

(4) The job processing starts from time zero.

(5) Maintenance work can be carried out across intervals. And every maintenance time is less than the length of any electricity tariffs interval.

The goal of the integrated energy-efficient scheduling for production and maintenance is determine the processing sequence of the jobs and its start and end time, and formulate a flexible maintenance plan for the machine (the number of machine maintenance and its start and end time) to minimize the total electricity cost (TEC) of order processing under the TOU mechanism.

In order to coordinate the scheduling of order jobs and machine maintenance, this paper regards the flexible periodic maintenance of the machine as special jobs. The processing time of the job is t_i .which has processing time is t_0 but does not consume power. Due to the flexible maintenance strategy, the time interval between two consecutive maintenance must be not less than v and not greater than u . In order to reduce the impact of switch on and off on production efficiency, the number of maintenances should be minimized under the premise of ensuring the flexible periodical maintenance strategy of the machine. according the order lead time $d_{\max}$ can be calculated that the scheduling plan requires at least maintenance times. We set the number of maintenances is m .

$$\begin{cases} m \geq \lceil d_{\max} / u \rceil \\ mt_0 + \sum_{i=1}^{n} t_i \leq d_{\max} \end{cases} \tag{1}$$

2.2 Modelling

Parameter:

$d_{\max}$: Order lead time

n : Number of order artifacts

m : Number of maintenance parts

N : Total number of jobs (total number of order jobs and maintenance jobs)

M : The number of electricity tariffs intervals.

t_i : The processing time of the job.

c_i : The unit power consumption rate of the job.

$c_i = 0; n < i \le N$: The unit power consumption rate of the maintenance job.

$t_i = t_0; n < i \le N$: Time to maintain artifacts.

v : The shortest time interval between two maintenance.

u : The longest time interval between two maintenance.

b_k : The start time of the first electricity tariffs interval.

b_{k+1} : End time of the first electricity tariffs interval.

p_k : The electricity tariffs in the k-*th* electricity tariffs interval.

A : Infinite number.

Decision variables:

$x_{i,k}$: The processing time of the job in the electricity tariffs range, $1 \le k \le M, 1 \le i \le N$

$y_{i,k}$: 0-1 variable, if the job is processed in the electricity tariffs range, its value is 1, otherwise it is 0. $1 \le k \le M, 1 \le i \le N$

The MIP model:

$$\min TEC = \sum_{i=1}^{N}\sum_{k=1}^{M} p_k c_i x_{i,k} \tag{2}$$

$$\sum_{k=1}^{M} x_{i,k} = t_i ; 1 \le i \le N \tag{3}$$

$$x_{i,k} \le t_i y_{i,k} ; 1 \le i \le N, 1 \le k \le M \tag{4}$$

$$\sum_{i=1}^{N} x_{i,k} \le b_{k+1} - b_k ; 1 \le k \le M \tag{5}$$

$$y_{i,k} + y_{i,k+1} + y_{j,k} + y_{j,k+1} \le 3; 1 \le i \le N, 1 \le j \le N, 1 \le k \le M-1, i \ne j \tag{6}$$

$$\sum_{k=h+1}^{l-1} y_{i,k} \ge (l-h-1)(y_{i,l} + y_{i,h} - 1); 1 \le i \le N, 3 \le l \le M, 1 \le h \le l-2 \tag{7}$$

$$x_{i,k} \ge (y_{i,k-1} + y_{i,k+1} - 1)(b_{k+1} - b_k); 1 \le i \le N, 2 \le k \le M-1 \tag{8}$$

$$\sum_{i=1}^{n}\sum_{h=1}^{k} x_{i,h} \ge v y_{n+1,k} ; 1 \le k \le M \tag{9}$$

$$-A\left(1 - y_{n+1,k}\right) + \sum_{i=1}^{n}\sum_{h=1}^{k} x_{i,h} \le u; 1 \le k \le M \tag{10}$$

$$\sum_{h=1}^{k} y_{i,h} - \sum_{h=1}^{k} y_{i+1,h} \ge 0; n+1 \le i \le N-1, 1 \le k \le M \tag{11}$$

$$\sum_{j=1}^{n}\sum_{h=k}^{l}x_{j,h} \geq v\left(y_{i,k}+y_{i+1,l}-1\right); n+1 \leq i \leq M-1, 1 \leq k \leq M-1, k<l<M ; \tag{12}$$

$$-A(2-y_{i,k}-y_{i+1,l})+\sum_{j=1}^{n}\sum_{h=k}^{l}x_{j,h} \leq u; n+1 \leq i \leq N-1, 1 \leq k \leq M-1, k \leq l \leq M \tag{13}$$

$$-A(1-y_{N,k})+\sum_{i=1}^{n}\sum_{h=k}^{M}x_{i,h} \leq u; 1 \leq k \leq M \tag{14}$$

The objective function (2) is to minimize the total power cost of order processing, TEC. Constraint (3) indicates that a job may be processed in multiple electricity tariffs intervals, but the sum of the time in each interval should be equal to the processing time of the job. Constraint (4) means that the processing time of a job in a certain electricity tariff interval cannot exceed the processing time of the job; if a job is not processed in a certain electricity tariff interval, the processing time of the job in the electricity tariff interval should be 0. Constraint (5) imposes that the total processing time of all jobs in any electricity tariffs interval cannot exceed the length of the electricity tariffs interval, and ensures that the job processing does not overlap. Constraint (6) means that for any two adjacent electricity tariffs intervals k and $k+1$, at most one job can be processed in both electricity tariffs intervals at the same time, which restricts that only one job can be processed across the boundary between electricity tariffs intervals. Constraint (7) means that if a job is processed across multiple electricity tariffs ranges, these electricity tariffs ranges must be connected; constraint (8) means that only if the job processing time is greater than a certain electricity tariffs range, will the job cross the electricity tariffs range; at the same time; Constraints (7) and (8) ensure that the continuous processing of the job is not interrupted.

Constraint (9) and constraint (10) ensure the time interval requirement of the first maintenance, requiring the machine to process the job from time 0, and the total time for processing the job must not be less than v and not greater than u . Constraint (11) means that the i-*th* maintenance must be before the $i+1$-*th* maintenance. Constraint (12) and constraint (13) ensure the time interval requirement for the i-*th* maintenance, the total time of processing jobs between intervals must not be less v than and not greater than u . Constraint (14) requires that the job processing time after the last maintenance work cannot be greater than u , otherwise this maintenance is not the last one.

3 Memetic algorithm

3.1 Algorithm design ideas and structure

Most of single scheduling problems under TOU mechanism are difficult to solve, which have been proved to be a typical NP-Hard problem by (Fang et al., 2016). Considering the complexity of our model integrating production and maintenance under TOU, this paper proposes an MA solution algorithm. The proposed MA uses a GA-based search framework. GA has the characteristics of good robustness and strong versatility, and is an effective algorithm for solving many scheduling problems (Wu, 2018).

However, the GA is easy to fall into a local optimum (R. Zhang & Chiong, 2016). This paper embeds two local search algorithms, TS and SA into the GA framework, and proposes an MA solution algorithm. The algorithm has the following three innovations:

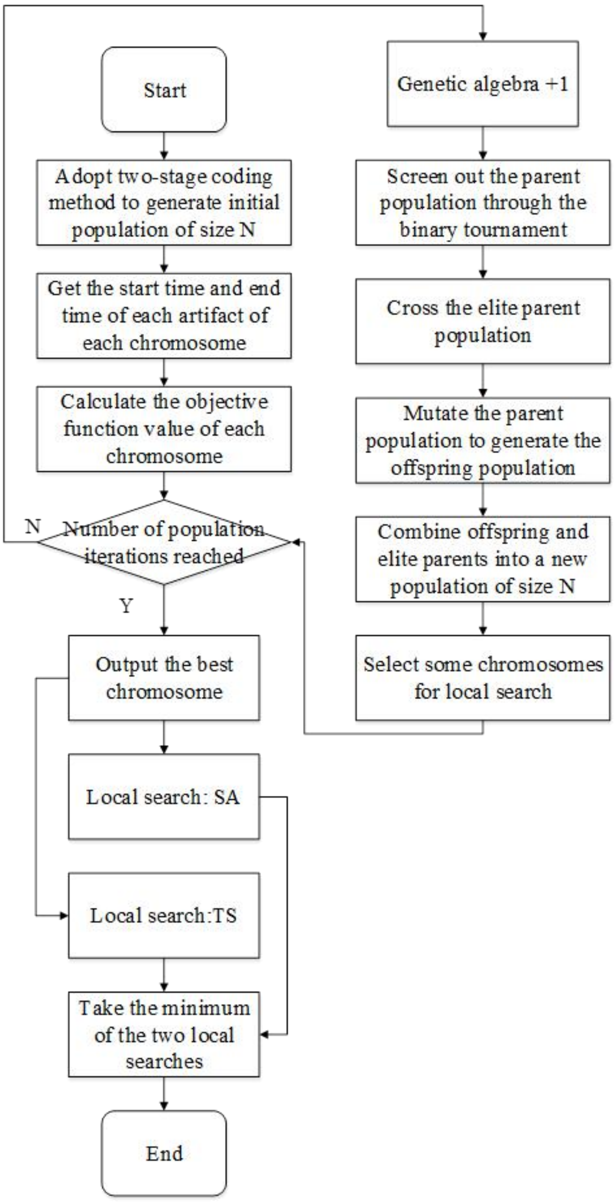


Figure 2: Flowchart of the MA.

(1) Parallel local search framework. On the basis of the results of the GA, the local optimal solution can jump out through the parallel local search enabled by TS and SA to reduce the error between the solution result and the optimal solution.

(2) Stacking adjustment strategy. Under the same job processing sequence, the difference in electricity prices is mainly caused by the different time intervals between the jobs. The local search algorithm is inserted in the algorithm solving process to improve the quality of chromosomes, and the time interval of adjacent jobs is dynamically adjusted. Compare the value of the objective function before and after adjustment to find a better chromosome.

(3) Penalty function-based search strategy. Due to the limitation of maintenance work, it is difficult to obtain qualified initial chromosomes when the problem is large. For this reason, the algorithm adds a penalty function in the decoding process to detect whether the total time length of the job between each two maintenance tasks meets the length of the maintenance interval. If it is not satisfied, the corresponding penalty value is added to the objective function value to reduce the probability of a chromosome being inherited.

The GA contains the time arrangement and sequence of the artifacts of the scheduling result information. In our algorithm, the sequence of all the artifacts and the start time of work need to be obtained through coding. If the sequence of job processing and the length of the interval between two adjacent jobs are determined, and the processing time of each job is combined, the starting time of each job in the scheduling time period can be obtained.

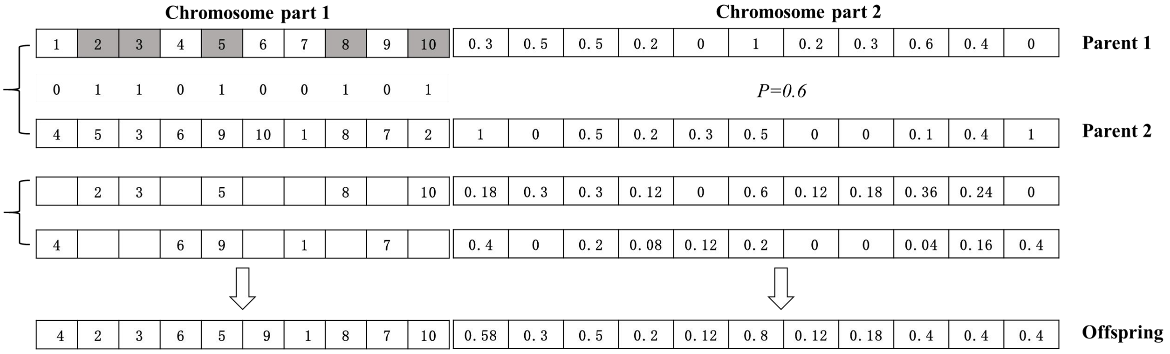
3.2 GA-based search framework

(Cui et al., 2019)used two-stage coding for job shop scheduling problems under TOU. In a scheduling problem with n processing job, the length of the encoding chromosome is $2n+1$, the 1 to n positions are the number of the randomly generated jobs, and the $n+1$ positions behind represents the time interval between two randomly generated jobs that are adjacent to each other, and the sum of all intervals should be equal to the total scheduling time minus the necessary processing time for all jobs, we called it is EM . The sequential combination of jobs processing time and interval can further obtain the start processing time and end time of each job, which is used to solve the electricity cost of each job in the sorting.

Chromosome part 1										**Chromosome part 2**										
4	5	3	6	9	10	1	8	7	2	1	0	0.5	0.2	0.3	0.5	0	0	0.1	0.4	1

Figure 3: Coding diagram.

The algorithm uses binary tournament selection operator. First, we randomly selected two chromosomes A and B from the population, and chose the chromosome with a small objective function value to enter the elite parent population. After n times selection, the elite parent population of size n is obtained, and the offspring population is obtained through crossover of this population. Because the coding of the initial population adopts a two-stage format, the two preceding and following genes cannot cross each other. For the previous paragraph genes, we randomly generate a Boolean variable code of length n , and place the gene at the corresponding position of the A chromosome at the position where the corresponding code of the Boolean variable is 1, which is the number of a certain job. Then we search and delete the job codes that have been placed in the B chromosome. If there are i positions with the code 1, there are $n-i$ position that needs to be selected from the B chromosome and placed in the progeny population. Finally, we randomly generate a probability number p ,and multiply all the second part genes on the A chromosome with p , all the second part genes on the B chromosome with $p-1$, and add the corresponding positions of the second part genes of the two chromosomes to obtain the offspring population. Get the interval between new artifacts in the offspring population. Repeat this method to $N/2$ times get the number of progeny population.



Chromosome part 1										**Chromosome part 2**											
1	2	3	4	5	6	7	8	9	10	0.3	0.5	0.5	0.2	0	1	0.2	0.3	0.6	0.4	0	**Parent 1**
0	1	1	0	1	0	0	1	0	1	*P=0.6*											
4	5	3	6	9	10	1	8	7	2	1	0	0.5	0.2	0.3	0.5	0	0	0.1	0.4	1	**Parent 2**
	2	3		5			8		10	0.18	0.3	0.3	0.12	0	0.6	0.12	0.18	0.36	0.24	0	
4			6	9		1		7		0.4	0	0.2	0.08	0.12	0.2	0	0	0.04	0.16	0.4	
4	2	3	6	5	9	1	8	7	10	0.58	0.3	0.5	0.2	0.12	0.8	0.12	0.18	0.4	0.4	0.4	**Offspring**

Figure 4: Crossover operator.

3.3 Stacking adjustment strategy

In the process of GA, the adjacent time interval of all chromosomes will be adjusted every fixed algebra, and the interval will be expanded as much as possible during the period of higher electricity tariffs. Processing and production will not be carried out in the interval of high electricity tariffs. The interval in the time period should be 0 as much as possible, and the job should be arranged in the time period with low electricity tariffs as much as possible. After many experiments, it was found that this method can quickly reduce the minimum energy cost of chromosomes. However, it is necessary to test every time interval of all chromosomes, which takes a long time, and the effect of frequent detection and adjustment is not obvious. We choose to adjust every 20 or 10 generations.

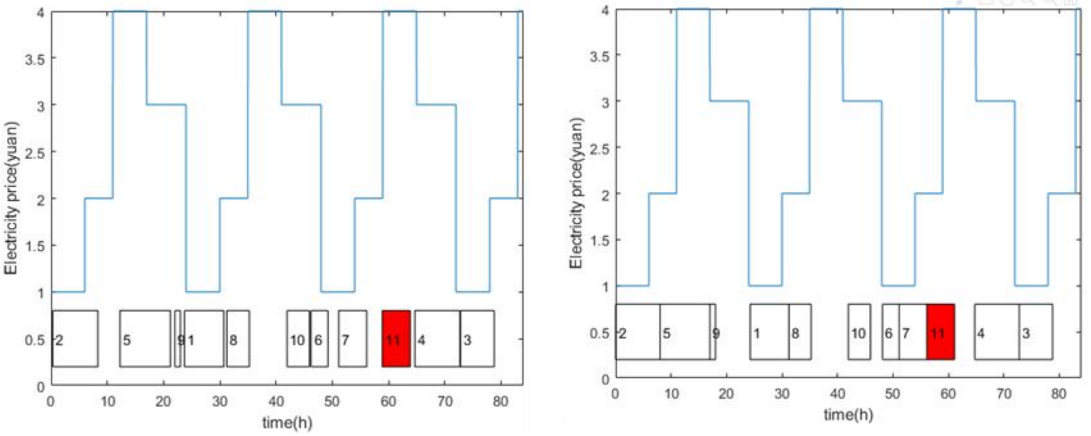


Figure 5: Stacking adjustment strategy.

3.4 Local search design

This paper designs a local search scheme to improve the quality of the GA. When the GA completed, the local search base on the optimal chromosome can quickly obtain a solution with a smaller error. The SA and TS will be used to realize local search.

The simulated annealing algorithm needs to set the initial temperature, randomly exchange genes at different positions on the target chromosome or mutate the processing time interval of the job to obtain a new chromosome, and determine the probability of accepting a poor solution according to the value of the objective function and the change of temperature. When the value of the objective function changes from $E(n)$ to $E(n+1)$, the probability formula for accepting the new solution is as follows.

$$P = \begin{cases} 1, E(n+1) < E(n) \\ e - \dfrac{E(n+1) - E(n)}{T}, E(n+1) \geq E(n) \end{cases} \tag{15}$$

In the early stage, the initial temperature is higher, there is a high probability that a worse solution will be accepted, so that it can jump out of the local optimum. As the number of algorithm operations increases, the temperature gradually decreases, and the probability of accepting poor solutions becomes smaller and smaller. The temperature change formula is as follows. We set the parameter λ to 0.99.

$$T(n+1)=\lambda T(n), n=1,2,3,... \quad (16)$$

The crucial stage of TS is to set the tabu table. In each generation of mutation, the mutation method with the smallest objective function value is selected as the initial chromosome for the next operation, and this method is recorded in the tabu table. After that, it cannot be selected within the length of the tabu table. In this way, the search is prevented from falling into the local optimum. The length of the tabu table is related to the scale of the problem. If the tabu length is too short, the loop will not be able to break out of the local best point; if the tabu length is too long, all candidate solutions will be tabu, resulting in a long calculation time, which may make the calculation impossible to proceed. The formula for setting the length (*L*) of the tabu table in this article is as follows.

$$L=\sqrt{2A(2A+1)} \quad (16)$$

Finally, the smaller value obtained by the two methods is selected as the optimal solution.

4 Numerical study

4.1 Algorithm performance

In order to verify the effectiveness and accuracy of the design algorithm, we used CPLEX to solve the model and compare the optimal solution with the algorithm result. We set up the number of jobs from 10 to 100 kinds of scale problem calculation examples, the time period of TOU is [6,5,6,7] four time periods (unit: hour), and the electricity price of each time period is [1,2,4,3] (Unit: Yuan). According to the change data of the TOU in a period, the total scheduling time length is divided into several periods of periodic change.

The experimental platform is based on Lenovo Tianyi 510Pro, Intel i7-9700 3.0 GHz, 16GB RAM. The algorithm is written in MATLAB R2018b, and the CPLEX solver is called through the java program to calculate the optimal solution of the example. The optimal solution is compared with the algorithm solution result to discuss the advantages and disadvantages of the algorithm.

Table 1: This is an example of a table

n	v	u	EM	CPLEX time(s)	MA		SA	TS
					times(s)	error	error	error
10	12	48	24	0.09	1.82	2.32%	3.68%	2.76%
	12	24	24	0.17	2.14	3.66%	7.44%	3.94%
	12	24	72	2.93	2.83	2.36%	5.88%	2.80%
30	24	48	36	157.79	14.39	1.69%	2.10%	2.18%
	24	48	72	213.00	14.80	1.33%	2.13%	1.52%
	24	72	72	342.97	13.97	2.52%	3.61%	2.77%
50	24	48	24	\	63.20	\	\	\
	24	48	48	\	61.74	\	\	\

According to the experimental results, when the scale of the calculation example is small, CPLEX can quickly solve the optimal solution. The improved GA algorithm can obtain an approximate solution with an error within 6%, and the error can be further reduced to 1% to 3% after the SA and TS domain search algorithms. When the scale of calculation examples gradually increases, the speed advantage of the algorithm is reflected. CPLEX may not find suitable upper and lower bounds for a long time. The algorithm's solving speed will not undergo sudden changes, and as the scale of the calculation example increases, the genetic algebra will increase slowly.

Table 2: The impact of key parameters on algorithm performance

n	v	u	EM	CPLEX time(s)	MA		SA	TS
					times(s)	error	error	error
10	12	48	24	0.09	1.82	2.32%	3.68%	2.76%
	12	24	24	0.17	2.14	3.66%	7.44%	3.94%
	12	24	72	2.93	2.83	2.36%	5.88%	2.80%
30	24	48	36	157.79	14.39	1.69%	2.10%	2.18%
	24	48	72	213.00	14.80	1.33%	2.13%	1.52%
	24	72	72	342.97	13.97	2.52%	3.61%	2.77%
50	24	48	24	\	63.20	\	\	\
	24	48	48	\	61.74	\	\	\

According to the analysis of the experimental results, the size of the maintenance interval and the length of the idle time have a greater impact on the solution speed. In order to verify the size of the maintenance interval and the length of the idle time, the following sensitivity analysis test is set up, keeping other parameters unchanged under the same job size and parameters, changing a single variable, and analyzing the impact of this variable on the performance of the algorithm. The results are as follows.

4.2 Sensitivity analysis

4.2.1 The effect of due date on TEC

To analyze the impact of TEC in the production process, this paper comprehensively considers the due date, maintenance intervals setting and the length of the maintenance window and other factors, and sets up related sensitivity experiments.

In the first experiment, we analye the impact of due date on TEC. The experiment data shows that when the jobs processing parameters are unchanged and the due date gradually increases, the TEC first reduces then keep consistent. After analysis, we learned that when the due date increases, the length of the lower electricity p periods also increases. Under the condition of ensuring maintenance constraints, more jobs can be arranged in the low electricity periods, TEC will become lower. When the due date further increases and all jobs can be arranged in the lowest electricity periods, the TEC drops to the minimum. TEC will not continue to drop. This will help managers to determine whether urgent orders are accepted taking into account total energy consumption.

Table 3: The effect of due date on TEC

$n=20\ \ T=60$		$n=10\ \ T=29$		$n=10\ \ T=29$	
$d_{\max}$	TEC	$d_{\max}$	TEC	$d_{\max}$	TEC
84	484	53	184	43	192
108	425	77	165	55	163
132	389	101	160	67	158
156	364	125	159	79	146
180	345	149	159	91	146
204	335	173	160	103	134
228	332	197	159	115	134
252	329	221	159	127	132
276	328	245	159	139	132
300	328	269	159	151	132

4.2.2 The effect of maintenance intervals on TEC

Then we analyze the impact of maintenance intervals on energy consumption. According to the previous analysis, we know that the maintenance interval setting will affect the number of maintenances required during the operation of the machine and the maintenance schedule range. While keeping other production factors unchanged, When the length of the maintenance interval is fixed, as the lower limit increases, the TEC will first increase and then decrease. When the lower limit is fixed, as the interval length becomes longer, the TEC gradually decreases. On the one hand when the length of the maintenance interval remains unchanged and the lower bound of the maintenance interval initially becomes larger, it limits the maintenance that cannot be scheduled during the period of high electricity prices in the early period, resulting the TEC increase. When the lower bound of the maintenance interval is further enlarged, the upper bound will increase accordingly, which will reduce the maintenance number, the TEC will decrease. On the other hand when the lower bound of the maintenance interval remains unchanged and the length of the maintenance interval increases, it means that the maintenance schedule is more flexible and the upper bound of the maintenance interval increases. The maintenance frequency is reduced and maintenance can be scheduled in a larger scope. Before the due date, the maintenance can be arranged more independently, which reduces the TEC.

Table 4: The effect of maintenance intervals on TEC

$n=30\quad T=84$				$n=50\quad T=149$			
v	u	L	TEC	v	u	L	TEC
24	48	24	590	24	48	24	1290
36	60	24	591	36	60	24	1297
48	72	24	602	48	72	24	1314
60	84	24	602	60	84	24	1301
72	96	24	588	72	96	24	1321
36	84	48	591	36	84	48	1289
48	120	72	590	48	120	72	1293
60	156	96	590	60	156	96	1299
72	192	120	588	72	192	120	1292

The finding obtained by analyzing the above factors can provide managers with suggestions for better management and maintenance arrangements. It benefits reduction of energy costs and operational expenses.

5 Conclusion

This paper considers an energy-efficient scheduling problem under TOU incorporating integrated scheduling decisions of flexible periodic preventive maintenance of production equipment. With the goal of minimizing TEC, we establish a mixed integer program model taking into account due date of customer order.

We design an improved MA based on GA-based population search combined with TS and SA. By comparing the experimental results of the MA with GA, MA can get better results than GA. Besides, the MA obtains near-optimal solutions (averagely 2.1%) compared to optimal solutions, requiring much less computation time compared by CPLEX.

Finally, we analyze the key factors that affect energy consumption, including the due date, maintenance interval length and lower limit. We find that TEC first reduces then keep consistent as the due date increases. This will help managers to determine whether urgent orders are accepted taking into account total energy consumption. When the length of the maintenance interval is fixed, as the lower limit increases, the TEC will first increase and then decrease. When the lower limit is fixed, as the interval length becomes longer, the TEC gradually decreases.

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References

- Allaoui, H., Artiba, A., Goncalves, G., & Elmaghraby, S. E. (2008). Scheduling n jobs and preventive maintenance in a single machine subject to breakdowns to minimize the expected total earliness and tardiness costs. *IFAC Proceedings Volumes*, *41*(2), 15843–15848. https://doi.org/10.3182/20080706-5-KR-1001.02678
- Che, A., Zeng, Y., & Lyu, K. (2016). An efficient greedy insertion heuristic for energy-conscious single machine scheduling problem under time-of-use electricity tariffs. *Journal of Cleaner Production*, *129*, 565–577. https://doi.org/10.1016/j.jclepro.2016.03.150
- Cui, W., Sun, H., & Xia, B. (2019). Integrating production scheduling, maintenance planning and energy controlling for the sustainable manufacturing systems under TOU tariff. *Journal of the Operational Research Society*, 1–20. https://doi.org/10.1080/01605682.2019.1630327
- Fang, K., Uhan, N. A., Zhao, F., & Sutherland, J. W. (2013). Flow shop scheduling with peak power consumption constraints. *Annals of Operations Research*, *206*(1), 115–145. https://doi.org/10.1007/s10479-012-1294-z
- Fang, K., Uhan, N. A., Zhao, F., & Sutherland, J. W. (2016). Scheduling on a single machine under time-of-use electricity tariffs. *Annals of Operations Research*, *238*(1–2), 199–227. https://doi.org/10.1007/s10479-015-2003-5
- Luo, H., Du, B., Huang, G. Q., Chen, H., & Li, X. (2013). Hybrid flow shop scheduling considering machine electricity consumption cost. *International Journal of Production Economics*, *146*(2), 423–439. https://doi.org/10.1016/j.ijpe.2013.01.028
- Moon, J.-Y., & Park, J. (2014). Smart production scheduling with time-dependent and machine-dependent electricity cost by considering distributed energy resources and energy storage. *International Journal of Production Research*, *52*(13), 3922–3939. https://doi.org/10.1080/00207543.2013.860251
- Sharma, A., Zhao, F., & Sutherland, J. W. (2015). Econological scheduling of a manufacturing enterprise operating under a time-of-use electricity tariff. *Journal of Cleaner Production*, *108*, 256–270. https://doi.org/10.1016/j.jclepro.2015.06.002
- Wu, X. (2018). A green scheduling algorithm for flexible job shop with energy-saving measures. *Journal of Cleaner Production*, 16.
- Zhang, H., Zhao, F., Fang, K., & Sutherland, J. W. (2014). Energy-conscious flow shop scheduling under time-of-use electricity tariffs. *CIRP Annals*, *63*(1), 37–40. https://doi.org/10.1016/j.cirp.2014.03.011
- Zhang, Q., Manier, H., & Manier, M.-A. (2012). A genetic algorithm with tabu search procedure for flexible job shop scheduling with transportation constraints and bounded processing times. *Computers & Operations Research*, *39*(7), 1713–1723. https://doi.org/10.1016/j.cor.2011.10.007
- Zhang, R., & Chiong, R. (2016). Solving the energy-efficient job shop scheduling problem: A multi-objective genetic algorithm with enhanced local search for minimizing the total weighted tardiness and total energy consumption. *Journal of Cleaner Production*, *112*, 3361–3375. https://doi.org/10.1016/j.jclepro.2015.09.097