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Energy-conscious maintenance and production scheduling for single machine systems under time-of-use tariffs

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Energy-conscious maintenance and production scheduling for single machine systems under time-of-use tariffs

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Abstract. In view of the joint optimization problem of preventive maintenance and production scheduling for modern production systems under time-of-use tariffs, a two-stage joint decision-making policy is proposed to achieve the peak-shifting reduction of production power. In the first stage, a dynamic preventive maintenance schedule is sequentially obtained based on the availability of machine. In the second stage, the production scheduling optimization of multi-workpiece processing is further carried out. The power consumption cost and the delay penalty cost under the time-of-use electricity tariff are considered, and the mixed integer programming model is established to achieve the balance of energy consumption and production delay. Numerical experiments have shown that by reasonably planning the idle time at the time of production batch conversion, the proposed model can effectively shift the on-peak power demand to off-peak, meet the stable electricity demand of enterprises, and improve the sustainable utilization level of power.

1. Introduction

With the deepening of China's energy supply-side reform, the proportion of electricity consumption in China's energy utilization is continuously increasing [1]. The increasing electricity demand has brought great pressure to power supply companies. In this context, demand-side management (DSM) has received much attention [2]. Among all DSM methods, time-of-use (TOU) tariffs are the most widely used in China. It is a power charging model that divides the 24-hour power supply into several periods and charges the electricity fee according to the average marginal cost of system operation to encourage customers to optimize the way of electricity consumption, and shift their power consumption activities from peak periods to off-peak periods [3].

Related research on TOU has become a focus of attention in today's industry and academia, but the existing research mainly focuses on the pricing policy by power companies and the demand response to the electricity market [4-6]. In the manufacturing field, due to the diverse production forms of enterprises, and variable working conditions [7], the joint decision-making and system performance analysis research on the manufacturing system under TOU tariffs are relatively limited. For single-machine production system research, F. Shrouf et al first introduced demand response into the production scheduling problem for single-machine systems [8]. At present, the production scheduling problem under TOU tariffs has gradually been widely studied [8-15]. Che Ada et al established a continuous-time mixed-integer linear programming model to find the production scheme for the single-machine system [11]. And Chen Bo et al established a pseudo-polynomial-time algorithm and formed an approximation scheme to minimize the total cost under TOU tariffs [14]. The current research on production system analysis under TOU tariffs usually takes the minimization of electricity cost and makespan as the decision-making goals [16-17]. However, there are relatively few studies on the joint decision-making of preventive maintenance (PM) and production scheduling under TOU tariffs.

In this paper, inspired by the two-stage decomposition concept [18], a two-stage decision-making model is proposed to solve the joint-scheduling problem of maintenance and production for a single machine system, which takes the influence of TOU tariffs on production and maintenance scheduling into account. Using the hierarchical method, the scientific problem is decomposed into two sub-problems, maintenance planning and production scheduling. The maintenance planning model dynamically outputs a sequential PM schedule. At the maintenance interval, the production scheduling optimization of multi-workpiece is carried out, and the power consumption cost and production delay penalty cost under TOU tariffs are both considered. Using this proposed model, the synthetical saving of machine PM costs, production delay penalty costs, and power consumption costs are achieved.

2. Methodology design

The time scale of the machine PM cycle is usually much larger than that of production. Therefore, a two-stage optimization model integrating machine failure trend and power consumption cost of TOU tariffs is constructed. In the first stage, the PM decisions are made to ensure stable machine status during sequential production [19]. In the second stage, the production scheduling is further carried out.

2.1. Problem description and assumptions

In the PM decision-making stage, the sequential PM interval is dynamically determined according to the hazard rate of the machine and is based on the principle of maximizing the availability of the machine (AOM). If the machine fails during the PM interval, a corrective repair (CR) will be carried out. There are only PM and CR maintenance actions during the whole decision cycle. In the production decision-making stage, the following assumptions should be followed: (1) N jobs are going to be processed on the single machine system within the planning horizon. (2) Each job has a specified processing time, due date, and delay penalty cost and is all available at time 0. (3) The machine can only process one job at a time. (4) No in-process interruption or preemption is allowed. The definitions and descriptions of parameters involved in this research are recalled as follows.

Indices and parameters:

m	: Index of PM cycles, $m = 1 \dots M$	T_F	: The length of one single CR action
j	: Index of jobs, $j = 1 \dots N$	C_{PM}	: The cost of one single PM action
T	: Total length of decision cycle	P	: The processing rated power of machine
$\lambda_m(t)$	: Hazard rate function in the mth PM cycle	$c(t)$	: The TOU electricity price function
a	: The age reduction factor	tp_j	: The processing time of job j
b	: The hazard rate increasing factor	Td_j	: The due date of job j
T_{PM}	: The length of one single PM action	Cp_j	: The delay penalty cost of job j

Decision variables:

T_m	: The PM interval of single machine system
x_{jm}	: Binary variable, $x_{jm} = 1$ means that job j is set to be processed in the mth PM interval, otherwise $x_{jm} = 0$
t_j	: The start time of job j

2.2. Two-stage modelling

Due to the large difference between the time scale of PM interval and that of production, the PM and production joint decision-making problem is transformed into a two-stage model. The PM scheduling is decided firstly to keep the availability of the machine, and the dynamic sequential PM plan in the whole cycle is output. After that, during each PM interval, the production scheduling for multispecies is carried out. Using this two-stage model, multi-objective optimization of machine reliability, energy cost, and delay penalty cost is achieved.

2.2.1. AOM-based maintenance scheduling. In the production process, the possibility of machine failure increases as the age of the machine increases due to the aging of its key components. At the same time, since the components after maintenance are usually not as good as new, there is a certain residual impact that increases the slope of the hazard rate function [20-22]. Therefore, the iteration formulation of the hazard rate before and after PM (the mth and $m+1$th cycle) is defined as

$$\lambda_{(m+1)}(t) = b\lambda_m(t + aT_m) \tag{1}$$

where b ($b > 1$) is the hazard rate increasing factor. a ($0 < a < 1$) is the age reduction factor. T_m is the length of the mth PM interval.

If a machine failure randomly occurs during the ith PM interval, the CR action will be carried out. Since the hazard rate function is determined by the model of Equation (1), the expected number of failures in the ith PM interval can be expressed as $N = \int_0^{T_m} \lambda_m(t)dt$, and the availability of machine (AOM) can be expressed as

$$A = \frac{MUT}{MUT+MDT} = \frac{T_m}{T_m+T_{PM}+T_F\int_0^{T_m}\lambda_m(t)dt} \tag{2}$$

where T_{PM} indicates the time required for a single PM action, T_F is the time required for a single CR action. And T_m is the decision variable. The optimal PM interval T_m^* can be solved by maximizing the AOM (Equation (2)). After the single optimal PM interval is obtained, the hazard rate is further updated, and the next cycle can be solved.

2.2.2. Production scheduling under TOU tariffs. After the PM scheduling is obtained, the production scheduling of multipiece processing is further carried out. The production scheduling problem for single-machine systems is a classic NP-hard problem, which can be described as there is only one machine with n mutually independent jobs going to be processed on it. Each job arrives at time 0, and has 3 specified and independent parameters: processing time tp_j, due date Td_j, and delay penalty cost Cd_j. The machine can only process one job at most at the same time, and intervals between jobs are allowed.

Compared with the classic single-machine production scheduling problem, since the whole day is split into peak, mid-peak, and off-peak periods with different levels of charging standards, idle time is added between the production. Therefore, the mixed integer programming (MIP) model in this research divides the decision variables into two categories: x_{jm} as a binary variable, indicating whether the job j is processed within the mth PM interval; and t_j as a continuous variable, indicating the specific processing start time of job j. The MIP model of production scheduling under TOU tariffs is as follows:

$$\min TC = EC + PC \tag{3}$$

s.t.

$$f_j(t) = \begin{cases} 1 & t_j \le t \le t_j + tp_j \\ 0 & otherwise \end{cases}, \quad \forall j = 1,2,\dots,N \tag{4}$$

$$EC = \int_0^T \left[c(t) * P * \sum_{j=1}^N f_j(t)\right] dt \tag{5}$$

$$PC = \sum_{j=1}^N Cp_j * max\left(t_j + tp_j - Td_j, 0\right) \tag{6}$$

$$t_j \ge \left[\sum_{i=1}^{m-1} T_i + (m-1)T_{PM}\right] * x_{jm}, \quad \forall j = 1,2,\dots,N, \forall m = 2,\dots,M \tag{7}$$

$$(t_j + tp_j) * x_{jm} \le \left[\sum_{i=1}^{m} T_i + (m-1)T_{PM}\right], \quad \forall j = 1,2,\dots,N, \forall m = 1,2,\dots,M \tag{8}$$

$$\sum_{m=1}^{M} x_{jm} = 1, \quad \forall j = 1,2, \dots, N \tag{9}$$

$$\sum_{j=1}^{N} f_j(t) \leq 1 \tag{10}$$

The production scheduling model takes the sum of power consumption and delay penalty cost as the objective. In order to accurately express the cost function according to the decision variables, Equation (4) is introduced to represent the process state of job j in the whole decision cycle. Equation (5) is the calculation formula of power consumption cost, in which the TOU electricity price function $c(t)$ is a piecewise function with time. Equation (6) is the formula for calculating the delay penalty cost, where $t_j + tp_j - Td_j$ represents the difference between the completion time and the due date of job j, Cp_j represents the delay penalty cost of job j. Equations (7) and (8) are constraints on processing continuity to ensure that the processing time of a single job j all falls within the same PM interval. Equation (9) is the constraint on the processing exclusiveness of the job, which ensures that each job has only one processing opportunity during all PM intervals. Equation (10) ensures that only one job is being processed on the machine at the same time.

3. Decision-making procedure

Procedure 1: PM related parameters input. From the Original Equipment Manufacturer (OEM) and long-term monitoring experience, obtain relevant parameters of maintenance, and input the total decision-making cycle in combination with the production plan.

Procedure 2: AOM based PM scheduling. Dynamically solve the machine maintenance scheduling based on the availability of the machine, and take the maximum availability $A = \frac{MUT}{MUT+MDT}$ as the objective to find the current optimal PM interval T_m^*.

Procedure 3: Determine whether the current total PM interval exceeds the total decision-making period. If it exceeds, the last PM interval in the total decision-making period will be advanced to $T_m^* = T - \sum_{i=0}^{m-1} T_i^*$; if not exceed, then record the optimal T_m^*, update the machine hazard rate, and repeat the dynamic solving in procedure 2.

Procedure 4: According to the PM interval sequence $T_1^*, T_2^*, \dots, T_M^*$, the total decision-making cycle is divided into PM action periods and PM intervals. The production action is scheduled in the PM intervals. According to the obtained PM interval T_m^* and single PM time T_{PM}, the mth PM interval is $[\sum_{i=1}^{m-1} T_i^* + (m-1) * T_{PM}, \sum_{i=1}^{m} T_i^* + (m-1) * T_{PM})$.

Procedure 5: Production related parameters input, such as the machine rated power of processing P, the TOU price function $c(t)$, the processing time of each job tp_j, the specified completion time Td_j, and the delay penalty cost per unit of time Cp_j and other production-related parameters.

Procedure 6: Generate the initial solution. The overall coding rule is shown in Figure 1.

	Production sequence										Idle time sequence									
Coding sequence	1	2	3	4	5	6	7	8	9	10	0.12	0.54	0.51	0	0.38	0.43	0.67	0.21	0.35	0.33
Production sequence	0.12	1	0.54	2	0.51	3	0	4	0.38	5	0.43	6	0.67	7	0.21	8	0.35	9	0.33	10

Figure 1. Encoding rules of GA.

Procedure 7: Enter the iterative solution, and determine whether the current iteration reaches the set number of iterations. If it is not reached, use $fit(x) = \frac{1}{TC}$ as the fitness function, where TC is the value of objective function corresponding to Equation (3). In each iteration, the highest fitness in the current population is recorded, and the best part of the chromosome is retained and copied into procedure 8. If the number of iterations is reached, skip to procedure 9.

Procedure 8: Crossover. Take the selection result as the parent, and perform crossover and mutation to generate new offspring. Since each chromosome has two parts, the order crossover (OX) method is used for the production sequence coding part, and the single-point crossover method is used for the idle time coding part. Combine the newly generated offspring with the parent to form a new population, and go back to procedure 7.

Procedure 9: Local search. In order to solve the problem of local optima, the output result of GA is further optimized locally. Using iterative local search as the optimization method, adding disturbance to the output result to obtain a new solution, thus reaching a new solution space. Further iterative optimization is performed until there is no better solution in the solution space or the number of iterations is reached.

4. Case study

4.1. Description of numerical parameters

To validate the developed two-stage optimization methodology under TOU tariffs, a typical type of additive manufacturing machine is taken as an example, numerical experiments are carried out based on machine reliability parameters and job processing parameters. For the first-stage, dynamic PM scheduling based on AOM, the total decision-making period T=60h is set, and the initial hazard rate function of machine obeys the Weibull distribution, that is, $\lambda(t)=\frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1}$, where the shape parameter $m=2$, characteristic life parameter $\eta=1000$, age reduction factor $a=0.02$, hazard rate increasing factor $b=1.05$, single PM time $T_{PM}=0.5$, single PM cost $C_{PM}=200$. For the second-stage, the related parameters are shown in Table 1.

Table 1. Parameters of TOU pricing profile and jobs.

Electricity price period	Electricity price(¥/kWh)	Duration	Jobs	1	2	3	4	5	6	7	8	9	10
On-peak	1.060	8:00-11:00, 13:00-15:00, 18:00-21:00	Processing time tp_j (h)	4.5	3.7	4.2	7.1	2.4	5.4	3.4	2.1	8.3	5.3
Mid-peak	0.693	6:00-8:00, 11:00-13:00, 15:00-18:00, 21:00-22:00	Delay penalty cost Cp_j (¥/h)	85	30	20	34	43	34	83	23	74	34
Off-peak	0.303	22:00-6:00	Due date Td_j (h)	30	30	40	60	50	50	40	60	50	20

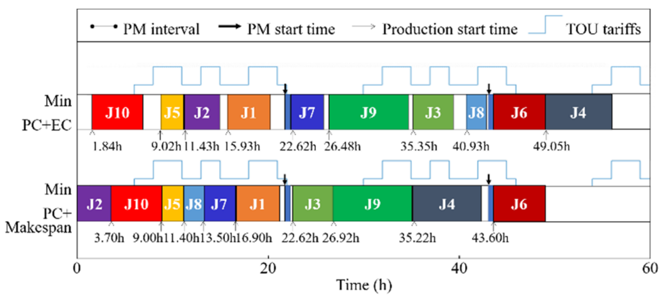

Figure 2. Gantt chart of PM and production scheduling of single machine production system.

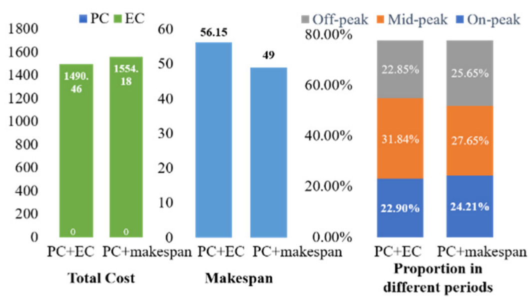

Figure 3. PM and production performance under different schemes.

4.2. Experiment and comparison

The proposed two-stage model of PM and production scheduling for single machine systems under TOU tariffs is used to carry out numerical experiments combined with the above parameters. Firstly, according to the hazard rate function, the PM cycle in the total decision-making cycle can be obtained from Equation (2): $T_1=21.82h$, $T_2=20.78h$, $T_3=16.40h$. Set the population size in the improved GA algorithm as 300, the probability of crossover $CR=0.8$, the probability of mutation $MR=0.2$, and terminate after 300 iterations. In order to prove the effectiveness of the production scheduling model in this study, the comparison scheme is carried out, which takes the minimum delay penalty cost and makespan as the decision objective. The optimal solution of multiple experiments is shown in Figure 2. And the performance results are shown in Figure 3.

It can be seen that both schemes achieve the lowest cost of delay penalty. Although the makespan of the comparison scheme is significantly smaller than that of the proposed scheme, under the background of TOU tariffs, pursuing the reduction of the makespan leads to a full load during daily peak hours, which results in a 24.21% proportion of electricity consumption during peak hours, causing an increase in the cost of power consumption. The scheme in this paper, by synthesizing the cost of delay penalty and the cost of power consumption, makes full use of the idle time of the machine at the time of production conversion, transfers the power load from peak periods to mid-peak periods, and reduces power consumption during peak periods to 22.90%. On the basis of ensuring the cost of delay penalty as 0, an effective balance of power consumption cost is realized.

To sum up, the two-stage decision-making model of PM and production scheduling for single machine systems under TOU tariffs can make full use of the wide adjustment space between the specified due date and the required processing time as the energy-saving opportunity on the basis of fully ensuring the AOM. By reasonably planning the idle time, the production plan in peak periods is transferred to mid-peak or off-peak periods, so as to effectively balance the delay penalty cost and power consumption cost. The rationality of the proposed model is proved through the above results.

5. Conclusions

This research takes the single machine system as the research object and proposes a two-stage decision-making model of preventive maintenance and production scheduling under TOU tariffs. The first stage makes maintenance decisions and outputs a dynamic sequential PM scheduling plan. In the second stage, the production scheduling is carried out, which is based on the integrated delay penalty cost and power consumption cost under TOU tariffs. By rationally planning the idle time during different jobs, the power demand in peak periods can be adjusted to the mid-peak and off-peak periods, and the delay penalty cost and power consumption cost can be balanced to achieve an integrated optimization. Results show that the proposed model can reasonably optimize the maintenance and production plan and achieve an effective saving on power energy and the total cost. Future research can be focused on the more complex production system structures and more efficient solving algorithms.

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