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OPTIMIZING ELECTRICITY COSTS DURING INTEGRATED SCHEDULING OF JOBS AND STOCHASTIC PREVENTIVE MAINTENANCE UNDER TIME-OF-USE ELECTRICITY TARIFFS

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Abstract
Time-of-use (TOU) electricity pricing has been applied in many countries around the world to encourage manufacturers to reduce their electricity consumption from peak periods to off-peak periods. This paper investigates a new model of Optimizing Electricity costs during Integrated Scheduling of Jobs and Stochastic Preventive Maintenance under time of-use (TOU) electricity pricing scheme in unrelated parallel machine, in which the electricity price varies throughout a day. The problem lies in assigning a group of jobs, the flexible intervals of preventive maintenance to a set of unrelated parallel machines and then scheduling of jobs and flexible preventive maintenance on each separate machine so as to minimize the total electricity cost. We build an improved continuous-time mixed-integer linear programming (MILP) model for the problem. To the best of our knowledge, no papers considering both production scheduling and Stochastic Preventive Maintenance under time of-use (TOU) electricity pricing scheme with minimization total Electricity costs in unrelated parallel machine. To evaluate the performance of this model, computational experiments are presented, and numerical results are given using the software CPLEX and MATLAB with then discussed.

Keywords
Scheduling, production, maintenance, electricity costs, time of use electricity tariffs, stochastic, flexible, MILP, optimization, modeling, CPLEX, MATLAB.

Introduction

With the development of social, economic and scientific development, energy demand is increasing rapidly. In addition, the manufacturing sector is one of the most energy-intensive sectors in the world.

Energy conservation has attracted a considerable amount of attention in recent years due to the fact that a large part of the energy resources used to produce energy are not sustainable [1] and that energy consumption has grown by as much as 300% over the last 50 years [2]. Inappropriate use of energy has also posed the serious problem of excessive emissions of greenhouse gases, which weigh heavily on the climate and the environment. Therefore, efficient use of energy is important for promoting economic growth and protecting the environment.

For parallel machine scheduling under the TOU pricing scheme, the author [3] investigated an unrelated parallel machine scheduling problem to minimize the weighted sum of makespan and electricity costs. They proposed a hybrid genetic algorithm with a blank job insertion algorithm for the problem, which is able to solve problems with up to 65 jobs and 20 machines. The authors [4] addressed a similar problem to minimize the total electricity cost. They first formulated a time interval based MILP model for the problem and then proposed a column generation heuristic. Their approaches can deal with problems with up to 200 jobs and 20 machines. The author [5] proposed an insertion heuristic and an iterative search framework for the bi-objective uniform parallel machine scheduling problem.

The author [6] proposed an improved MILP model to obtain optimal solutions for small-size problems to solve the problem of energy-conscious unrelated parallel machine scheduling problem under the TOU tariffs.

On the other hand, timely and cost effective production is becoming increasingly important in today's global competitive markets. For the manufacturers, it is vital to optimize the machine resource utilization by ensuring an efficient and stabilized schedule at the operational level. Traditional literatures on scheduling assume that machines are available at all times. However, in many realistic situations, machines may be unavailable during the scheduling horizon for different reasons [7–9], such as breakdowns and scheduled maintenances in typical industrial settings. This availability consideration adds complexity to any scheduling problem.

To the best of authors' knowledge, no papers considering both production scheduling and Stochastic Preventive Maintenance under time of-use (TOU) electricity pricing scheme with minimization total Electricity costs in unrelated parallel machine.

In this paper, a new model of Optimizing Electricity costs during Integrated Scheduling of Jobs and Stochastic Preventive Maintenance under time of-use (TOU) electricity pricing scheme in unrelated parallel machine, in which the electricity price varies throughout a day, is described. The problem lies in assigning a group of jobs to a set of unrelated parallel machines and then scheduling jobs on each separate machine so as to minimize the total electricity cost. Authors create an improved continuous-time mixed-integer linear programming (MILP) model for the problem. To evaluate the performance of this model, computational experiments are presented, and numerical results are given using the software CPLEX and then discussed.

The remainder of this paper is organized as follows. A detailed description and modelling for the problem considered and formulates an improved MILP model and computational results of the problem are described in the next sections. Finally, the conclusion are drawn.

Problem description and modelling

In this section, an improved continuous-time mixed-integer linear programming (MILP) model to formulate the problem in a mathematical way in unrelated parallel machine in order to integrate the policy of Integrated scheduling of maintenance and production, including the period of flexible preventive maintenance, to minimize the total electricity cost (TEC). With the addition the constraints for minimize the total energy cost and for integrated scheduling of maintenance and production, including preventive maintenance (PM) in the unrelated parallel machine on the existed model of [6]. This joint model for integrating the production and PM planning to optimize the objective of the total energy cost is inspired from the models presented in [6]. Model is adapted to consider the different constraints of energy cost and the preventive maintenance. Indices, parameters and variables being used in this formulation are given in Table 1.

Problem assumptions and formulation

In the considered problem, there are n jobs to be processed on m parallel machines.

- Each job, eg. job i, is characterized by its processing time $T_{i,j}$ on machine j and power consumption per unit time, called electricity consumption rate, on machine j, $P_{i,j}$, $i \in J = \{1, 2, \ldots, N\}$, $j \in M = \{1, 2, \ldots, M\}$.
- The processing time and the power consumption rate of a job are dependent on both the machine and the job itself. Thus, the problem under investigation is an unrelated parallel machine scheduling problem.
- Each machine can process only one job at a time and each job cannot be processed on more than one machine at the same time.
- No preemption is allowed.
- All jobs and machines are available at the beginning of the production horizon.
- The machines breakdown and the preventive maintenance (PM) are processed simultaneously for scheduling of jobs.

As mentioned above, the electricity prices follow a TOU pricing scheme. That is to say, the prices of electricity, depending on its demands, may vary throughout a day. In a TOU pricing scheme, the time horizon is divided into a set of K time periods. Period k, $k \in K = \{1, 2, \ldots, K\}$, is featured by its start time S_k and electricity price C_k, $k \in K = \{1, 2, \ldots, K\}$

- Without loss of generality, we set $S_1 = 0$.
- Period k can be represented by the interval $[S_k, S_{k+1}]$, $k \in K = \{1, 2, \ldots, K\}$.
- The duration of period k is denoted by $t_k = S_{k+1} - S_k$, $k \in K = \{1, 2, ldots, K\}$.
- Let S_{k+1} be the given makespan (maximum completion time) for processing all jobs.

Table 1
Parameters and variables being used.

Indices:	
i	Index of jobs
j	Index of machines
k	Index of periods on machine j
Sets:	
J	Set of jobs; $J = \{1, 2, \ldots, N\}$
M	Set of machines; $M = \{1, 2, \ldots, M\}$
K	Set of time periods; $K = \{1, 2, \ldots, K\}$
Parametres:	
N	Number of jobs
M	Number of machines
K	Number of periods
S_k	Start time of time periods k
t_k	Duration of period k is denoted by $t_k = S_{k+1} - S_k$
C_k	Electricity price in period k
$T_{i,j}$	Processing time of job i in machine j
PM_j	Preventive maintenance time on machine j
$P_{i,j}$	Power consumption per unit time, called electricity consumption rate, on machine j
Decision variables:	
$T'_{i,j,k}$	The actual processing time of job i in period k of machine j, for $i \in J = \{1, 2, \ldots, N\}$, $j \in M = \{1, 2, \ldots, M\}$, $k \in K = \{1, 2, \ldots, K\}$
$X_{i,j,k}$	$\begin{cases} 1 & \text{if job } i \text{ is processed in period } k \text{ on machine } j \\ 0 & \text{Otherwise} \end{cases}$
$Y_{i,j,k}$	$\begin{cases} 1 & \text{if PM is processed before the period } k \text{ on machine } j \\ 0 & \text{Otherwise} \end{cases}$
$u_{i,j,k}$	$\begin{cases} 1 & \text{if job } i \text{ is processed across period } k \text{ and k+1 on } j \text{ machine } j \\ 0 & \text{Otherwise} \end{cases}$
$v_{i,j}$	$\begin{cases} 1 & \text{if job } i \text{ is processed on machine } j \\ 0 & \text{Otherwise} \end{cases}$
$a_{i,j,k}$	The machine's age after the job i in period k on machine j
$b_{i,j,k}$	The machine's age before the job i in period k on machine j

The problem considered in this paper consists in assigning the N jobs to the M unrelated parallel machines and then allocating available time periods on each machine to the jobs assigned to it so as to minimize the total electricity cost. Note that a job may be processed across two or more adjacent periods on a machine.

Modelling of the problem

The mixed integer linear programming model (MILP) can be finally established as follows:

$$\text{Minimize TEC} = \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{K} P_{i,j}.C_k\, T'_{i,j,k}, \tag{1}$$

S.t

$$\sum_{k=1}^{K}\sum_{j=1}^{M}(T'''_{i,j,k}/T_{i,j}) = 1; \quad \forall i = 1, \ldots, N, \tag{2}$$

$$T'_{i,j,k} \le T_{i,j} X_{i,j,k}; \quad \forall i = 1, \ldots, N, \quad k = 1, \ldots, K, \quad j = 1, \ldots, M, \tag{3}$$

$$\sum_{i=1}^{N}(T'_{i,j,k} + \mathrm{PM}_j.Y_{i,j,k}) \le t_k; \quad \forall j = 1, \ldots, M, \quad k = 1, \ldots, K, \tag{4}$$

$$u_{i,j,k} \ge X_{i,j,k} + X_{i,j,k+1} - 1; \quad \forall i = 1, \ldots, N, \quad k = 1, \ldots, K-1, \quad j = 1, \ldots, M, \tag{5}$$

$$\sum_{i=1}^{N} u_{i,j,k} \le 1; \quad \forall j = 1, \ldots, M, \quad k = 1, \ldots, K, \tag{6}$$

$$\sum_{l=k+2}^{K} X_{i,j,l} \le (1 - X_{i,j,k} + X_{i,j,k+1}); \quad \forall i = 1, \ldots, N, \quad k = 1, \ldots, K-2, \quad j = 1, \ldots, M, \tag{7}$$

$$T'_{i,j,k} + \mathrm{PM}_j.Y_{i,j,k}) \geq (X_{i,j,k-1} + X_{i,j,k+1} - 1)\, t_k;$$
$$\forall i = 1,\ldots,N, \quad k = 2,\ldots,K-1, \quad j = 1,\ldots,M, \tag{8}$$

$$b_{1,j,1} = 0, \quad y_{1,j,1} = 0; \qquad \forall j = 1,\ldots,M, \tag{9}$$

$$a_{i,j,k} = b_{i,j,k} + T'_{i,j,k};$$
$$\forall i = 1,\ldots,N, \quad k = 1,\ldots,K, \quad j = 1,\ldots,M, \tag{10}$$

$$b_{i+1,j,k+1} = a_{i,j,k}(1 - Y_{i+1,j,k+1});$$
$$\forall i = 2,\ldots,N, \quad k = 2,\ldots,K, \quad j = 1,\ldots,M, \tag{11}$$

$$v_{i,j} \geq \sum_{k=1}^{K} X_{i,j,k}/z_{i,j}; \tag{12}$$
$$\forall i = 1,\ldots,N, \quad j = 1,\ldots,M,$$

$$\sum_{j=1}^{M} v_{i,j} = 1; \qquad \forall i = 1,\ldots,N, \tag{13}$$

$$X_{i,j,k} \in \{0,1\};$$
$$\forall i = 1,\ldots,N, \quad k = 1,\ldots,K, \quad j = 1,\ldots,M, \tag{14}$$

$$Y_{i,j,k} \in \{0,1\};$$
$$\forall i = 1,\ldots,N, \quad k = 1,\ldots,K, \quad j = 1,\ldots,M, \tag{15}$$

$$u_{i,j,k} \in \{0,1\};$$
$$\forall i = 1,\ldots,N, \quad k = 1,\ldots,K, \quad j = 1,\ldots,M, \tag{16}$$

$$v_{i,j} \in \{0,1\};$$
$$\forall i = 1,\ldots,N, \quad k = 1,\ldots,K, \quad j = 1,\ldots,M, \tag{17}$$

$$T'_{i,j,k} \geq 0;$$
$$\forall i = 1,\ldots,N, \quad k = 1,\ldots,K, \quad j = 1,\ldots,M, \tag{18}$$

$$\sum_{k=1}^{K} T'_{i,j,k} \leq v_{i,j} T_{i,j}; \tag{19}$$
$$\forall i = 1,\ldots,N, \quad j = 1,\ldots,M,$$

$$\sum_{k=1}^{K} X_{i,j,k} \leq v_{i,j} z_{i,j}; \tag{20}$$
$$\forall i = 1,\ldots,N, \quad j = 1,\ldots,M.$$

The goal is to minimize the total electricity cost (TEC) required for processing all the jobs.

Constraints (2)–(4) are associated with the processing time constraints and the PM time when it exists (i.e., $Y_{i,j,k} = 1$), Constraint (2) guarantees that the total processing time of a job assigned in all periods on all machines is equal to its corresponding processing time.

Constraint (3) ensures if job i is not processed in period k on machine j (i.e., $X_{i,j,k} = 0$), then the actual processing time of job i in period k on machine j should take the value of 0.

Constraint (4) requires that the total processing time and the PM time of all jobs assigned in a period on any machine cannot exceed its duration. Constraint (5) specifies the mathematical relation between the two decision variables $u_{i,j,k}$ and $X_{i,j,k}$. Constraint (6) ensures that at most one job can be processed across periods k and $k+1$ of machine j. Constraints (7) and (8) are connected with the processing and the PM continuity constraint if some job is processed across multiple periods.

Constraint (7) ensures if job i is processed on some machine across more than one period, then these periods must be continuous. To be more specific, for any adjacent periods k and $+1$, $k \in \{1,2,\ldots,K-2\}$ on machine j used for processing job i, if $X_{i,j,k} = 1$ and $X_{i,j,k+1} = 0$, then $X_{i,j,l} = 0$ must hold for all $l \in \{k+2,\ldots,K\}$ to ensure the continuity of processing periods for job i.

Constraint (8) requires that if a job and the preventive maintenance (PM) are processed in periods $k-1$ and $k+1$ on some machine, when is exist of the i-th job (the possible PM time), then the middle period k must be fully occupied by the job due to the non-preemption assumption.

Constraints (9) specify the initial condition of the system.

Constraint sets (10) and (11) specify the machines age before and after each job i, respectively. Constraint (12) ensures the consistency in the definitions of binary variables $X_{i,j,k}$ and $v_{i,j}$. Specifically, it restricts that if $X_{i,j,k} = 1$ for some i, j and k, then $v_{i,j} = 1$ must hold. Note that this constraint can also be formulated as $v_{i,j} \geq X_{i,j,k}$. which has in total NMK inequalities. We prefer to use constraint (12) in its current form since it consists of NM inequalities and is more compact. Constraint (13) guarantees that each job can only be processed on one machine.

Constraints (14)–(17) and (18) are binary and non-negativity restrictions on the variables, respectively. Inequality (19) restricts that if job i is not processed on machine j, i.e., $v_{i,j} = 0$, then the total processing time of job i in all periods on machine j should be equal to zero. Similarly, inequality (20) specifies that if job i is not handled on machine j, then the total number of periods occupied by job i on machine j should be zero.

Linearized constraint sets

It should be noted that the constraint (11) is nonlinear, which contains the nonlinear term of $a_{i,j,k}$ $(1 - Y_{i+1,j,k+1})$.

Since there are many local optical solutions in the feasible region of nonconvex models, it is difficult to solve these models optimally. Therefore, we linearize the nonlinear constraint by adding a very large positive number, namely Z and in this case the $b_{i+1,j,k+1}$ counts as an intermediate variable to linearize this expression $a_{i,j,k}$ $(1-Y_{i+1,j,k+1})$ and which serves to replace it.

Therefore, the non-linear term $a_{i,j,k}$ $(1 - Y_{i+1,j,k+1})$ is replaced by the linear term of $b_{i+1,j,k+1}$ is intended to linearize the constraint (11)

$$b_{i+1,j,k+1} \geq a_{i,j,k} - Z.Y_{i+1,j,k+1}; \quad \forall i = 2,\dots,N, \quad k = 2,\dots,K, \quad j = 1,\dots,M, \tag{21}$$

$$b_{i+1,j,k+1} \leq a_{i,j,k} + Z.Y_{i+1,j,k+1}; \quad \forall i = 2,\dots,N, \quad k = 2,\dots,K, \quad j = 1,\dots,M, \tag{22}$$

$$b_{i+1,j,k+1} \leq Z\,(1 - Y_{i+1,j,k+1})\,; \quad \forall i = 2,\dots,N, \quad k = 2,\dots,K, \; j = 1,\dots,M, \tag{23}$$

$$b_{i,j,k} \geq 0; \qquad \forall i = 1,\dots,N, \quad j = 1,\dots,M. \tag{24}$$

Constraint sets (21)–(24) force $b_{i+1,j,k+1} = a_{i,j,k}$ $(1 - Y_{i+1,j,k+1})$ to be always true.

In detail, if $Y_{i+1,j,k+1} = 0$, constraint sets (21), (22) enforce $b_{i+1,j,k+1}$ to be no less than and be no more than $a_{I,j}$, and this makes $Y_{i+1,j}$ is equal to $a_{I,j,k}$ $(b_{i+1,j,k+1} = a_{I,j,k} = a_{I,j,k}(1 - Y_{i+1,j,k+1}))$. If, $Y_{i+1,j,k+1} = 1$, constraint sets (23), (24) enforce $b_{i+1,j}$ to be no less than 0 and be no more than 0, and this makes $b_{i+1,j}$ is equal to $0(b_{i+1,j,k+1} = 0 = a_{i,j,k}(1 - Y_{i+1,j,k+1}))$.

1. Computational results

This part is devoted to the exact analysis of the performance of the linear model corresponding to the studied system. However, the mathematical model represents a linear programming for which an exact resolution through a commercial software of linear programming is necessary to qualify the complexity and the state of optimality of the considered problem.

In order to evaluate the computational power of the proposed model, the problem should be examined in its most difficult cases; in fact, 45 different instances for each fixed dimension of n jobs and m machines have been generated.

Moreover, in the experimental design adopted for the problem considered, the operating times were generated uniformly in the interval [1, 100]. According to [10], the generation of operating times between 1 and 100 is based on two reasons:

- The first reason is related to the historical uniformity, that is to say that the majority of the research work relating to the linear model calculation tests, including scheduling problems, generate the operating times from a uniform distribution in the interval [1, 100];
- The second reason is related to the fact that it is preferable to use data representative of the real problems of scheduling since the generation of small intervals will certainly lead very easily to optimal solutions. These solutions will not necessarily be realistic because of the inadequate conclusions that may result.

Table 2 reports the average computation times obtained using the CPLEX 12.6 software to find the optimal total energy cost of the integrated scheduling problems of production and maintenance jobs. To gain more insight into the capability of the above model, comparative studies of average computation times between small and large problems are performed as shown in Figs 1, 2 and 3.

For all instances, the processing powers P are derived from the uniform distribution [2, 8]. The duration of period k is generated randomly from the set {40, 80, 100}, followed by the PM preventive maintenance time is generated randomly from the set {9, 12, 15} and the electricity price in period k is generated randomly from the set {2, 3, 5}.

All MILP formulations are modeled using IBM ILOG CPLEX12.6 and the OPL language. The 45 instances are resolved on an HP 4300U notebook with an Intel Core i5 Duo processor clocked at 2.50 GHz and 8GB of RAM. The time limit is 3600 seconds. In other words, the analyzes are completed after 3600 seconds. If no optimal solution is obtained within 3600 seconds, the best current solution is returned.

In relation to all the problems considered, the average calculation times are relatively reasonable for the different instances. As a result, we notice that the execution time is increased during the treatment the both production scheduling and Stochastic Preventive Maintenance under time of-use (TOU) electricity pricing scheme with minimization total Electricity costs in different unrelated parallel machine from the small problem to large problems; As soon as the size of the problem increases, computation times become very important for different studied instances.

Table 2

Comparison of the results obtained from the different bodies to minimize the total energy cost (TEC).

Machines × Jobs		PM	T	t	P	C	TEC	Time [sec]
2×3	Inst. 1	9	[10,50[	40	[2,4[	2	180	00,60
	Inst. 2	12	[50,70[	80	[4,6[	3	1800	00,71
	Inst. 3	15	[70,100]	100	[6,8]	5	6300	00,75
2×5	Inst. 1	9	[10,50[	40	[2,4[	2	300	00,62
	Inst. 2	12	[50,70[	80	[4,6[	3	3300	00,72
	Inst. 3	15	[70,100]	100	[6,8]	5	11200	00,79
2×8	Inst. 1	9	[10,50[	40	[2,4[	2	480	00,69
	Inst. 2	12	[50,70[	80	[4,6[	3	6000	00,76
	Inst. 3	15	[70,100]	100	[6,8]	5	19600	00,81
5×5	Inst. 1	9	[10,50[	40	[2,4[	2	360	00,72
	Inst. 2	12	[50,70[	80	[4,6[	3	2400	00,79
	Inst. 3	15	[70,100]	100	[6,8]	5	7500	00,83
5×7	Inst. 1	9	[10,50[	40	[2,4[	2	280	00,89
	Inst. 2	12	[50,70[	80	[4,6[	3	4200	00,92
	Inst. 3	15	[70,100]	100	[6,8]	5	16500	00,96
5×12	Inst. 1	9	[10,50[	40	[2,4[	2	480	00,93
	Inst. 2	12	[50,70[	80	[4,6[	3	7680	00,98
	Inst. 3	15	[70,100]	100	[6,8]	5	30400	01,04
7×5	Inst. 1	9	[10,50[	40	[2,4[	2	300	00,90
	Inst. 2	12	[50,70[	80	[4,6[	3	2400	04,20
	Inst. 3	15	[70,100]	100	[6,8]	5	7500	04,88
7×7	Inst. 1	9	[10,50[	40	[2,4[	2	420	00,98
	Inst. 2	12	[50,70[	80	[4,6[	3	3360	04,60
	Inst. 3	15	[70,100]	100	[6,8]	5	10500	05,01
7×12	Inst. 1	9	[10,50[	40	[2,4[	2	960	02,11
	Inst. 2	12	[50,70[	80	[4,6[	3	5760	05,23
	Inst. 3	15	[70,100]	100	[6,8]	5	18000	05,47
10×5	Inst. 1	9	[10,50[	40	[2,4[	2	200	05,45
	Inst. 2	12	[50,70[	80	[4,6[	3	3000	08,02
	Inst. 3	15	[70,100]	100	[6,8]	5	11100	08,43
10×7	Inst. 1	9	[10,50[	40	[2,4[	2	280	19,47
	Inst. 2	12	[50,70[	80	[4,6[	3	4200	49,04
	Inst. 3	15	[70,100]	100	[6,8]	5	16500	51,12
10×10	Inst. 1	9	[10,50[	40	[2,4[	2	400	32,18
	Inst. 2	12	[50,70[	80	[4,6[	3	6240	53,98
	Inst. 3	15	[70,100]	100	[6,8]	5	24600	64,82
50×10	Inst. 1	9	[10,50[	40	[2,4[	2	400	60,03
	Inst. 2	12	[50,70[	80	[4,6[	3	6000	87,23
	Inst. 3	15	[70,100]	100	[6,8]	5	21000	93,32
50×15	Inst. 1	9	[10,50[	40	[2,4[	2	600	83,14
	Inst. 2	12	[50,70[	80	[4,6[	3	9000	120,09
	Inst. 3	15	[70,100]	100	[6,8]	5	31500	144,23
50×20	Inst. 1	9	[10,50[	40	[2,4[	2	800	98,46
	Inst. 2	12	[50,70[	80	[4,6[	3	12000	176,66
	Inst. 3	15	[70,100]	100	[6,8]	5	42000	187,67
100×20	Inst. 1	9	[10,50[	40	[2,4[	2	860	1204,17
	Inst. 2	12	[50,70[	80	[4,6[	3	12300	1856,26
	Inst. 3	15	[70,100]	100	[6,8]	5	42244	1944,54
100×80	Inst. 1	9	[10,50[	40	[2,4[	2	OUT OF MEMORY	1432,97
	Inst. 2	12	[50,70[	80	[4,6[	3		2599,17
	Inst. 3	15	[70,100]	100	[6,8]	5		2643,22
100×100	Inst. 1	9	[10,50[	40	[2,4[	2		1533,12
	Inst. 2	12	[50,70[	80	[4,6[	3		2833,05
	Inst. 3	15	[70,100]	100	[6,8]	5		2876,44

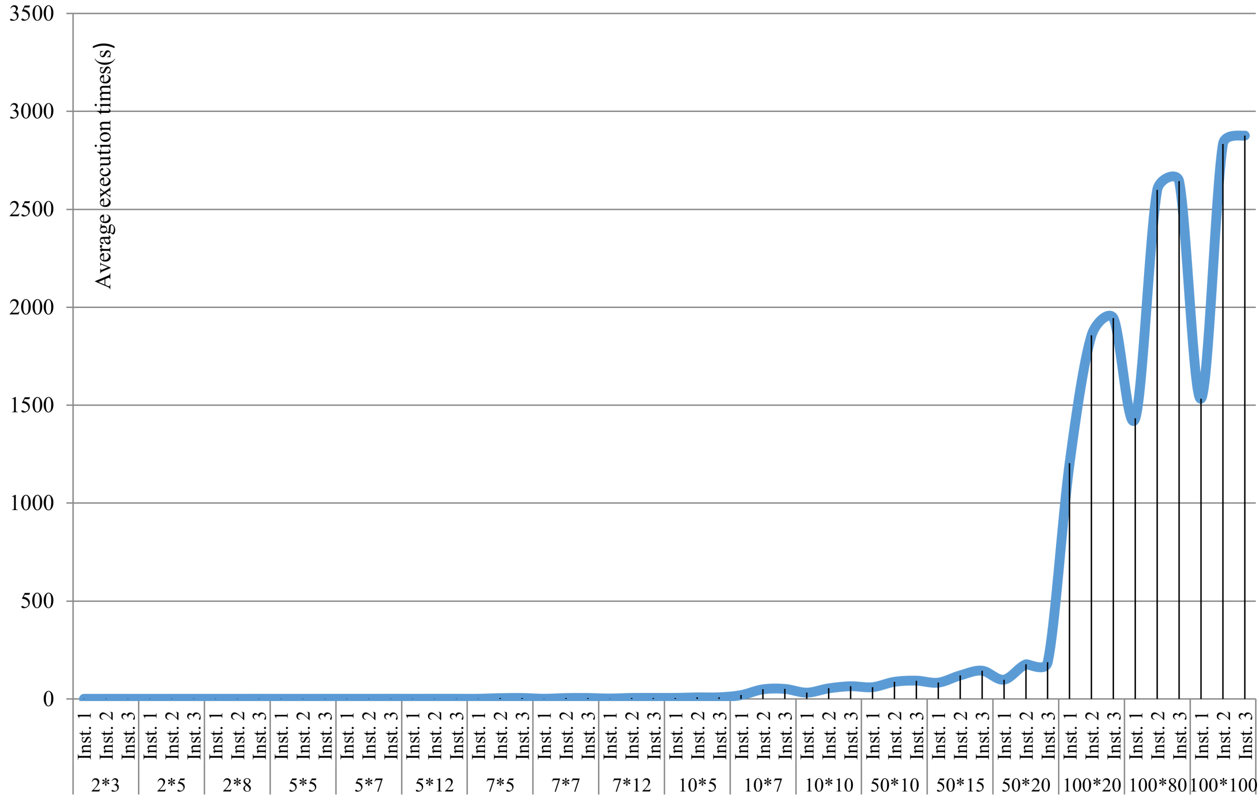

Fig. 1. Average execution times for different instances.

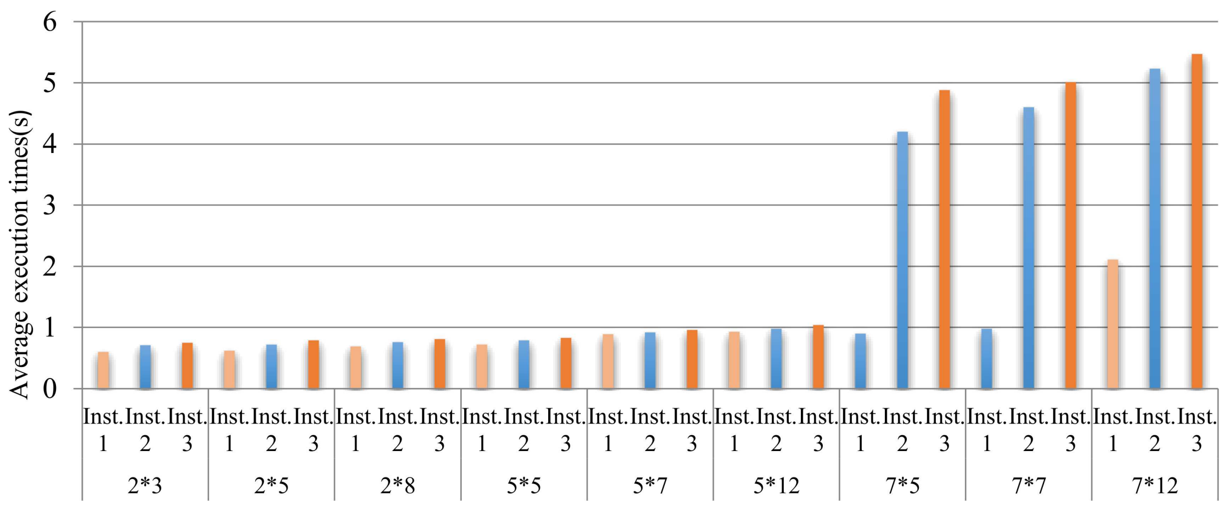

Fig. 2. Comparison of average execution times for small problems.

As Table 2 shows, the average calculation times are relatively reasonable (less than 50 seconds) when the problem size is less than 10*5 (10 machines and 5 jobs). As soon as the size is greater than 10*5, the calculation times become very important. As an example, for the problem (10*10) (10 machines and 10 jobs) with the value of the PM preventive maintenance time is 12, the processing times of jobs were generated uniformly in the interval [50, 70] in this instance, The processing powers P are derived from the uniform distribution [4, 6] and The duration of period k is 80, followed by the electricity price in period k is 3.

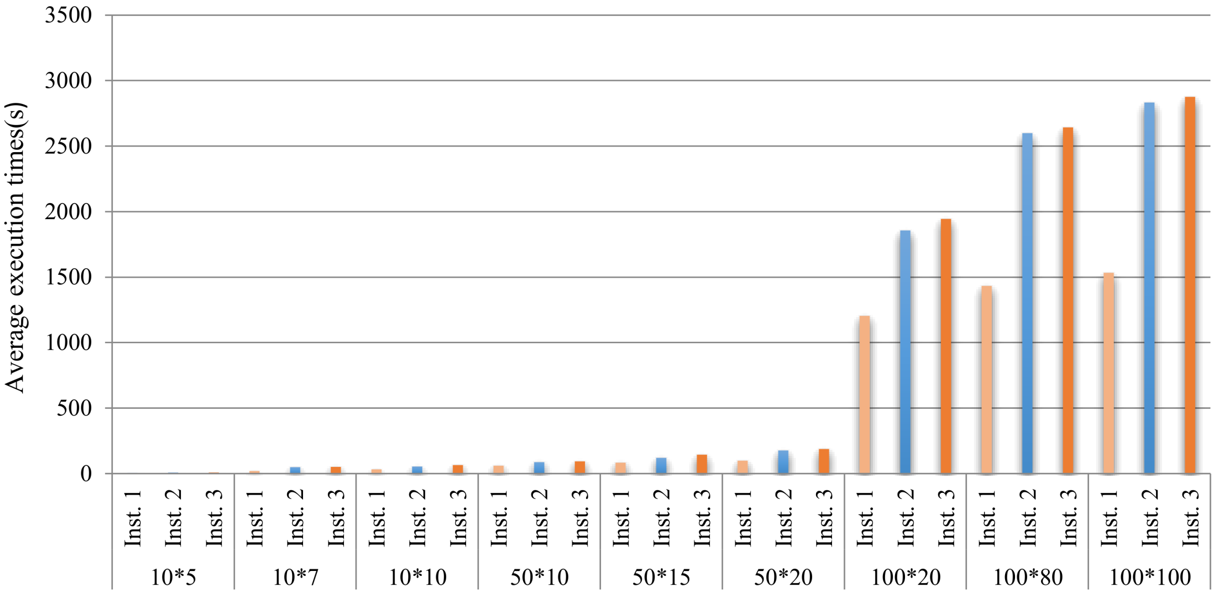

Fig. 3. Comparison of average execution times for large problems.

For this instance, results are obtained for an execution time of 53.98 seconds and for the scheduling problem with 100*20 (100 machines and 20 jobs), we get an execution time of 1856, 26 seconds for the same instance with the PM preventive maintenance time is 12, the processing times of jobs were generated uniformly in the interval [50, 70] in this instance. The processing powers P are derived from the uniform distribution [4, 6] and The duration of period k is 80, followed by the electricity price in period k is 3.

In relation to all the problems considered, the average calculation times are relatively reasonable (less than 50 seconds) when the size of the problem is less than 10*50 (10 jobs and 50 machines). As soon as the size is greater than 10*100, the computation times become very important as the 100*100 problem (100 jobs and 100 machines) its calculation time increases to 2876,44 seconds with the values of this instance, the PM preventive maintenance time is 15, the processing times of jobs were generated uniformly in the interval [70, 100] in this instance, the processing powers P are derived from the uniform distribution [6, 8] and the duration of period k is 100, followed by the electricity price in period k is 5.

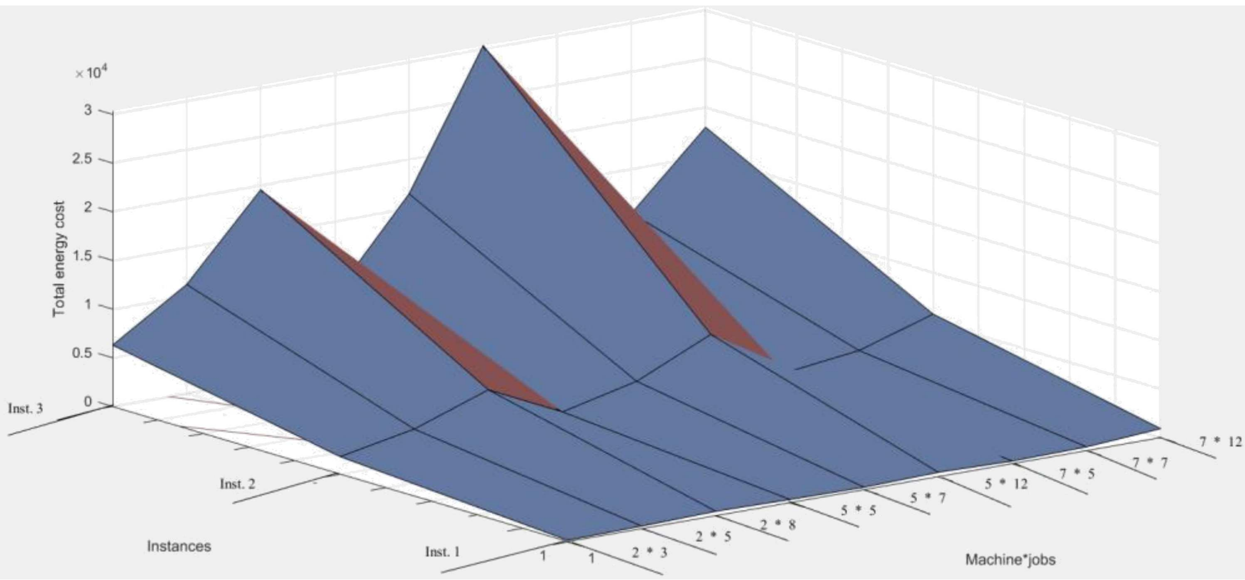

Fig. 4. Comparison of the evolution of the total energy cost according to average execution times for small problems.

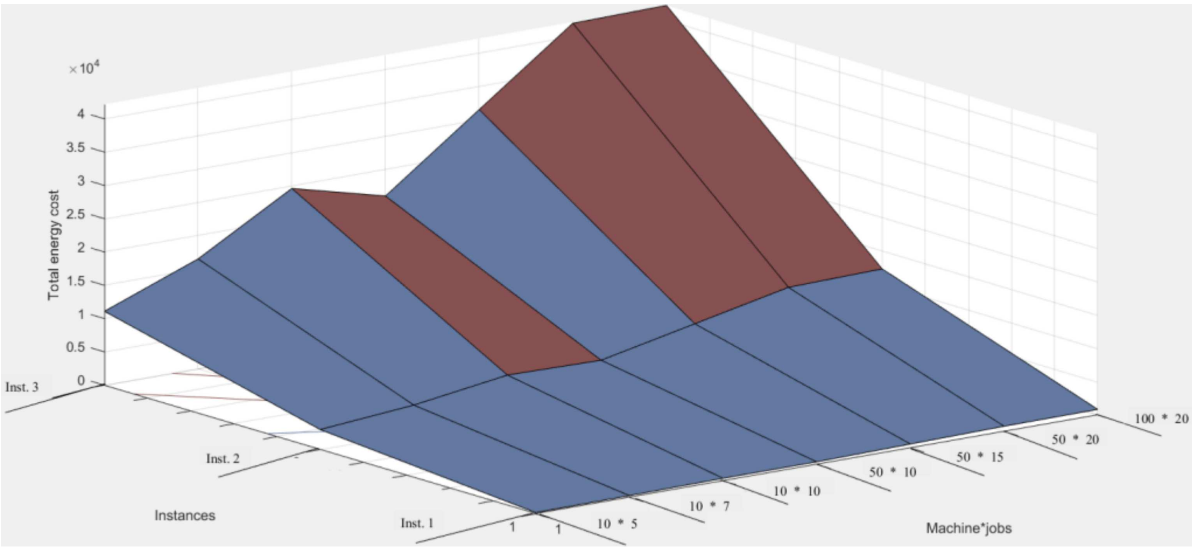

Fig. 5. Comparison of the evolution of the total energy cost according to average execution times for large problems.

We notice that when you do the same number of tasks in one shop to another, you will have almost the same TEC.

As an example, we take the 3rd instance of the scheduling problem (5*5), ie with The PM preventive maintenance time is 15, the processing times of jobs were generated uniformly in the interval [70, 100] in this instance, The processing powers P are derived from the uniform distribution [6, 8] and The duration of period k is 100, followed by the electricity price in period k is 5. We will have the same value of TEC 7500 for the scheduling problem (7*5) and also we find almost the same results for the problems of scheduling (7*5) and (7*7) for value of 16500 and 10500 monetary units.

And of course if we run a large number of spots on different machines, we will have a large TEC.

For large scheduling problems situation is similar. We notice that when you do the same number of tasks in one shop to another, you will have almost the same TEC.

As an example, we take the 3rd instance of the scheduling problem (10*10), ie with The PM preventive maintenance time is 15, the processing times of jobs were generated uniformly in the interval [70, 100] in this instance, The processing powers P are derived from the uniform distribution [6, 8].

The duration of period k is 100, followed by the electricity price in period k is 5.

We will have the same value of TEC 21000 for the scheduling problem (50*10) and also we find almost the same results for the problems of scheduling (10*10) and (50*10) for value of 24600 and 21000 monetary units.

Similarly for scheduling problems (50*20) and (100*20) we will have as value of TEC 42000 and 42244 monetary units, respectively. And of course if we execute a large number of tasks on different machines, we will have a large TEC.

Conclusion

This paper considers an unrelated parallel machine joint scheduling of jobs and preventive maintenance problem under time of-use (TOU) electricity pricing scheme under the TOU tariffs to minimize the total electricity cost.

We first formulate an improved MILP model for the problem.

To evaluate the performance of this model, computational experiments are presented, and numerical results are given using the software CPLEX and MATLAB with then discussed.

Overall, we found the right results for this type of scheduling of jobs and preventive maintenance problem under time of-use (TOU) electricity pricing scheme under the TOU tariffs to minimize the total electricity cost.

To tackle large-size problem, we will develop an efficient two-stage Heuristic.

We will extend the proposed models to other scheduling problems and take more realistic factors such as peak power load, setup and transportation time into consideration. Besides, due to the inefficiency of MILP models on large-scaled problems, we will explore energy-efficient dispatching rules and energy-efficient metaheuristic algorithms to solve these problems in further studies.

Future research can be focused on the extension of the problem to other machine environments, such as flow shop and job shop, and investigating the multi-objective version of the problem using multi-objective optimization approaches.

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