Journal of Mathematical Modeling
Vol. 9, No. 2, 2021, pp. 215–227

JMM

Flow shop scheduling under Time-Of-Use electricity tariffs using fuzzy multi-objective linear programming approach

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Abstract. Given the reduction of non-renewable energy resources and increase of energy costs during recent years, developing an efficient scheduling model considering energy consumption is necessary in manufacturing systems. This paper is dedicated to flow shop scheduling problem under Time-Of-Use electricity tariffs. In this regard, a bi-objective mixed-integer programming model is formulated for the problem. Two objectives, namely, the minimization of the total electricity cost and the sum of earliness and tardiness of jobs, are considered simultaneously. The bi-objective model is converted into an equivalent single objective linear programming model using fuzzy multi-objective programming approach. The CPLEX solver in GAMS software is used to solve the proposed model for an instance. The numerical example shows that the proposed model is reasonable and applicable.

Keywords: mixed-integer programming, bi-objective model, electricity price, earliness, tardiness.
AMS Subject Classification 2010: 90C90, 90C11, 90B35.

1 Introduction

With the reduction of non-renewable energy resources and increase of energy costs during recent years, efficient energy consumption has been the focus of many industry managers. Many energy

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Received: 29 March 2020 / Revised: 3 September 2020 / Accepted: 13 September 2020
DOI: 10.22124/jmm.2020.16104.1406

providers have set an incentive scheme for electricity costs called Time-Of-Use electricity tariffs. In this way, energy costs are calculated per kilowatt-hour at different prices for different hours of day. This tariff can be considered as a great opportunity for subscribers, especially for energy-intensive factories and industries, to reduce the total costs of their energy consumption. There are three main types of electricity pricing: Time-Of-Use (TOU), real-time pricing (RTP) and critical peak pricing (CPP) [10, 17].

In the TOU scheme, electricity prices are adjusted based on demand in the power grid. One day is divided into several periods, including on-peak, mid-peak and off-peak periods. The price of electricity varies in different periods. The on-peak period price is the highest, then the mid-peak price, and the price of the o-peak period is the lowest. This scheme encourages manufacturers to shift their operating time from on-peak periods to off-peak or mid-peak to avoid excessive electricity costs.

Energy tariffs in Iran are also divided into three types of periods per day (on-peak, mid-peak and off-peak periods), each with a separate electricity price. To comply with the TOU scheme, manufacturers must optimize their production plans in order to reduce the total costs of energy. In some countries, energy tariffs are different in some months and seasons. As illustrated in Figure 1, tariffs are constant and unchanged on weekends. As can be seen, energy tariffs for different time intervals are not the same during winter and summer seasons.

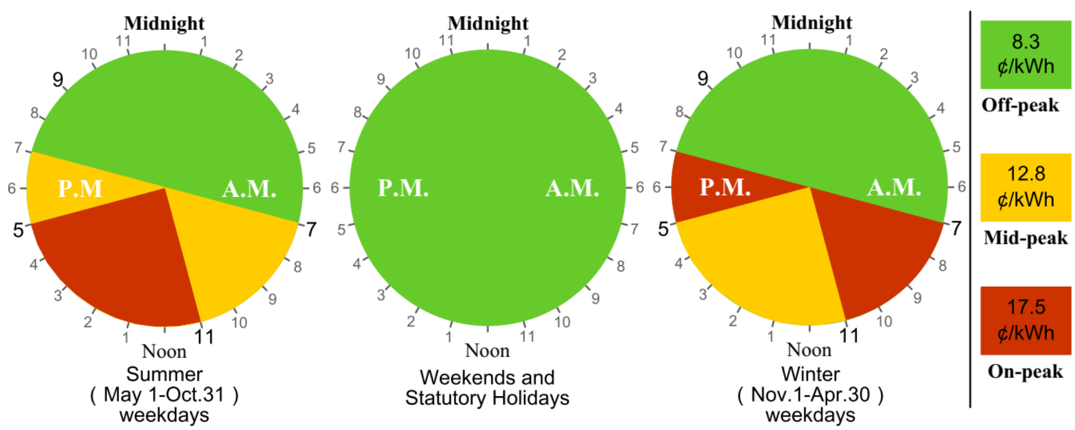

Figure 1: Time-Of-Use energy tariffs in the province of Ontario-Canada [3].

More than 90 percent of the energy required by industrial units is used in manufacturing and operating sectors [14]; therefore, in recent years, many researchers have focused on scheduling problem considering energy consumption.

In 2020, Ho et al. [7] studied a two-machine flow shop scheduling problem under Time-Of-Use electricity tariffs and optimal makespan. They proposed three heuristics based on Johnson's rule and three heuristics based on Hadda's algorithm [6]. In 2019, Zhang et al. [16] investigated the flexible flow shop scheduling problem considering Time-Of-Use electricity tariffs. In their article, machine tools energy consumption included various costs associated with processing time, stand-by time and set-up time. The Experiments and analysis revealed that their proposed method is suitable for trade-off of electricity cost and delivery time. Abikarram et al. [1] examined the minimization of energy costs in unrelated parallel machine environment. Unlike other studies that only considered different energy tariffs in periods, their study took into account the amount of demand for energy in different periods. Wu et al. [13] studied a single-machine batch scheduling problem under TOU electricity tariffs to minimize the total electricity cost and makespan simultaneously.

Li et al. [8] presented an algorithm for hybrid flow shop scheduling problem to minimize the makespan and the energy consumptions. Their proposed algorithm performed very well in solving sets of benchmark instances with different sizes compared to the existing algorithms. Zeng et al. [15] investigated the uniform parallel machine scheduling problem considering the cost of electricity under Time-Of-Use electricity tariffs. Their goal was to minimize the cost of electricity consumption and the number of machines used. They proposed an iterative search algorithm to solve the bi-objective model. The proposed algorithm minimized the cost of electricity consumption for a certain number of machines. The computational results in relation to the real-life and randomly generated instances showed the good performance of the proposed approach for solving large-size problems up to 5000 jobs. Wang et al. [12] considered scheduling jobs on two-machine permutation flow shop with TOU electricity tariffs. They proposed two heuristic algorithms based on Johnson's rule and a dynamic programming method.

Che et al. [4] addressed the unrelated parallel machine scheduling problem to minimize the cost of electricity consumption. They provided a mixed-integer linear programming model for solving small-size problems. To tackle large-size problems, they proposed a two-stage heuristic algorithm. The first stage in their proposed algorithm was to assign jobs to machines, and in the second stage, jobs were scheduled on machines. The case study and the computational results showed the good performance of the proposed model and algorithm. Wang et al. [11] studied a single machine batch scheduling problem to simultaneously minimize makespan and total energy consumption costs. They proposed an integer program and a constructive heuristic to solve the bi-objective problem. Ding et al. [5] proposed a mixed integer programming formulation for unrelated parallel machine under TOU tariffs to minimize the total electricity cost respecting given makespan. They designed a column generation based heuristic algorithm to solve the problem.

Given the importance of efficient energy consumption and just-in-time (JIT) philosophy where both job earliness and tardiness have penalties, this paper presents a new mixed integer programming model for the flow shop scheduling problem considering Time-Of-Use electricity tariffs. The goal is to minimize the cost of electricity consumption and the sum of earliness and tardiness of jobs. In order to achieve the solution, the proposed bi-objective model is first converted to single-objective linear programming model using fuzzy multi-objective programming approach. Then, the single-objective model is coded in GAMS software and solved optimally by CPLEX solver.

The remainder of the paper is structured as follows. The problem is described in Section 2. Section 3 presents the proposed mathematical model for the problem. Section 4 is dedicated to numerical example. Finally, in Section 5, conclusions and some suggestions for future studies are presented.

2 Problem description

The flow shop scheduling problem consists of n jobs and m machines and all the jobs follow the same route on these machines. The amount of energy consumed by the machines in the processing state as well as the processing time of each job on each machine is deterministic and known in advance. Based on the predicted electricity consumption, energy tariffs at different time intervals are predetermined. The problem is to determine the start/completion times of the jobs on each machine, so that the two objectives including the cost of electricity consumption and the sum of earliness and tardiness time of jobs are minimized. The main assumptions of the problem are as follows:

- All jobs and machines are available at time zero.
- Each machine can process only one job at a time and each job is processed on at most one machine at a time.
- Machines are available at all times.
- Job preemption is not allowed.
- An operation of a job cannot be processed until its preceding operations are completed.
- All programming parameters such as processing time, electricity consumption, electricity price, and due date are deterministic and known in advance.

3 Mathematical model

In this section, the proposed bi-objective mixed-integer programming model will be described. Notations used in the mathematical formulation are as follows:

Indices	
i, i'	index of jobs, $i, i' = 1, \ldots, n$
j	index of machines, $j = 1, \ldots, m$
k, k'	index of pricing intervals (periods), $k, k' = 1, \ldots, K$
z	index of objectives, $z = 1, 2$

Parameters	
n	total number of jobs
m	total number of machines in a flow shop
K	total number of pricing intervals
$t_{i,j}$	processing time of job i on machine j
d_i	due date of job i
P_k	duration of the kth pricing interval
CE_k	electricity price in the kth pricing interval (unit money per unit electricity)
PE_j	power consumption rate of processing jobs on machine j
M	a large enough integer

Decision Variables	
$C_{i,j}$	completion time of job i on machine j
C_i	completion time of job i
E_i	earliness of job i, $E_i = max\{d_i - C_i, 0\}$
T_i	tardiness of job i, $T_i = max\{C_i - d_i, 0\}$
$x_{i,j,k}$	assigned processing time of job i on machine j in period k
$y_{i,j,k}$	a binary variable that is equal to 1 if job i or part of job i is processed on machine j in period k, and 0 otherwise
$w_{i,i',j}$	a binary variable that is equal to 1 if job i' is immediately processed after job i on machine j, and 0 otherwise

The following bi-objective mixed integer optimization model seeks to find a schedule that minimizes (1) the total electricity cost, and (2) the sum of earliness and tardiness of jobs for the flow shop scheduling problem under Time-Of-Use energy tariffs.

$$\min f_1 = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{K} PE_j \times CE_k \times x_{i,j,k}, \tag{1}$$

$$\min f_2 = \sum_{i=1}^{n} E_i + \sum_{i=1}^{n} T_i, \tag{2}$$

Subject to

$$\sum_{k=1}^{k} x_{i,j,k} = t_{i,j}, \qquad i = 1,\dots,n;\ j = 1,\dots,m, \tag{3}$$

$$\sum_{i=1}^{n} x_{i,j,k} \le P_k, \qquad j = 1,\dots,m;\ k = 1,\dots,K, \tag{4}$$

$$x_{i,j,k} \le t_{i,j} \times y_{i,j,k}, \qquad i = 1,\dots,n;\ j = 1,\dots,m;\ k = 1,\dots,K, \tag{5}$$

$$y_{i,j,k} \le x_{i,j,k}, \qquad i = 1,\dots,n;\ j = 1,\dots,m;\ k = 1,\dots,K, \tag{6}$$

$$x_{i,j,k} \ge (y_{i,j,k-1} + y_{i,j,k+1} - 1)P_k, \qquad i = 1,\dots,n;\ j = 1,\dots,m;\ k = 2,\dots,K-1, \tag{7}$$

$$\sum_{k'=k+2}^{K} y_{i,j,k'} \le (K-k-1)(1 - y_{i,j,k} + y_{i,j,k+1}), \qquad i = 1,\dots,n;\ j = 1,\dots,m;\ k = 1,\dots,K-2, \tag{8}$$

$$y_{i,j,k} + y_{i,j,k+1} + y_{i',j,k} + y_{i',j,k+1} \le 3, \qquad i = 1,\dots,n;\ i' = 1,\dots,n;\ i \ne i';\ j = 1,\dots,m;\ k = 1,\dots,K-1, \tag{9}$$

$$C_{i,j} \ge C_{i,j-1} + t_{i,j}, \qquad i = 1,\dots,n;\ j = 2,\dots,m, \tag{10}$$

$$C_{i',j} \geq C_{i,j} + t_{i',j} - M(1 - w_{i,i',j}), \quad i = 1,\dots,n;\ i' = 1,\dots,n;\ i \neq i';\ j = 1,\dots,m, \tag{11}$$

$$C_{i,j} \geq C_{i',j} + t_{i,j} - M(w_{i,i',j}), \quad i = 1,\dots,n;\ i' = 1,\dots,n;\ i \neq i';\ j = 1,\dots,m, \tag{12}$$

$$C_{i,j} \geq y_{i,j,k} \sum_{k'=1}^{k-1} P_{k'} + x_{i,j,k}, \quad i = 1,\dots,n;\ j = 1,\dots,m;\ k = 2,\dots,K, \tag{13}$$

$$C_i = C_{i,j}, \quad i = 1,\dots,n;\ j = m, \tag{14}$$

$$E_i \geq d_i - C_i, \quad i = 1,\dots,n, \tag{15}$$

$$T_i \geq C_i - d_i, \quad i = 1,\dots,n, \tag{16}$$

$$C_i \geq 0, \quad i = 1,\dots,n, \tag{17}$$

$$T_i \geq 0, \quad i = 1,\dots,n, \tag{18}$$

$$E_i \geq 0, \quad i = 1,\dots,n, \tag{19}$$

$$x_{i,j,k} \geq 0, \quad i = 1,\dots,n;\ j = 1,\dots,m;\ k = 1,\dots,K, \tag{20}$$

$$y_{i,j,k} \in \{0,1\}, \quad i = 1,\dots,n;\ j = 1,\dots,m;\ k = 1,\dots,K, \tag{21}$$

$$w_{i,i',k} \in \{0,1\}, \quad i = 1,\dots,n;\ i' = 1,\dots,n;\ i \neq i';\ k = 1,\dots,K, \tag{22}$$

Equation (1) denotes the first objective function of the model. This objective function minimizes the total electricity cost (f_1). Equation (2) is the second objective function of the model that minimizes the total earliness and tardiness of jobs (f_2). Constraint (3) states that the total processing time of a job on a machine assigned in all periods is exactly equal to its corresponding processing time. Constraint (4) guarantees that the total processing time on a machine which assigned to a period cannot exceed the duration of that period. Constraint (5) states that if a job is not assigned to a machine in a period (i.e. $y_{i,j,k} = 0$), then no part of that job can be processed on that machine in that period (i.e. $x_{i,j,k} = 0$).

Constraint (6) guarantees that if no part of a job is processed on a machine in a given period (i.e., $x_{i,j,k} = 0$), then that job cannot be assigned to that machine during that period (i.e. $y_{i,j,k} = 0$). Constraint (7) states that if part of a job is performed on a machine in periods $k-1$ and $k+1$, then the whole period of k is assigned to that job on that machine. Constraint (8) states that if a part of a job is processed on a machine in a period and is not processed in the next period, then it cannot be processed in subsequent periods. Constraint (9) states that two different jobs cannot be processed on the same machine in two consecutive periods. Constraints (7)-(9) actually prevent the processing of jobs from being interrupted. Constraint (10) ensures that until the previous operation of a job is not completed, the subsequent operation cannot be performed. In fact, this constraint represents the sequence of processing a job on different machines. Constraints (11) and (12) indicate that there is no overlap of processing jobs on a machine. In other words, two different jobs are not assigned to a machine at the same time.

Constraint (13) indicates the relationship between the completion time of processing a job on a machine and the length of periods. Constraints (14)-(16) calculate the completion, earliness and tardiness times for jobs, respectively. Constraints (17)-(22) indicate the type of problem decision variables.

The proposed bi-objective model can be transformed into single-objective linear programming problem by using Bellman and Zadeh fuzzy decision making principle [2] and Zimmermann fuzzy programming method [18]. The steps are as follows:

Step 1: Obtain positive ideal solution (PIS) and negative ideal solution (NIS) for each objective function by solving problems (23)-(26) separately (lexicographic technique is used here).

$$f_1^{PIS} = \min f_1, \tag{23}$$
Subject to: (3)-(22) ,

$$f_2^{PIS} = \min f_2, \tag{24}$$
Subject to: (3)-(22) ,

$$f_1^{NIS} = \min f_1, \tag{25}$$
Subject to: (3)-(22) and $f_2 = f_2^{PIS}$,

$$f_2^{NIS} = \min f_2, \tag{26}$$
Subject to: (3)-(22) and $f_1 = f_1^{PIS}$,

where f_z, f_z^{PIS} and f_z^{NIS} are respectively the values of the objective function z, the positive ideal solution of the objective function z and the negative ideal solution of the objective function z.

Step 2: For each objective function, consider the linear membership function as in (27).

$$\mu_z(f_z) = \begin{cases} 1, & \text{for } \; f_z \leq f_z^{PIS}, \\ \dfrac{f_z^{NIS} - f_z}{f_z^{NIS} - f_z^{PIS}}, & \text{for } \; f_z^{PIS} \leq f_z \leq f_z^{NIS} \\ 0, & \text{for } \; f_z \geq f_z^{NIS}. \end{cases} \qquad z = 1, 2, \tag{27}$$

Step 3: Using the linear membership functions and following the fuzzy decision making principle of Bellman and Zadeh [2], consider the multi-objective linear programming problem as follows:

$$\max \left[\min \left\{ \frac{f_1^{NIS} - f_1}{f_1^{NIS} - f_1^{PIS}}, \frac{f_2^{NIS} - f_2}{f_z^{NIS} - f_2^{PIS}} \right\} \right],$$
Subject to: (3)-(22) . (28)

Step 4: Based on Zimmermann's method [18] and considering $0 \leq \lambda \leq 1$, write the multi-objective linear programming problem as the single-objective linear programming problem of

(29). λ is the satisfaction level of objective functions and a high value of λ shows that all objectives are optimized with a high degree of satisfaction.

$$\max \lambda,$$
Subject to: (3)-(22) and
$$\lambda \leq \frac{f_1^{NIS} - f_1}{f_1^{NIS} - f_1^{PIS}},$$
$$\lambda \leq \frac{f_2^{NIS} - f_2}{f_2^{NIS} - f_2^{PIS}}. \quad (29)$$

4 Numerical example

For illustrative purposes, a flow shop scheduling problem with 6 jobs and 5 machines is considered in this section. According to the study of Minella et al. [9], the processing times (i.e. $t_{(i,j)}$) are generated from a uniform distribution on the interval [1, 99]. The due dates of the jobs (i.e. d_i) follow the expression: $T_i^{'} \times (1 + u \times 3)$, where $T_i^{'}$ is the sum of the processing times over all machines for job i and u is random number uniformly distributed on the interval [0, 1]. The power consumption per hour for each machine (i.e. PE_j) follows a uniform distribution between 30 and 100 kW. Table 1 shows the processing time of jobs on machines, due date of jobs and the power consumption per unit of time for each machine. The number of periods, the duration of periods and the cost of electricity consumption in each period are listed in Table 2.

Table 1: Data related to the jobs and machines in numerical example.

	processing time (min)						power consumption rate
	Job1	Job2	Job3	Job4	Job5	Job6	(kWh)
Machine 1	54	83	15	71	77	36	65
Machine 2	79	3	11	99	56	70	68
Machine 3	16	89	49	15	89	45	30
Machine 4	66	58	31	68	78	91	88
Machine 5	58	56	20	58	53	35	32
Due date	767	770	328	1239	591	592	

Table 2: Data related to the periods in numerical example.

Period	Type	Duration (min)	Electricity price (IRR/kWh)
1	Mid-peak	300	821
2	On-peak	120	1642
3	Mid-peak	360	821
4	On-peak	120	1642
5	Mid-peak	120	821
6	Off-peak	420	410.5

The proposed mixed integer linear programming model is coded in GAMS software. The numerical example is solved via CPLEX solver on a laptop with Intel® Core^{TM} i7-8550U CPU @ 1.8 GHz and 8 GB RAM in Windows 10 with 64-bit operating system. The results are presented in Table 3.

Table 3: Results of GAMS software.

Scheme	Problem	f_1	f_2
Scheme 1	Problem (23)	811674.808	3520
Scheme 2	Problem (24)	1609734.700	87
Scheme 3	Problem (25)	1239203.717	87
Scheme 4	Problem (26)	811674.808	3458
Scheme 5	Problem (29)	976189.525	1383

Based on the results of GAMS software, if each of the objectives, minimizing the cost of energy consumption and minimizing the total earliness and tardiness, are considered separately, their optimal value will be 811674.808 and 87, respectively. If the two objectives are considered simultaneously, the satisfaction level of the objective functions is 0.615. Gantt charts of five different scheduling schemes are shown in Figure (2)-(6).

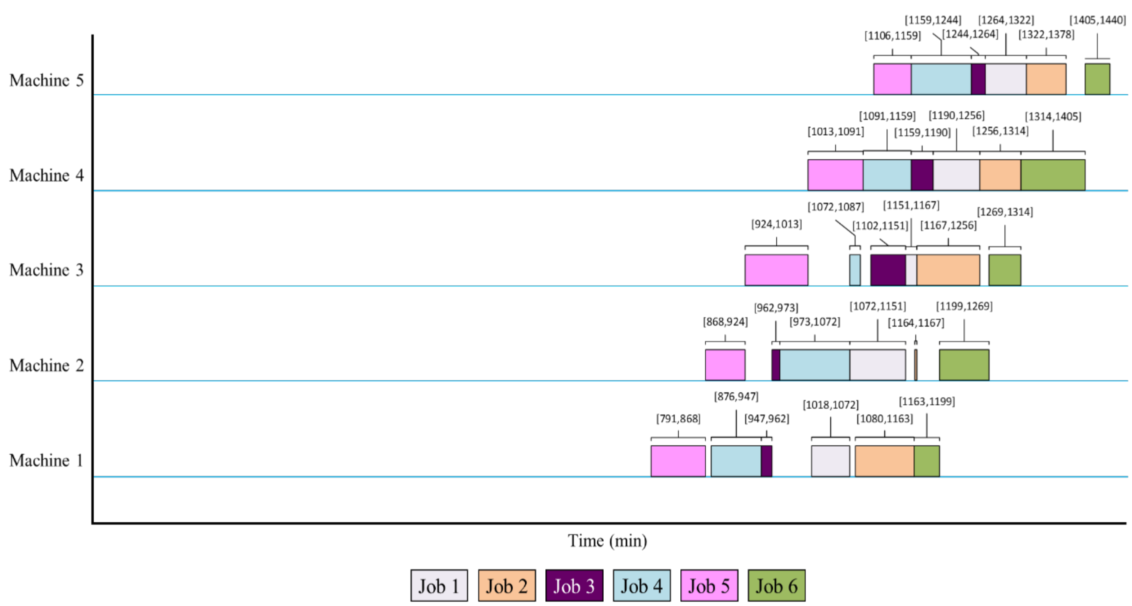

Figure 2: The Gantt chart of scheme 1, with $f_1 = 811674.808$ and $f_2 = 3520$.

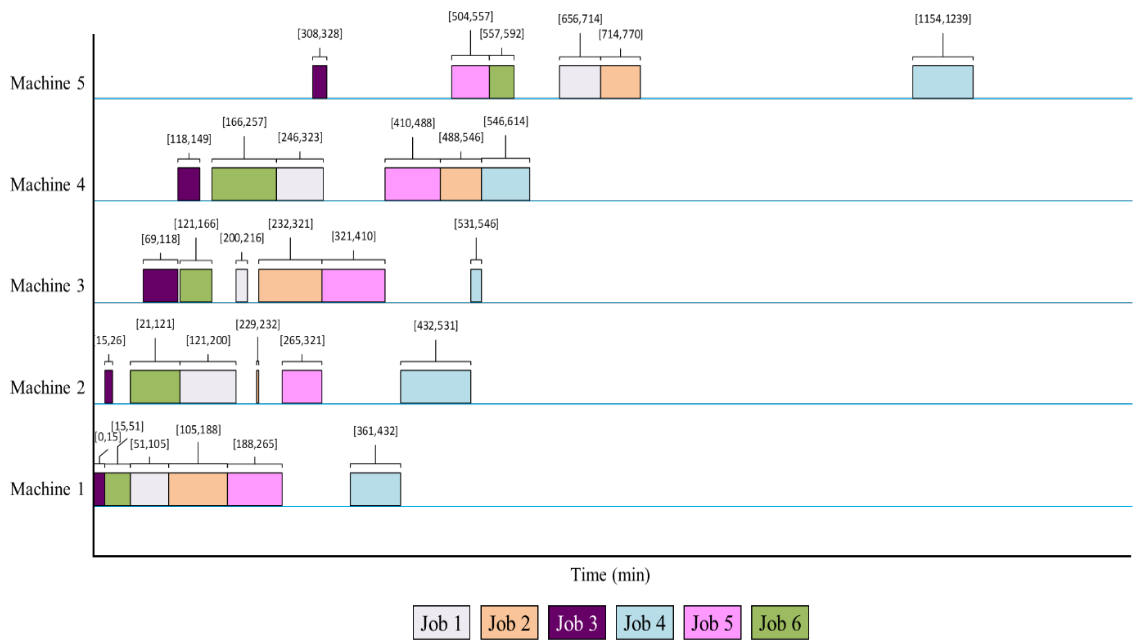

Figure 3: The Gantt chart of scheme 2, with $f_1 = 1609734.700$ and $f_2 = 87$.

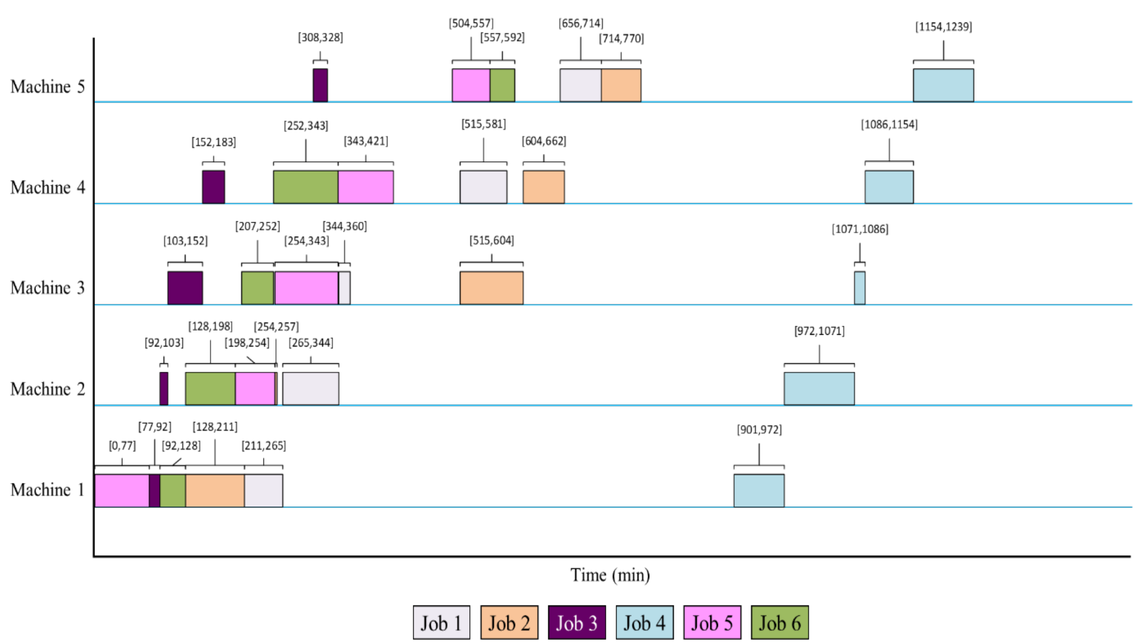

Figure 4: The Gantt chart of scheme 3, with $f_1 = 1239203.717$ and $f_2 = 87$.

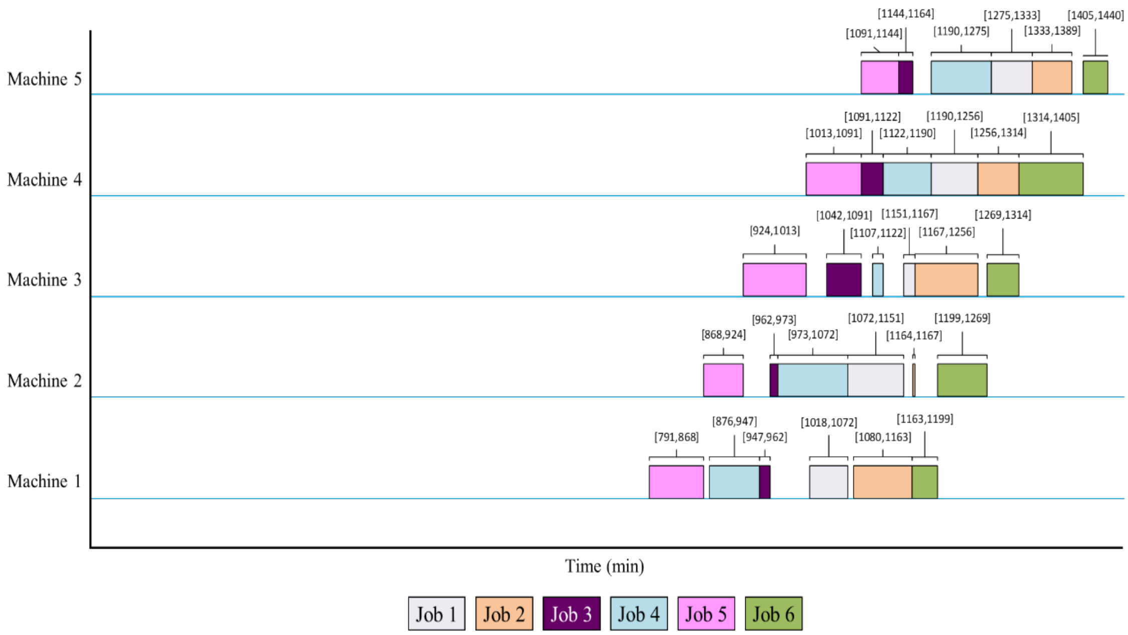

Figure 5: The Gantt chart of scheme 4, with $f_1 = 811674.808$ and $f_2 = 3458$.

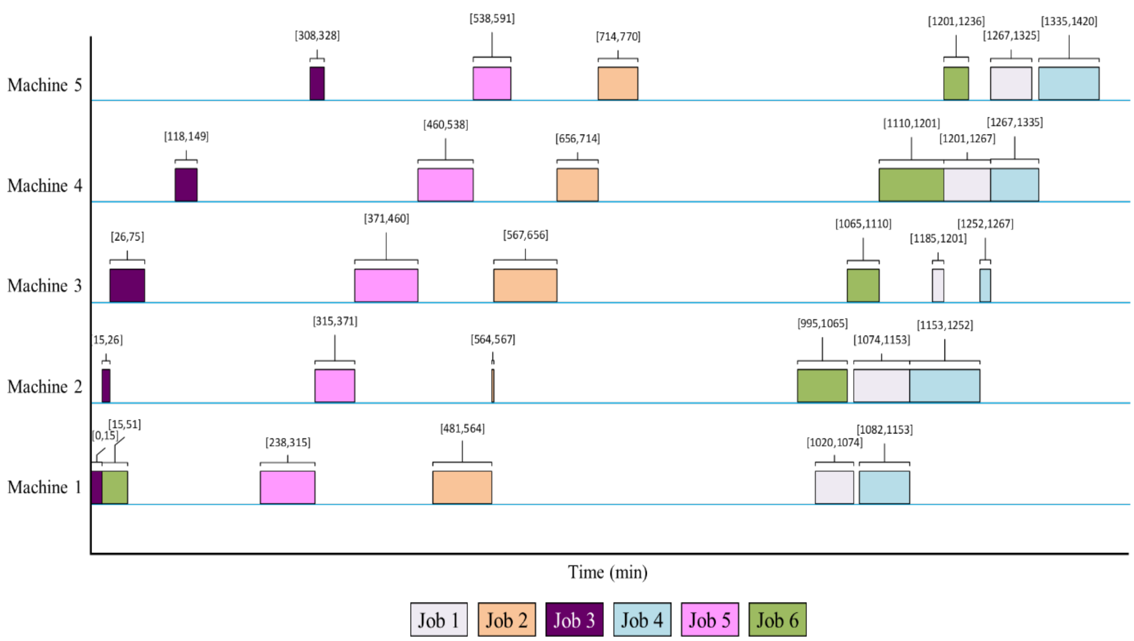

Figure 6: The Gantt chart of scheme 5, with $f_1 = 976189.525$ and $f_2 = 1383$.

5 Conclusion

Due to the importance of flow shop scheduling and efficient energy consumption, a new bi-objective mixed-integer programming model for the flow shop scheduling problem under Time-Of-Use electricity tariffs is proposed in this paper. In many manufacturing systems, early jobs may generate costs such as inventory costs, and tardy jobs may also generate costs such as loss of clients. Therefore, in the proposed model, in addition to the goal of minimizing the cost of energy consumption, minimizing the total earliness and tardiness of jobs is also considered. The bi-objective model is converted into a single-objective linear programming problem based on Zimmermann fuzzy programming method, and the CPLEX solver in GAMS software is used to solve the proposed model for an instance. A numerical example demonstrated the application of the proposed model developing meta-heuristic algorithms for solving large-scale problems, considering uncertainty, considering breakdown and preventive maintenance, and considering other production environments such as job shop are directions for future research.

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