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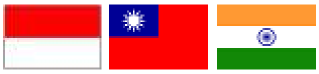
This issue has been available online since **30th August 2020** for the regular issue of **August 2020**. All articles in this issue (**10 articles (case study and research)**) were authored/co-authored by **25 authors** from **3 countries (Indonesia, Taiwan,** and **India).**



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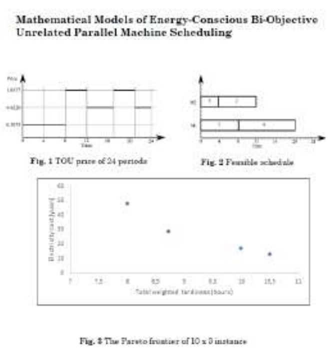
Article



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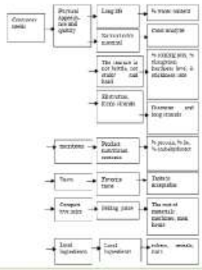

Concept	Flour Mesh	Compotition Mocaf flour : Corn flour (%)	Compotition Rice flour : Soy flour (%)	Guar gum (%)
1	40	35 : 25	35 : 5	1
2	40	30 : 30	30 : 10	1.5
3	40	25 : 35	25 : 15	2
4	60	35 : 25	30 : 10	1.5
5	60	30 : 30	25 : 15	1
6	60	25 : 35	35 : 5	1.5
7	80	35 : 25	25 : 15	1.5
8	80	30 : 30	35 : 5	2
9	80	25 : 35	: 10	1

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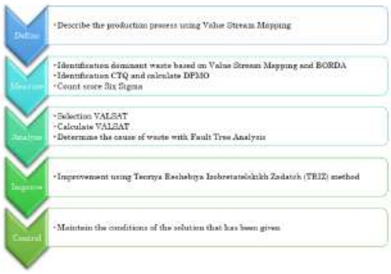

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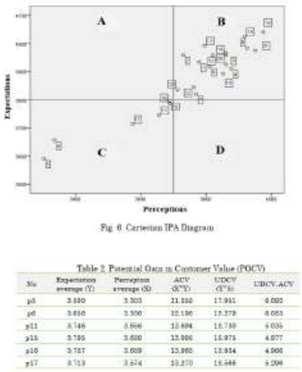

No	Expectation average (Y)	Perception average (X)	ACV (X*Y)	UDCV (Y*5)	UDCV-ACV
p5	3.590	3.303	11.850	17.951	6.099
p6	3.656	3.306	12.196	18.279	6.083
p11	3.746	3.666	13.694	18.730	5.036
p15	3.795	3.600	13.996	18.973	4.977
p10	3.787	3.689	13.968	18.934	4.966
p17	3.713	3.574	13.270	18.568	5.298

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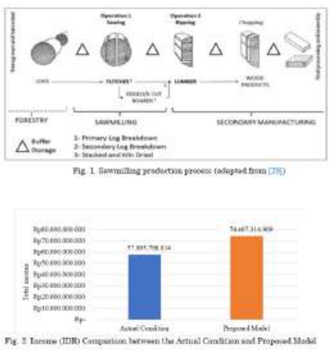

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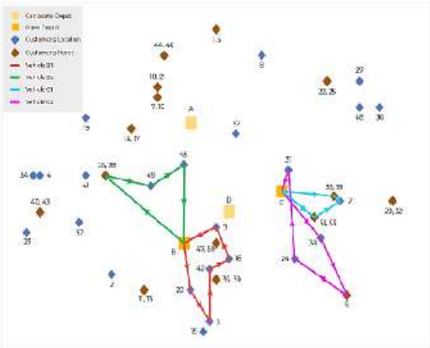

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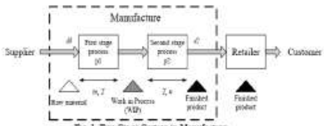

Fig. 1. Two-Stage System in Manufacture

Table 2. Software Calculation Results

Iteration	Population	Objective Function	Decision Variables		
		Profit (IDR)	m	n	T
10	10	566,810,000	1	1	0.2615
	50	569,340,000	1	2	1
	100	569,380,000	1	2	0.9142
50	10	568,640,000	3	1	1
	50	569,380,000	1	2	0.8843
	100	569,380,000	1	2	0.8844
100	10	569,160,000	2	3	1
	50	569,380,000	1	2	0.8844
	100	569,380,000	1	2	0.8844

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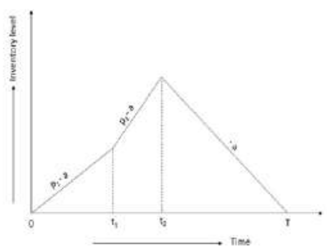

Multi Objective Optimization Model of Multi-Pass Turning Operations to Minimize Energy, Carbon Emissions, and Production Costs

Table 2. The results of the sensitivity analysis

Skenario	D	$d_{r,i}$	d_s	$f_{r,i}$	f_s	$V_{r,i}$	V_s
-40%	48	0.0%	-0.00000013%	42.36971%	0.00000%	0.0000000%	-1.781075%
-30%	56	0.0%	-0.00000051%	24.00817%	24.00815%	0.0000000%	-10.200298%
-20%	64	0.0%	-0.00000009%	17.32097%	0.00011%	0.0000000%	-0.000059%
-10%	72	0.0%	-0.00000051%	7.97614%	0.00000%	0.0000000%	0.000008%
0%	80	0.0%	0.00000000%	0.00000%	0.00000%	0.0000000%	0.000000%
10%	88	0.0%	0.00000006%	0.00000%	0.00000%	0.0000008%	-0.000033%
20%	96	0.0%	-0.00000011%	0.00000%	0.00000%	0.0000003%	-0.000022%
30%	104	0.0%	0.00000001%	0.00000%	0.00000%	0.0000000%	-0.000005%
40%	112	0.0%	-0.00000012%	0.00000%	0.00000%	0.0000001%	-0.000018%

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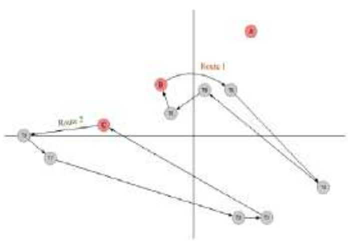

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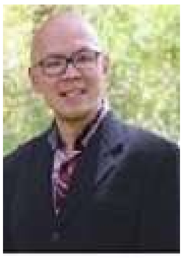

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Mathematical Models of Energy-Conscious Bi-Objective Unrelated Parallel Machine Scheduling

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ABSTRACT

The industrialization has led to the prosperity of human life. However, it causes the side effect that harms the environment. Moreover, the source of energy used to drive the industrialization comes from non-renewable resources that can be extinct. As the extensive energy user, the manufacturing sector can use energy efficiently by scheduling and planning. A scheduling system that incorporates environmental and the energy consumption is one of the initiatives to reduce energy consumption and reduce environmental effects. Therefore, this study addresses bi-objective unrelated parallel machine scheduling to minimize the total tardiness and energy consumption. The energy consumption follows the Time-Of-Use (TOU) tariffs price scheme. The problem is formulated as two mixed-integer programming (MIP) models, using the time-indexed and disjunctive formulation, and solved using the weighted sum method. We perform complexity and computational analysis to evaluate the performance of models. Numerical experiments show that the time-indexed formulation is more efficient than the disjunctive formulation. The results provide useful insights for decision-makers in the manufacturing sectors to be energy-conscious without neglecting the production efficiency.

1. Introduction

Although economic development contributes to human prosperity, it produces undesirable side effects that will threaten the environment. Accumulated greenhouse gas emissions resulting from fossil fuel combustion are attributed to global warming [1]. Fossil fuel is the primary source in generating energy to drive the economy. Therefore, several issues will arise with the increasing demand for electricity due to industrialization and population growth [2]. First, it produces energy scarcity because fossil fuel depletes over time and cannot be renewed. Second, it makes the quality of the environment deteriorated. Governments have implemented policies to stimulate energy-saving and sustainability practices among energy users to anticipate such high demand. The policies are imposed on the energy suppliers, particularly the manufacturing sector, as an extensive energy user. It has been investigated that the manufacturing industry expedites more than half

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of the total world consumption [3]. As a response, the manufacturing industry has implemented a new paradigm for its operational activities. In this paradigm, energy reduction and sustainability must be taken into account as a performance measure. As a result, research on the implementation of energy-saving and sustainability in manufacturing is abundant. Notably, research in scheduling also considers energy consumption as an objective besides the traditional ones.

The manufacturing sector can reduce its consumption by designing and installing energy-efficient machines and equipment [4] [5]. However, this approach requires massive investment. Small companies cannot afford to fund such investments. Therefore, researchers have paid the "soft method", such as scheduling as an alternative approach. Research that has been conducted in the past demonstrated the importance of scheduling as an energy-reduction and sustainability method [6] [7]. For instance, Mouzon et al. [8] implemented a machine power on/off mechanism. A machine was turn-off if it was in an idle state. Machine-speed scaling was another approach to reduce energy consumption. A job can be processed faster but requires more energy [9]. A hybrid sine cosine algorithm was proposed to reduce carbon emissions in a manufacturing company [10]. Recently, energy providers implemented Time-Of-Use tariffs (TOU) to reduce generation and operations costs. The policy provides incentives for consumers that adjust their consumption patterns. In this policy, electricity price in a period is different from those of other periods. Periods are categorized as peak periods (higher prices), middle-peak periods, and off-peak periods (lower prices) [11] [12]. The manufacturer that schedules its operational time from peak to off-peak periods can reduce its operational cost. As a result, the maximum load can be lowered so that energy suppliers can reduce operational and maintenance costs [13], [14]. Therefore, the TOU policy provides the energy-saving measure for energy providers and consumers. Accordingly, the research topic of energy, especially scheduling under TOU, has been abundant [15], [16].

For research of Unrelated Parallel Machine Scheduling (UPMS) under TOU, Moon et al. [17] have studied UPMS under TOU to minimize the sum of the weighted makespan and electricity cost. They proposed a hybrid genetic algorithm (GA) to tackle the problem. Koo and Kim [18] improved Moon et al.'s model. Kurniawan et al. [19] have proposed a GA with a self-adaptive mechanism to solve the same problem as Moon et al. Ding et al. [20] have developed a mixed-integer programming (MIP) model and proposed a column generation method in dealing with UPMS to minimize the electricity consumption. A mathematical model for UPMS under TOU has been presented by Hossein et al. [21]. For research of multi-objective UPMS, Nikabadi and Naderi [22] have proposed a hybrid genetic algorithm (GA) and simulated annealing (SA) to handle the multi-objective UPMS. The objectives are the number of tardy jobs and total tardiness/earliness. Li et al. [23] proposed ten heuristic rules to solve UPMS with energy consideration. A multi-objective UPMS subject to resource constraints was investigated by Wang and Liu [24]. They proposed a meta-heuristic based on an artificial immune system combined with a non-dominated sorting strategy to solve the problem.

The discussion above shows that energy and the environment are essential research topics because they are critical to human life. Hence, the energy-saving method is fostered by the government, energy suppliers, and energy users. Some research has reported the importance of scheduling as an energy-saving measure. Previous research of UPMS under TOU only considered the electricity cost. Similarly, previous studies of multi-objectives did not consider TOU. The current study tries to fill the energy-conscious multi-objective scheduling problem gap, especially the TOU schedule. Therefore, this research addresses multi-objective energy-conscious scheduling for unrelated parallel machine environments under TOU. The objectives are to minimize the total tardiness and

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electricity cost simultaneously. The problem is formulated as two MIP models. The time-index formulation [25] is used to formulate the first model. In contrast, the second model is formulated based on disjunctive formulation [26]. Both models are solved using the weighted sum method (WSM) and calculated using CPLEX. The WMS method possesses several advantages compared to other multi-objective algorithms, such as Nondominated Sorting Genetic Algorithm II (NSGA-II) [27] and Multi-Objective Evolutionary Algorithm Based On Decomposition (MOEA/D) [28]. A multi-objective evolutionary algorithm (NSGA-II and MOEA/D) can generate a set of non-dominated solutions in one run. However, the optimality of the solutions is not yet known and not guaranteed to be optimum.

On the other hand, the WMS is easy to be implemented and high search efficiency, and the ability to find a non-dominated solution [29]. However, a priori preference must be determined manually [30], and it is hard to decide on the weight for each objective. As a result, the WMS must be executed in more than one run to obtain a Pareto frontier. In sum, the contributions of this research are as follows. First, the multi-objective energy-conscious UPMS under TOU that differs from previous research is investigated. Then, two MIP models are developed using the disjunctive and time-indexed formulations. Finally, the sum of the weighted method solved the models.

The remainder of this paper is structured as follows. Section 2 describes the problem formulation and the proposed method. Section 3 presents the results and analysis. Section 4 concludes this research and provides some future works.

2. Methods

2.1 Formulation

The problem considered in this research is stated as follows. A factory has N jobs, $j = 1,2,..,N$, that must be processed in M machines, $i = 1,2,\ldots,M$. Each job has a due date d_j. The processing time of job j in machines i is p_{ij}. All jobs must be finished within a discrete-time horizon $[0, U]$. The time horizon is divided into U periods with length one. A period t represents an interval $[t-1, t], t = 1,2,\ldots,T$. Electricity cost incurs when a job is processed on a machine and depends on the job period. The electricity price in each period, a_t, is different from those in other periods. The objectives are to minimize the total tardiness and electricity cost.

Fig. 1 illustrates a daily TOU price in China, and Fig. 2 shows an example of a schedule. Periods 1–8 denote the off-peak in which electricity price is lower compare with other periods. Periods 13–17 and 22–24 denote the mid-peak periods. Periods 9–12 and 22–24 denote the peak periods in which the electricity prices are the highest.

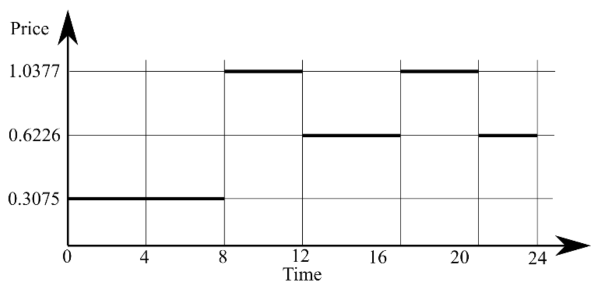

Fig. 1 TOU price of 24 periods

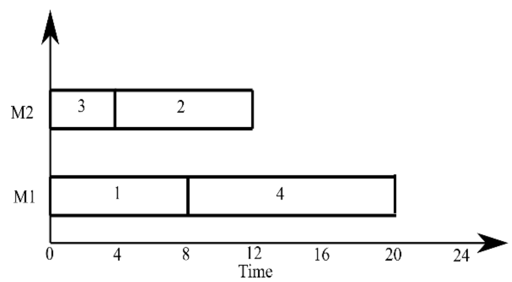

Fig. 2 Feasible schedule

Consider a schedule of 4 jobs and two machines, as shown in Fig. 2. The calculation of the electricity price is demonstrated using job 1. Job 1 starts at time zero and finishes

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at time 8. Period 1 starts at period one and finishes at period 1. Therefore, job 1 is processed from period one until period 8. Using the price in Fig. 1, the electricity cost to process job 1 is 0.3075 * 8 = 2.46.

2.2 Assumptions

The problem of UPMS under TOU is formulated to become model 1 (P_1) and model 2 (P_2). Model P_1 is developed based on time-index formulation, whereas model P_2 is derived based on disjunctive formulation. In modeling the scheduling problems, the most crucial consideration is how to formulate the decision variable for sequencing. The variable used in the sequencing is binary. The differences in modeling the binary variables lead to different complexity.

Several assumptions for the model P_1 and P_2 are as follows.

(1) No pre-emption is allowed, i.e., all jobs must be processed until finished without interruption.
(2) The machines can be idle and require no electricity cost.
(3) All jobs are available at time zero.
(4) Machines are always available, i.e., no machine breakdowns.
(5) There are no maintenances activities.

Notations used by model P_1 and P_2 are:

d_j = the due date of job j

p_{ij} = the processing time of job j on machine i

ω_1, ω_2 = the weight of total weighted tardiness objective and electricity cost objective, respectively, where $\omega_1 + \omega_2 = 1$.

2.3 Model 1 (P1)

The binary variables, integer variables, and parameters used in this model are as follows.

Variables :

x_{ijt} : 1 if job j is processed on machine i in period t, 0 otherwise

y_{ij} : 1 if job j is processed on machine i, 0 otherwise

$z_{ijt(t+1)}$: 1 if job j is processed on machine i during period t and $t+1$, 0 otherwise

C_j : completion time of job j

T_j : tardiness of job j

Parameters

a_t : the electricity price in period t

Model P_1 is formulated as follows.

$$\text{Minimize } \omega_1 \sum_{j=1}^{N} T_j + \omega_2 \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{t=1}^{U} a_t x_{ijt} \quad (1)$$

$$\sum_{t=1}^{U} \sum_{i=1}^{M} x_{ijt} \leq 1, \quad 1 \leq j \leq N \quad (2)$$

$$\sum_{t=1}^{U} x_{ijt} = p_{ij} y_{ij}, \quad 1 \leq i \leq M; 1 \leq j \leq N \quad (3)$$

$$\sum_{i=1}^{M} y_{ij} = 1, 1 \le j \le N \tag{4}$$

$$x_{ijt} + x_{ij(t+1)} \ge 2z_{ijt(t+1)}, 1 \le i \le M; 1 \le j \le N;\ 1 \le t \le U \tag{5}$$

$$\sum_{t=1}^{U-1} z_{ijt(t+1)} \ge \sum_{t=1}^{U} x_{ijt} - 1, 1 \le i \le M; 1 \le j \le N \tag{6}$$

$$x_{ijt} \ge z_{ijt(t+1)},\ \ 1 \le i \le M; 1 \le j \le N; 1 \le t \le U-1 \tag{7}$$

$$x_{ij(t+1)} \ge z_{ijt(t+1)},\ \ 1 \le i \le M; 1 \le j \le N;\ 1 \le t \le U-1 \tag{8}$$

$$tx_{ijt} \le C_j, \forall i = 1, 2, \dots, M;\ 1 \le i \le M; 1 \le j \le N;\ 1 \le t \le U \tag{9}$$

$$C_j - d_j \le T_j,\ \ 1 \le j \le N \tag{10}$$

Eq. (1) expresses the objective functions. Specifically, the first and second term denotes the total tardiness and electricity cost, respectively. Eq. (2) guarantees that each job can be processed only at one machine at a time. Eq. (3) enforces that once job j is allocated on machine i, its processing time must be equal p_{ij}. Eq. (4) enforces every job at least is allocated only on one machine. Eqs. (5)–(8) guarantee that the job pre-emption is satisfied. Eq. (9) calculates the completion time of each job. Finally, Eq. (10) calculates the tardiness of each job.

2.4 Model 2 (P_2)

This model introduces a dummy job (job 0); all parameters' values are zero. The dummy job indicates the first and the last job in the sequence. The binary variables, integer variables, and parameters used in this model are as follows.

Variables:
X_{ijk} : 1 if job j is processed before job k on machine i, 0 otherwise
Y_{ij} : 1 if job j is processed on machine i, 0 otherwise
Y_{ik} : 1 if job k is processed on machine i, 0 otherwise
Z_{ijt} : 1 if job j finishes being processed on machine i on period t, 0 otherwise
μ_j, μ_k : completion time of job j and job k, respectively
τ_j : tardiness of job j
Parameters:
V : a very big number
a_v : electricity price at period v
E_{ijt} : electricity cost incurs if job j processed on machine i finishes at period t

$$E_{ijt} = \sum_{v=t-p_{ij}+1}^{t} a_v, 1 \le i \le M; 1 \le j \le N; p_{ij} \le t \le U$$

Model P_2 is formulated as follows.

$$\text{Minimize } \omega_1 \sum_{j=1}^{N} \tau_j + \omega_2 \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{t=1}^{U} E_{ijt} Z_{ijt} \tag{11}$$

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$$\sum_{i=1}^{M} Y_{ij} = 1, 1 \leq j \leq N \tag{12}$$

$$\sum_{j=0}^{N} X_{ijk} = Y_{ik}, 1 \leq k \leq N; k \neq j; 1 \leq i \leq M \tag{13}$$

$$\sum_{k=0}^{N} X_{ijk} = Y_{ij}, 1 \leq j \leq N; k \neq j; 1 \leq i \leq M \tag{14}$$

$$\sum_{k=1}^{N} X_{i0k} \leq 1, \ \ 1 \leq i \leq M \tag{15}$$

$$\mu_k \geq \mu_j + p_{ik} - (1 - X_{ijk})V, 1 \leq i \leq M; 0 \leq j \leq N; \ 1 \leq k \leq N; j \neq k \tag{16}$$

$$\mu_0 = 0 \tag{17}$$

$$\mu_j - d_j \leq \tau_j, \ \ 1 \leq j \leq N \tag{18}$$

$$\sum_{j=1}^{N} Z_{ijt} = 1, 1 \leq i \leq M; 1 \leq t \leq U \tag{19}$$

$$\sum_{t=1}^{U} Z_{ijt} \leq Y_{ij}, 1 \leq i \leq M; 1 \leq j \leq N \tag{20}$$

$$\sum_{i=1}^{M} \sum_{t=1}^{U} tZ_{ijt} = \mu_j, 1 \leq j \leq N \tag{21}$$

Eq. (11) states the objective functions; the first term is the total tardiness, whereas the second term is electricity cost. Eq. (12) guarantees that each job can be processed only at one machine at a time. Eq. (13) guarantees that each job is processed only on one machine. Eqs. (14)–(15) ensure each job have only one predecessor and successor. Eq. (16) ensures that a maximum of one dummy job is sequenced as the first job on each machine. Eq. (16) is the disjunctive constraint. Eq. (17) forces the completion time of the dummy job is zero. Eq. (18) expressed the tardiness of each job. Eq. (19) enforces that each job is processed only by one machine and finishes only on a period. Eq. (20) guarantees that if job j is allocated on machine i, its completion time only occupies a one-time slot. Eq. (21) defines the relationship between binary variables Z_{ijt} and the completion time μ_j, i.e., if $Z_{ijt} = 1$, then the jobs finished are to be processed on period μ_j.

2.5 Experiment Method

The instances are generated using a combination of the number of jobs and machines. The number of jobs is $N = \{6, 10,15,20\}$, and the number of machines is $M = \{3,4,5\}$. For each job, the processing time is randomly generated follows the uniform distribution of [1,10]. Once the processing time of each job in each instance is determined,

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each job's due date is calculated as $d_j = \left\lfloor \frac{\sum_{i=1}^{M} p_{ij}}{M} \right\rfloor$ and the number of periods as $U = \left\lfloor \frac{N\sum_{i=1}^{M} p_{ij}}{M^2} \right\rfloor$. The TOU price follows the pattern Fig. 1 and is repeated after 24 periods.

The computational experiments are performed on a Dual Core Laptop with 3 GB RAM. Model P_1 and P_2 are coded using OPL modeling language and solved using CPLEX solver. For each model, each instance is run eleven times. The weight of the total tardiness objective is set to $\omega_1 = 0.2$. The maximum time of each run is set to 3,600 seconds. Suppose CPLEX cannot find an optimum solution within 3,600 seconds. In that case, the calculation of CPELX is stopped. The results (the computation time, the gap, the number of binary variables, integer variables, and constraints) are returned. The gap denotes the duality gap, i.e., the deviation between the upper and lower bound calculated by CPLEX. If the gap is zero, then the solution is optimum. Therefore, the lower the gap, the better the solution.

The procedure of one run of CPLEX is as follows. First, determine the weight of each objective ($\omega_1 = 0.2$ and $\omega_2 = 0.8$). Using this combination, model P_1 is calculated using CPLEX. This process is called one run. The process is repeated for other combinations of weights. The same process is conducted for model P_2.

2.6 Analysis of Model Complexity

The number of binary variables, integer variables, and constraints characterizes the complexity of a MIP model. Therefore, we assess model P_1 and P_2 by using the three indicators mentioned above. Let us consider an unrelated parallel machine scheduling under TOU of N jobs, M machines, and U periods.

For model P_1, the binary variables are x_{ijt}, y_{ij}, and $z_{ijt(t+1)}$. Therefore, the number of binary variables are $MNU + MN + MNU(U+1) = MNU^2 + 2MNU + MN$. The integer variables are $C_j$and T_j, so the number of integer variables is $2N$. We omit Eq. (1) because it does not depend on N, M, or U. Eqs. (2) and (4) have $2N$ constraints. Eqs. (3), (6), and (10) consist of $2MN$ constraints. Eq. (5) and (9) have $2MNU$ constraints. Finally, Eqs. (7) and (8) constitute $2MN(U-1)$. In total, model P_1 has $2N + 2MN + 2MNU + 2MN(U-1) = 4MNU + 2N$.

Model P_2 has MN^2(from X_{ijk}), N^2 (from Y_{ij}), and MNU(from Z_{ijt}). The number of integer variables is $2N$. Lastly, the number of constraints is $MN^2 + 3MN + MU + 2N + M$. The summary of the number of binary variables, integer variables, and constraints of the model P_1 and P_2 is shown in Table 1.

Table 1 The size complexity of the model P_1 and P_2

	Model P_1	Model P_2
Binary	$MNU^2 + 2MNU + MN$	$MN^2 + N^2 + MNU = MN$
Integer	$2N$	$2N$
Constraints	$4MNU + 2N$	$MN^2 + 3MN + MU + 2N + M$

3. Results and Discussion

Fig. 3 shows the non-dominated solutions found for the 10×3 instance. There are four non-dominated solutions found. Fig. 3 is obtained by solving model P_1 with CPLEX. Fig. 3 shows that the Pareto front is not convex. It can be explained since the objective functions of scheduling problems are not convex. Note that although the instance is run 11 times with different weight values, the number of non-dominated solutions is only 4.

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Therefore, even a weight has been assigned and solved by the exact approach. The solution found is not guaranteed to be non-dominated [30].

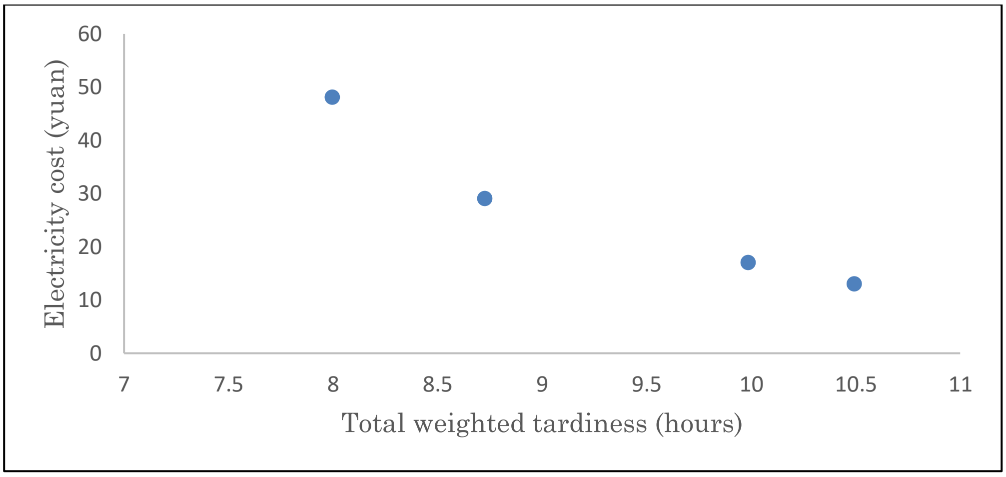

Fig. 3 The Pareto frontier of 10 × 3 instance

Table 2 Results of numerical experiments using $\omega_1 = 0.2$ and $\omega_2 = 0.8$

Instance	Period	Time (s)		Gap (%)		Binary		Integer		Constraints	
		P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
6×2	24	3.15	3.7	0	0	300	386	13	14	1202	138
10×2	28	99.51	*	0	25.99	580	802	21	22	2298	779
15×2	38	*	*	32.53	59.43	1170	1652	31	32	4638	606
20×2	49	*	*	42.35	61.85	2000	2842	41	42	7940	2797
6×3	24	3.78	0.66	0	0	450	579	13	14	1796	193
10×3	24	182	136	0	0	930	1263	21	22	3682	437
15×3	24	*	*	23.55	20.13	1980	2703	31	32	7856	2655
20×3	30	*	*	30.48	43.23	1800	3123	41	42	7272	3066
6×4	24	0.22	0.36	0	0	600	772	13	14	2390	248
10×4	24	1.53	11.7	0	0	1000	1444	21	22	3918	568
15×4	24	1520	*	0	28.43	1500	2464	31	32	5828	1148
20×4	30	*	*	24.11	45.32	2480	4164	41	42	9682	3949
Average		1651	2113	12.75	23.75	1232	1849	26.5	27.5	4875	1382

Table 2 shows the results of computational experiments using CPLEX. Table 2 only shows the experiments using $\omega_1 = 0.2$ and $\omega_2 = 0.8$. CPLEX requires an average of 1,651 seconds to solve all instances using model P_1. For solving all instances using model P_2, CPLEX needs 2,113 seconds on average. Therefore, model P_1 is more efficient than model P_2 because it requires about 80% percent of model P_2 to solve the same number of instances. The average solution gap resulted from a model P_1 is also better than those of P_2. Model P_1 requires fewer binary variables than P_2. The addition of dummy jobs makes model P_2 has more one integer variables than model P_1. As for the constraints, we can see from Table 2 model P_1 needed more constraints than model P_2. Therefore, we can say that time-indexed formulation is more compact than the disjunctive formulation. For other combinations of ω_1 and ω_2, the results are similar to those shown in Fig. 2. The results support the findings of Moon et al. [17] and Ding et al. [20]. Although their model has one objective (electricity cost), they showed that a single objective UPMS under TOU is hard to solve. Therefore, they proposed a hybrid Genetic Algorithm [17] and Column Generation [20] to solve UPMS under TOU.

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From the results in Table 2, several findings are as follows. First, the time-indexed formulation is more suitable for solving the unrelated parallel machine scheduling under TOU than the disjunctive formulation. We imply this finding based on the average solutions and gap resulted from both formulations. Second, the time-indexed formulations provide a more compact model than the disjunctive formulation, based on the number of binary variables. Lastly, the performance of a MIP model largely depends on the number of binary variables. Although the time-indexed formulation is efficient than the disjunctive formulation, both cannot solve more than 15 jobs and 24 periods. It is not practical in a real-world application where the number of jobs is significant. Hence, other approaches, such as heuristic [31] and metaheuristics [32], can be applied in a real-world application.

4. Conclusion

This study addressed the bi-objective unrelated parallel machine scheduling under TOU tariffs. The problem is modeled as two MIP models using time-indexed and disjunctive formulations. We analyzed the complexity of both models based on the number of binary variables, integer variables, and constraints. After that, we performed computational experiments to compare the effectiveness of both models. The models were solved using the weighted sum method and computed using CPLEX. The results showed that the time-indexed formulation is more efficient than the disjunctive formulation to solve the bi-objective scheduling problem. However, both models cannot find an optimum solution for more than 15 within a reasonable time. It indicates that the problem needs a suitable approach to solve the problem of large instances. Metaheuristics such as NSGA-II, Non-dominated Sorting Genetic Algorithm III, the Strength Pareto Evolutionary Algorithm 2 (SPEA2), and MOEA/D are good candidates as a solution approach.

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References

[1] R. Zhang and R. Chiong, "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,* vol. 112, pp. 3361-3375, 2016. https://doi.org/10.1016/j.jclepro.2015.09.097.

[2] K. Constant, C. Nourry, and T. Seegmuller, "Population growth in polluting industrialization," *Resource and Energy Economics,* vol. 36, pp. 229-247, 2014. https://dx.doi.org/10.1016/j.reseneeco.2013.05.004.

[3] S. Okajima and H. Okajima, "Analysis of energy intensity in Japan," *Energy Policy,* vol. 61, pp. 574-586, 2013. https://dx.doi.org/10.1016/j.enpol.2013.05.117.

[4] M. Mori, M. Fujishima, Y. Inamasu, and Y. Oda, "A study on energy efficiency improvement for machine tools," *CIRP Annals,* vol. 60, pp. 145-148, 2011. https://dx.doi.org/10.1016/j.cirp.2011.03.099.

[5] G. Y. Zhao, Z. Y. Liu, Y. He, H. J. Cao, and Y. B. Guo, "Energy consumption in machining: Classification, prediction, and reduction strategy," *Energy,* vol. 133, pp. 142-157, 2017. https://dx.doi.org/10.1016/j.energy.2017.05.110.

[6] G. Mouzon and M. B. Yildirim, "A framework to minimise total energy consumption and total tardiness on a single machine," *International Journal of Sustainable Engineering,* vol. 1, pp. 105-116, 2008. https://dx.doi.org/10.1080/19397030802257236.

[7] K. Gao, Y. Huang, A. Sadollah, and L. Wang, "A review of energy-efficient scheduling in intelligent production systems," *Complex & Intelligent Systems,* vol. 6, pp. 237-249, 2020. https://dx.doi.org/10.1007/s40747-019-00122-6.

[8] G. Mouzon, M. B. Yildirim, and J. Twomey, "Operational methods for minimization of energy consumption of manufacturing equipment," *International Journal of Production Research,* vol. 45, pp. 4247-4271, 2007. https://dx.doi.org/10.1080/00207540701450013.

[9] D. Tang and M. Dai, "Energy-efficient approach to minimizing the energy consumption in an extended job-shop scheduling problem," *Chinese Journal of Mechanical Engineering,* vol. 28, pp. 1048-1055, 2015. https://dx.doi.org/10.3901/CJME.2015.0617.082.

[10] D. M. Utama, "An Effective Hybrid Sine Cosine Algorithm to Minimize Carbon Emission on Flow-shop Scheduling Sequence Dependent Setup," *2019,* vol. 20, p. 11, 2019. https://dx.doi.org/10.22219/JTIUMM.Vol20.No1.62-72.

[11] K. Fang, N. A. Uhan, F. Zhao, and J. W. Sutherland, "Scheduling on a single machine under time-of-use electricity tariffs," *Annals of Operations Research,* vol. 238, pp. 199-227, 2016. https://dx.doi.org/10.1007/s10479-015-2003-5.

[12] B. Kurniawan, A. A. Gozali, W. Weng, and S. Fujimura, "A genetic algorithm for unrelated parallel machine scheduling minimizing makespan cost and electricity cost under time-of-use (TOU) tariffs with job delay mechanism," in *2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, 2017, pp. 583-587. https://dx.doi.org/10.1109/IEEM.2017.8289958.

[13] S. Rubaiee, S. Cinar, and M. B. Yildirim, "An Energy-Aware Multiobjective Optimization Framework to Minimize Total Tardiness and Energy Cost on a Single-Machine Nonpreemptive Scheduling," *IEEE Transactions on Engineering Management,* vol. 66, pp. 699-714, 2019. https://dx.doi.org/10.1109/TEM.2018.2846627.

[14] B. Kurniawan, A. A. Gozali, W. Weng, and S. Fujimura, "A Mix Integer Programming Model for Bi-objective Single Machine with Total Weighted Tardiness and Electricity Cost under Time-of-use Tariffs," in *2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, 2018, pp. 137-141. https://dx.doi.org/10.1109/IEEM.2018.8607420.

[15] W. Chandramitasari, B. Kurniawan, and S. Fujimura, "Building Deep Neural Network Model for Short Term Electricity Consumption Forecasting," in *2018 International Symposium on Advanced Intelligent Informatics (SAIN)*, 2018, pp. 43-48. https://dx.doi.org/10.1109/SAIN.2018.8673340.

[16] M. B. Yildirim and G. Mouzon, "Single-Machine Sustainable Production Planning to Minimize Total Energy Consumption and Total Completion Time Using a Multiple Objective Genetic Algorithm," *IEEE Transactions on Engineering Management,* vol. 59, pp. 585-597, 2012. https://dx.doi.org/10.1109/TEM.2011.2171055.

[17] J.-Y. Moon, K. Shin, and J. Park, "Optimization of production scheduling with time-dependent and machine-dependent electricity cost for industrial energy efficiency," *The International Journal of Advanced Manufacturing Technology,* vol. 68, pp. 523-535, 2013. https://dx.doi.org/10.1007/s00170-013-4749-8.

[18] J. Koo and B.-I. Kim, "Some comments on "Optimization of production scheduling with time-dependent and machine-dependent electricity cost for industrial energy efficiency"," *The International Journal of Advanced Manufacturing Technology,* vol. 86, pp. 2803-2806, 2016. https://dx.doi.org/10.1007/s00170-016-8375-0.

[19] B. Kurniawan, W. Chandramitasari, A. A. Gozali, W. Weng, and S. Fujimura, "Triple-chromosome genetic algorithm for unrelated parallel machine scheduling under time-of-use tariffs," *IEEJ Transactions on Electrical and Electronic Engineering,* vol. 15, pp. 208-217, 2020. https://dx.doi.org/10.1002/tee.23047.

[20] J. Ding, S. Song, R. Zhang, R. Chiong, and C. Wu, "Parallel Machine Scheduling Under Time-of-Use Electricity Prices: New Models and Optimization Approaches," *IEEE Transactions on Automation Science and Engineering,* vol. 13, pp. 1138-1154, 2016. https://dx.doi.org/10.1109/TASE.2015.2495328.

[21] H. Saberi-Aliabad, M. Reisi-Nafchi, and G. Moslehi, "Energy-efficient scheduling in an unrelated parallel-machine environment under time-of-use electricity tariffs," *Journal of Cleaner Production,* vol. 249, p. 119393, 2020. https://dx.doi.org/10.1016/j.jclepro.2019.119393.

[22] M. S. Nikabadi and R. Naderi, "A hybrid algorithm for unrelated parallel machines scheduling," *International Journal of Industrial Engineering Computations,* vol. 7, pp. 681-702, 2016. https://dx.doi.org/10.5267/J.IJIEC.2016.2.004.

[23] Z. Li, H. Yang, S. Zhang, and G. Liu, "Unrelated parallel machine scheduling problem with energy and tardiness cost," *The International Journal of Advanced Manufacturing Technology,* vol. 84, pp. 213-226, 2016. https://dx.doi.org/10.1007/s00170-015-7657-2.

[24] W. Zhu and L. Tianyu, "A Novel Multi-Objective Scheduling Method for Energy Based Unrelated Parallel Machines With Auxiliary Resource Constraints," *IEEE Access,* vol. 7, pp. 168688-168699, 2019. https://dx.doi.org/10.1109/ACCESS.2019.2954601.

[25] E. H. Bowman, "The Schedule-Sequencing Problem," *Operations Research,* vol. 7, pp. 621-624, 1959. https://dx.doi.org/10.2307/167010.

[26] A. S. Manne, "On the Job-Shop Scheduling Problem," *Operations Research,* vol. 8, pp. 219-223, 1960. https://dx.doi.org/10.2307/167204.

[27] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multi-objective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation,* vol. 6, pp. 182-197, 2002. https://dx.doi.org/10.1109/4235.996017.

[28] Q. Zhang and H. Li, "MOEA/D: A Multi-objective Evolutionary Algorithm Based on Decomposition," *IEEE Transactions on Evolutionary Computation,* vol. 11, pp. 712-731, 2007. https://dx.doi.org/10.1109/TEVC.2007.892759.

[29] R. Wang, Z. Zhou, H. Ishibuchi, T. Liao, and T. Zhang, "Localized Weighted Sum Method for Many-Objective Optimization," *IEEE Transactions on Evolutionary Computation,* vol. 22, pp. 3-18, 2018. https://dx.doi.org/10.1109/TEVC.2016.2611642.

[30] R. T. Marler and J. S. Arora, "The weighted sum method for multi-objective optimization: new insights," *Structural and Multidisciplinary Optimization,* vol. 41, pp. 853-862, 2010. https://dx.doi.org/10.1007/s00158-009-0460-7.

[31] S. M. Khoiroh, "Pengembangan Algoritma Non Delay Pada Kasus Penjadwalan Non-Permutation Hybrid Flowshop Untuk Minimasi Mean Flowtime," *2018,* vol. 19, p. 9, 2018. https://dx.doi.org/10.22219/JTIUMM.Vol19.No2.148-156.

[32] B. Kurniawan, W. Song, W. Weng, and S. Fujimura, "Distributed-elite local search based on a genetic algorithm for bi-objective job-shop scheduling under time-of-use tariffs," *Evolutionary Intelligence,* 2020. https://dx.doi.org/10.1007/s12065-020-00426-4.

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