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Energy-efficient Approach to Minimizing the Energy Consumption in An Extended Job-shop Scheduling Problem

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Abstract: The traditional production planning and scheduling problems consider performance indicators like time, cost and quality as optimization objectives in manufacturing processes. However, environmentally-friendly factors like energy consumption of production have not been completely taken into consideration. Against this background, this paper addresses an approach to modify a given schedule generated by a production planning and scheduling system in a job shop floor, where machine tools can work at different cutting speeds. It can adjust the cutting speeds of the operations while keeping the original assignment and processing sequence of operations of each job fixed in order to obtain energy savings. First, the proposed approach, based on a mixed integer programming mathematical model, changes the total idle time of the given schedule to minimize energy consumption in the job shop floor while accepting the optimal solution of the scheduling objective, makespan. Then, a genetic-simulated annealing algorithm is used to explore the optimal solution due to the fact that the problem is strongly NP-hard. Finally, the effectiveness of the approach is performed small- and large-size instances, respectively. The experimental results show that the approach can save 5%–10% of the average energy consumption while accepting the optimal solution of the makespan in small-size instances. In addition, the average maximum energy saving ratio can reach to 13%. And it can save approximately 1%–4% of the average energy consumption and approximately 2.4% of the average maximum energy while accepting the near-optimal solution of the makespan in large-size instances. The proposed research provides an interesting point to explore an energy-aware schedule optimization for a traditional production planning and scheduling problem.

Keywords: energy consumption, makespan, production planning and scheduling, job-shop floor, different cutting speeds

1 Introduction

Nowadays, manufacturing enterprises are not only facing strong economic pressure due to complex and diverse economic trends of shorter product life cycles, rapidly changing science and technology, increased diversity in customer demand, and the globalization of production activities, but also facing enormous environmental challenges due to global climate change, rapid exhaustion of various non-renewable resources, and decreasing biodiversity. Manufacturing activities play a major role in industrial energy consumption; relevant statistical data shows that manufacturing was responsible for approximately 90% of industry energy consumption; the corresponding amount of industry CO_2 emissions generated by the energy was 84%[1]. It is therefore significant that the manufacturing community should have manufacturing systems that demonstrate major potential to reduce energy consumption and environmental impacts in terms of the development of sustainable manufacturing[2–3].

Recently, there has been growing interest in sustainable manufacturing with considering the increasing awareness of energy savings due to a sequence of serious environmental and economic impacts. Research on minimizing the energy consumption of manufacturing systems has focused on two aspects: one is the local optimization of energy consumption, including the machine level[4–6] and the product level[7–10], and the other is the global optimization of energy consumption based on the manufacturing system level. This paper attempts to minimize energy consumption without any machine or product reengineering from the manufacturing system-level perspective. In the specialized literature regarding production planning and scheduling, it is clear that economic sustainability has been the main

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focus for the optimization of the key production objectives, such as cost, time, and quality while environmental sustainability like reducing energy consumption in manufacturing systems through production scheduling has received little attention. One of the most well-known studies in the literature describing the energy efficiency was the work by MOUZON, et al[11], who developed a multi-objective mathematical programming model and several algorithms to investigate the problem of scheduling jobs on a single CNC machine in order to reduce energy consumption and total completion time. They pointed out that there was a significant amount of energy savings when non-bottleneck machines were turned off until needed; the relevant share of savings in total energy consumption could add up to 80%. They also reported that the inter-arrivals would be forecasted and therefore more energy-efficient dispatching rules could be adopted for scheduling. In further research, MOUZON, et al[12], addressed a greedy randomized adaptive search algorithm to solve a multi-objective optimization schedule that minimized the total energy consumption and the total tardiness on a machine. FANG, et al[13], provided a new mixed integer linear programming model for scheduling a classical flow shop that incorporated the peak total power consumption, the carbon footprint, and the makespan. BRUZZONE, et al[14], reported an energy-aware scheduling algorithm based on a mixed integer programming formulation to realize energy savings for a given flexible flow shop that was required to keep fixed original job assignment and sequencing. LIU, et al[15], considered reducing the total wasted energy consumption using a branch and bound algorithm in a permutation flow shop scheduling problem. In addition, HE, et al[16], proposed a bi-objective model to minimize the energy consumption and the makespan for the job-shop scheduling problem. ZHANG, et al[17–18], developed a mathematical model for the dynamic scheduling in a flexible job shop scheduling problem, which considered the energy consumption and the schedule efficiency. Although the majority of the research on production scheduling to date has not completely considered energy-saving strategies, the efforts mentioned above provide a starting point for exploring an energy-aware schedule optimization from the viewpoint of the energy efficiency.

In addition, some scientific results agree on the fact that process parameters selection has a direct impact on energy consumption[19–22]; cutting speed which is recognized as one of the most important process parameters has been regarded with a particular interest in this paper. RAJEMI, et al[23], addressed the power distribution of a machine tool with different cutting speeds in a turning process. They pointed out that the percentage of power consumption by the actual machining process was increased as the cutting speed increased. FANG, et al[13], considered a finite and discrete set of operation speeds as a factor to affect the peak load and energy consumption in a flow shop schedule environment. Due to the fact that different cutting speeds of one machine tool have influence on energy consumption, an extended job shop scheduling problem where jobs' cutting speeds are allowed to vary is presented to account for energy consumption in this paper.

This paper addresses an extended job shop scheduling problem, where the scheduling plans of the operations are a priori known, by incorporating energy consumption into a traditional scheduling objective, i.e., the makespan. BRUZZONE, et al[14], pointed out that the approach which adjusted the original timetable of the operations can minimize the shop floor power's peak. However, the drawback of the approach was at the cost of accepting possible worsening of the makespan. In this paper, a new approach to modify the given schedule generated by a production planning and scheduling system in a job shop floor, adjusting the cutting speeds of the operations while keeping the original assignment and the processing sequence of the operations fixed, is proposed to account for energy consumption. The approach changes the total idle time of the given schedule in order to minimize energy consumption while keeping the optimal solution of the makespan.

The outline of this paper is organized as follows. An extended job shop scheduling problem is described, and a given schedule from the viewpoint of the energy consumption is presented in section 2. An approach based on a mathematical model for the given schedule is illustrated to account for energy consumption. And then a heuristic approach based on a genetic-simulated annealing algorithm is used to solve the given schedule problem with energy saving in section 3. To evaluate the approach, extensive experimental instances are tested in section 4. The conclusions are presented in section 5.

2 Problem Description

Formally, the extended job shop scheduling problem where the operations' cutting speed is allowed to vary can be described as follows. There is a set $J=\{1, 2, \cdots, n\}$ of n jobs and a set $M=\{1, 2, \cdots, m\}$ of m machines. Each job $j \in J$ is characterized by the set of o_j operations $O_j=\{1, 2, \cdots, o_j\}$, which have to be executed in a fixed order. In addition, owing to different cutting speeds required in the job shop, a set of cutting speeds $S=\{1, 2, \cdots, s\}$ is also presented. The extended job-shop schedule satisfies the following constraints.

(1) Each machine can not process more than one operation at a time;

(2) The operations of each job have to be sequentially processed on assigned machines;

(3) Preemption is not allowed for machining each operation, i.e., once one operation is started, it must be finished without interruption;

(4) There are no precedence relationships between operations of different jobs, but there are precedence

relationships between different operations of one job;

(5) Each operation of one job can be executed in a machine at a given speed.

On the one hand, the scheduling objective requires the minimization of the latest operation completion time, i.e., the makespan. The problem is proved to be NP-hard since it is a job-shop one denoted as $J||C_{\max}$ according to the classification rules presented by BLAZEWICZ, et al[24]. A number of methods (exact methods, heuristic methods, metaheuristic methods, etc) have been proposed to solve it. On the other hand, the job shop scheduling influences energy consumption of the manufacturing system. Thus, a suitable scheduling decision can reduce energy waste.

In this work it is assumed that a feasible schedule has been generated by a production planning and scheduling system; hence, the assignment and processing sequence of all jobs are fixed (Fig. 1). The attention is focused on the optimization of the energy consumption for the given schedule as shown in Fig. 1. In order to reduce the energy requirements of machine tools, the proposed approach aims at minimizing the total energy consumption of the job-shop floor by adjusting the cutting speeds of the operations while keeping the original assignment and processing sequence of operations of each job fixed in section 3.

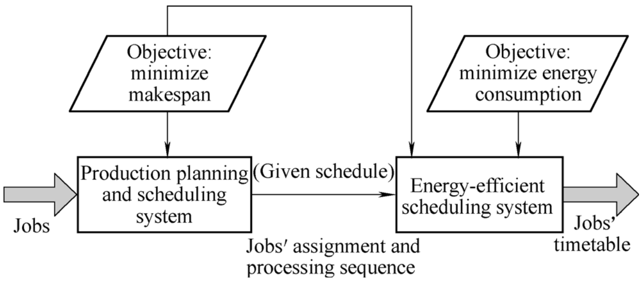

Fig. 1. A given schedule with considering energy consumption

3 Modeling and Solving a Mathematical Formulation for a Given Schedule with Energy Saving

In previous scientific approaches, production decision is barely considered for an energy-efficient scheduling. Hence, the proposed approach integrates energy savings in the extended job-shop scheduling problem. The implementation of the approach can be divided into three steps. The first step is identifying the energy consumption in order to minimize energy usage. In the second step, a mixed integer programming mathematical model with energy saving for the job-shop scheduling problem is proposed. Finally a hybrid metaheuristic algorithm based on a genetic-simulated annealing algorithm is employed to obtain optimization results. Decision variables and parameters are defined in the following:

E—Total energy consumption of a job-shop floor,

E_1—Energy required to start up the machine tools and spindles,

E_2—Machining energy required during the production time,

E_3—Idle energy required during the non-production time,

P_m^{i}—Input power required to start up the mth machine tool and its spindle, $m \in M$,

P_{ljms}^{u}—Idle power consumption when operation l of job j is processed on machine tool m with cutting speed s, $l \in O_j$, $j \in J$, $m \in M$, $s \in S$,

P_{ljms}^{c}—Cutting power consumption when operation l of job j is processed on machine tool m with cutting speed s, $l \in O_j$, $j \in J$, $m \in M$, $s \in S$,

p_{ljms}—Processing time when operation l of job j is processed on machine tool m with cutting speed s, $l \in O_j$, $j \in J$, $m \in M$, $s \in S$,

S_{ljm}—Starting time when operation l of job j is processed on machine tool m, $l \in O_j$, $j \in J$, $m \in M$,

C_{ljm}—Completion time when operation l *of* job j is processed on machine tool m, $l \in O_j$, $j \in J$, $m \in M$,

C_j—Completion time of each job, $j \in J$,

MaxEnergy—Sum of the highest energy consumption of each operation of all the jobs on the machine tools.

X_{ljms}—Integer variable that has two possible values: 0 or 1. It is equal to 1 if operation l of job j is required to be processed on machine m with cutting speed s; it is equal to 0 otherwise, $l \in O_j$, $j \in J$, $m \in M$, $s \in S$,

Y_{hiljm}—Integer variable that has two possible values: 0 or 1. It is equal to 1 if operation h of job i precedes operation l of job j where operation h and l are processed sequentially on machine tool m; it is equal to 0 otherwise, $h, l \in O_j$, $i, j \in J$, $m \in M$,

L—A very large positive number.

3.1 Identification of energy consumption for a job-shop floor

For a job-shop floor, the energy required by each machine tool consists of three parts during the normal production in terms of the energy decomposition[6, 25–26].

(1) When a machine tool is at the readiness operation stage, the energy is consumed to activate machine components (like the start-up of the machine tool and spindle) and to ensure the operational readiness of the machine tool. The energy consumption E_1 can be expressed as

$$E_1 = \sum\nolimits_{m \in M} \int_0^{t_0} P_m^{\mathrm{i}}(t)\mathrm{d}t, \tag{1}$$

where t_0 is the readiness time of the mth machine tool.

(2) When a machine tool is at the machining operation stage, the energy is consumed to remove workpiece

material and to maintain the normal operation of machine components. The required energy E_2 is described in the following:

$$E_2 = \sum_{l\in O_j} \sum_{j\in J} \sum_{m\in M} \sum_{s\in S} (\alpha {P^{c}_{ljms}}^{2} + \beta P^{c}_{ljms} + P^{u}_{ljms}) \times p_{ljms} X_{ljms}, \quad (2)$$

where α and β are the coefficients of the load power consumption, and they can be obtained by using the equations of linear regression based on the idle power consumption within the different cutting speeds.

(3) When a machine tool is at the idle running stage, the machine components that implement activities such as loading or unloading workpiece, positioning and clamping, and changing cutting tools have energy demand; in addition, the machine tool that waits for the next operation to be executed also consumes energy. The energy demand for a job shop at the non-production time can be calculated as

$$E_3 = \sum_{l\in O_j} \sum_{j\in J} \sum_{h\in O_i} \sum_{i\in J} \sum_{m\in M} \sum_{s\in S} P^{u}_{ljms} \times X_{ljms}((C_{ljm} - p_{ljms}) - C_{him})Y_{hiljm}. \quad (3)$$

In summary, the total energy consumption of the job-shop schedule can be calculated by Eq. (4):

$$E = E_1 + E_2 + E_3. \quad (4)$$

According to the presentation given by SALIDO, et al[27], the energy consumption increases as the speed of one machine tool becomes increased, but the processing time decreases; meanwhile the energy consumption decreases and the processing time increases as the speed becomes decreased. The total energy consumption (E) could be minimized by decreasing the speed of machine tools for a given schedule in the job-shop floor. Moreover, without any machine or product reengineering, the energy saving could be obtained in the non-production time. Therefore, it is available to reduce the energy consumption changing the total idle time of the given schedule while accepting the optimal solution of the scheduling objective.

3.2 Mathematical model

A mathematical model that minimizes the total energy consumption of the job-shop floor by adjusting the cutting speeds of the operations while keeping the original assignment and processing sequence of operations of each job fixed is presented in the following:

$$f = \min(\max_{j\in J}(C_j)), \quad (5)$$

s.t.,

$$S_{ljm} + p_{ljms} X_{ljms} \leqslant C_{ljm},\ l \in O_j;\ j \in J;\ m \in M;\ s \in S, \quad (6)$$

$$C_{ljm} \leqslant S_{(l+1)jn},\ l \in O_j;\ j \in J;\ m, n \in M, \quad (7)$$

$$C_j \leqslant C_{\max},\ j \in J, \quad (8)$$

$$S_{ljm} \geqslant S_{him} + \sum_{s\in S} p_{hims} X_{hims} - L(1 - Y_{hiljm}),\ l, h \in O_j;\ i, j \in J;\ m \in M, \quad (9)$$

$$S_{him} \geqslant S_{ljm} + \sum_{s\in S} p_{ljms} X_{ljms} - LY_{hiljm},\ l, h \in O_j;\ i, j \in J;\ m \in M, \quad (10)$$

$$\sum_{m\in M} X_{ljms} = 1,\ l \in O_j;\ j \in J;\ s \in S, \quad (11)$$

$$\sum_{s\in S} X_{ljms} = 1,\ l \in O_j;\ j \in J;\ m \in M, \quad (12)$$

$$E \leqslant MaxEnergy. \quad (13)$$

Constraints (6) and (7) represent the precedence relationships between operations of each job on the machine tools and ensure that the processing sequence of the operations corresponds to the predetermined order. Constraint (8) defines that the completion time of each job cannot be allowed to exceed the maximum completion time in the schedule, i.e., the makespan. Constraints (9) and (10) ensure that each machine tool can process at most one operation at a time, and that two different operations cannot be allowed to execute on the same machine tool simultaneously. Constraint (11) imposes that one operation can be processed by only one machine tool at a time, i.e., it does not allow one operation to be executed on more than one machine tool at a time. Constraint (12) is the speed constraint and ensures that each operation of one job is processed with one given speed on one machine tool. Constraint (13) points out that the total energy consumption required by the job-shop is imposed by introducing a bound, i.e., the sum of the highest energy consumption of all operations.

3.3 Optimization of the given schedule

In this section, a genetic-simulated annealing algorithm is proposed to optimize the energy consumption for the given schedule. There are many metaheuristic algorithms for solving objective optimization. Among these algorithms, genetic algorithm can quickly approach to an optimized solution, but a fatal shortcoming is that it is liable to be trapped in a local optimum, i.e., premature convergence. Fortunately, simulated annealing algorithm has the ability to jump out of the local optimization and explore the best solution. Therefore, this paper proposes to incorporate the strengths of a simulated annealing algorithm into a genetic algorithm. Genetic algorithm is developed to rapidly search for an optimal or near-optimal solution among the solution space and an improved simulated annealing algorithm inspired from hormone modulation mechanism is employed to seek a better one on the base of the solution. In our previous research, an improved genetic-simulated annealing algorithm for flexible flow-shop scheduling problems has been proposed and it has been proved to be effective[28]. Thus, the metaheuristic algorithm will be applied to the above problem. The flow chart of the genetic-simulated annealing algorithm is illustrated in Fig. 2.

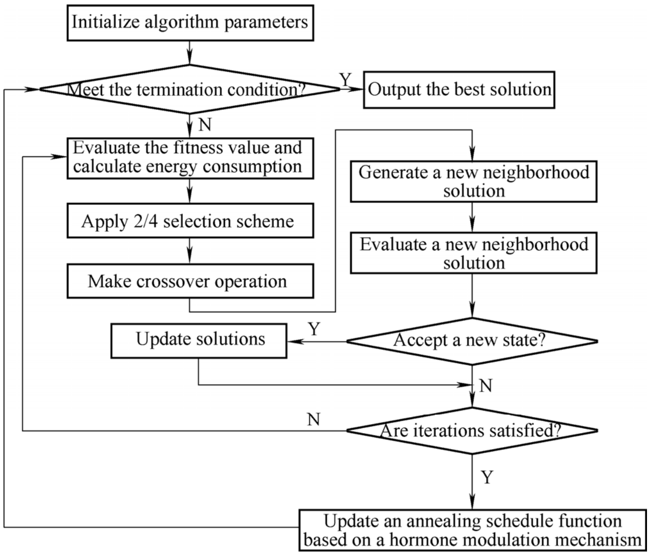

Fig. 2. Flow chart of a genetic-simulated annealing algorithm

4 Case Study

To verify the efficiency of the approach, the algorithm is performed on the benchmarks proposed by AGNETIS, et al[29]. All test instances are characterized by the number of machine tools (m), the number of jobs (j), the number of operations for each job (o) and the range of processing time (p). For each problem size, 10 test instances are randomly produced, drawing processing times from a uniform distribution in the appointed range. The partial instances are depicted as shown in Table 1[29]. We modeled the test instances to be solved by the genetic-simulated annealing algorithm. Two sets of experimental instances, namely small- and large-size instances were tested. The algorithm was carried out by utilizing the Matlab programming language. The tests were carried out on a personal computer with Intel Pentium (R) with 1 GB RAM and 3.20 GHz clock, and Windows XP.

In addition, the three cutting speeds, namely the full cutting speed, the medium cutting speed and the low cutting speed, for machining the operations of the jobs is represented in Fig. 3.

Table 1. Test instances with three jobs

Problem size	m	o	p	Problem size	m	o	p	Problem size	m	o	p
3_5_10	3	5	[1, 10]	5_5_10	5	5	[1, 10]	7_5_10	7	5	[1, 10]
3_7_10	3	7	[1, 10]	5_7_10	5	7	[1, 10]	7_7_10	7	7	[1, 10]
3_10_10	3	10	[1, 10]	5_10_10	5	10	[1, 10]	7_10_10	7	10	[1, 10]
3_5_50	3	5	[1, 50]	5_5_50	5	5	[1, 50]	7_5_50	7	5	[1, 50]
3_7_50	3	7	[1, 50]	5_7_50	5	7	[1, 50]	7_7_50	7	7	[1, 50]
3_10_50	3	10	[1, 50]	5_10_50	5	10	[1, 50]	7_10_50	7	10	[1, 50]
3_5_100	3	5	[1, 100]	5_5_100	5	5	[1, 100]	7_5_100	7	5	[1, 100]
3_7_100	3	7	[1, 100]	5_7_100	5	7	[1, 100]	7_7_100	7	7	[1, 100]
3_10_100	3	10	[1, 100]	5_10_100	5	10	[1, 100]	7_10_100	7	10	[1, 100]

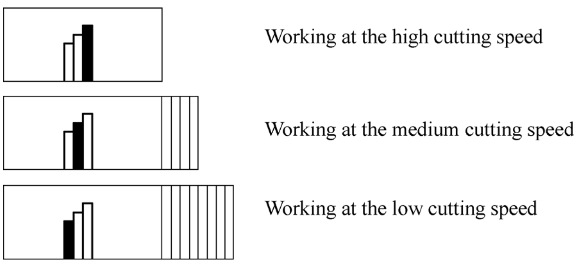

Fig. 3. Different cutting speeds for machining an operation

Each cutting speed has a close relation with the processing time and energy consumption. When the machine tool works at the high cutting speed, a solid white rectangle presents a mandatory processing time; when the machine tool works at the medium/low cutting speed, a rectangle can be divided into two regions: one is the mandatory processing time with a solid white color and the other is extra processing time with vertical lines. The latter region represents the used time to save energy and the energy saving increases when the cutting speed decreases. According to the original instances proposed in Ref. [29], we extend the three processing times (p_1, p_2, p_3) and the associated three energy consumptions (e_1, e_2, e_3) to each operation of the jobs. In particular, p_1 is equal to the original processing time in the Agnetis' instances; p_2 and p_3 are expressed as below, respectively:

$$p_2 = \max(\max pt * 0.1 + p_1, rand(1.25 * p_1, 2.25 * p_1)), \quad (14)$$

$$p_3 = \max(\max pt * 0.1 + p_2, rand(1.25 * p_2, 2.25 * p_2)), \quad (15)$$

where max pt is the maximum processing time of a operation for the given instance; $rand(\bullet)$ is a random value. The three energy consumptions with different cutting speeds are calculated as follows, respectively:

$$e_1 = rand(p_1, 3 * p_1), \quad (16)$$

$$e_2 = \max(1, \min(e_1 - \max pt * 0.1, rand(0.25 * e_1, 2.25 * e_1))), \quad (17)$$

$$e_3 = \max(1, \min(e_2 - \max pt * 0.1, rand(0.25 * e_2, 2.25 * e_2))), \quad (18)$$

The optimization results of the makespan and energy consumption are shown in Table 2. Specifically, column 2 represents the average makespan of each problem size; column 3 represents the gaps (percentage) between the original optimal solutions generated by the traditional production planning and scheduling system and the new optimal solutions obtained by the proposed approach; column 4 represents the average initial energy consumption based on the traditional production planning and scheduling system; column 5 represents the average optimized energy consumption based on different cutting speeds; column 6 represents the average energy saving ratio (percentage) of each problem size; column 7 represents the maximum energy saving ratio (percentage) of each problem size.

Table 2. Data collection of the small-size instances

Problem size	Makespan t	Gap $\Delta/\%$	Initial energy consumption Ei	Optimized energy consumption Eo	Average energy saving ratio $\Delta Ea/\%$	Maximum energy saving ratio $\Delta Em/\%$
3_5_10	41	0	152	138.1	9.14	15.71
3_7_10	54.1	0	221.9	205.4	7.44	12.35
3_10_10	61.2	0	243.3	229.1	5.84	8.70
3_5_50	190.3	0	768.5	708.7	7.78	16.40
3_7_50	252.8	0	1050.4	960.6	8.55	14.13
3_10_50	333.8	0	1361.6	1273.3	6.49	14.34
3_5_100	375.4	0	1422.9	1307.1	8.14	12.96
3_7_100	531.9	0	2039.9	1895.4	7.08	12.58
3_10_100	729.1	0	3028.7	2830.5	6.54	9.44
5_5_10	35	0	151	140.4	7.02	16.95
5_7_10	46	0	199.5	186.3	6.62	11.52
5_10_10	51.5	0	213.6	199.9	6.41	10.27
5_5_50	165.5	0	732.5	671.5	8.33	14.29
5_7_50	225.2	0	1014.3	951.2	6.22	9.14
5_10_50	317	0	1420.6	1303.6	8.24	13.50
5_5_100	325.5	0	1383.1	1253.2	9.40	14.64
5_7_100	436.9	0	2057.1	1909	7.20	12.03
5_10_100	610.3	0.11	2804.1	2587.5	7.72	14.34
7_5_10	28.7	0	117.8	110.9	5.86	13.59
7_7_10	39.3	0	174	162.2	6.78	11.30
7_10_10	56.5	0	263.9	241.6	8.45	14.92
7_5_50	159.7	0	656.6	607	7.55	13.12
7_7_50	220.8	0	985.9	919.1	6.78	9.95
7_10_50	304.6	0	1429	1310.5	8.29	14.12
7_5_100	351	0	1523.7	1422.9	6.66	11.86
7_7_100	426.1	0	2108	1978.3	6.15	11.91
7_10_100	625.9	0	2935.1	2664.1	9.23	17.00

It can be observed that the range of the average energy saving ratio varies from 5% to 10% for one given schedule in small-size instances. In addition, the average maximum energy saving ratio of all the instances can reach to 13.00%. It is therefore that the makespan of all jobs on machine tools are optimal in different conditions, and the energy savings can be obtained by adjusting the processing speeds of machine tools in small-size instances.

More specifically, Fig. 4 shows an optimal solution of a 3_5_10 job shop scheduling problem, i.e., three jobs, three machines, and five operations for each job, which is obtained by the genetic-simulated annealing algorithm. Each operation of the jobs has a processing time ranging interval from 1 to 10. It is represented by a rectangle and the rectangle with the solid white color represents the mandatory processing time when the machine tool is working at full speed and the rectangle with vertical lines represents the extra processing time if the machine tool doesn't work at full speed. It can be shown that when all the operations are carried out by the machine tools at the full cutting speed, the optimal makespan of the given schedule based on the traditional production planning and scheduling system is 46 units. Furthermore, the proposed approach is performed on the instance. It demonstrates that the original assignment and processing sequence of the operations are kept fixed by adjusting the cutting speed of the operations, i.e., the forth process (operation 2 of job 2) on machine tool 1 (M1) is executed at the medium cutting speed; the first process (operation 2 of job 3) on machine tool 2 (M2) is executed at the low cutting speed and the second process (operation 3 of job 1) on machine tool 2 (M2) is executed at the medium cutting speed; the second process (operation 1 of job 2) on machine tool 3 (M3) is executed at the low cutting speed and the first process (operation 4 of job 1) on machine tool 3 (M3) is executed at the low cutting speed; the remainder operations on machine tools are executed at the full cutting speed. It can be found that the makespan is the same value (46 units) in Fig. 4, and the associated energy consumption for each machine tool is changed as depicted in Fig. 5. The initial total energy consumption is 210 units, and the optimized total energy consumption is 177 units. It can save 33 units of the energy consumption. Compared with the initial energy consumption of each machine tool based on the traditional production planning and scheduling system, the proposed approach can realize energy-saving production in Fig. 5.

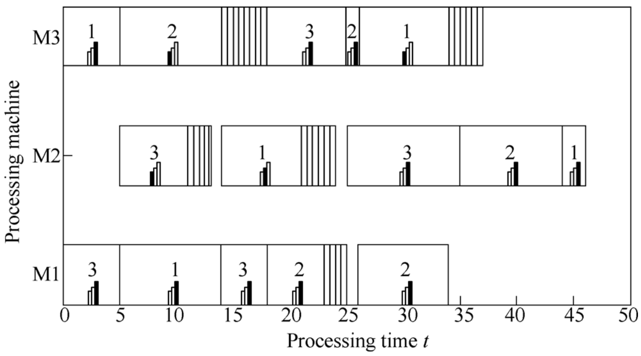

Fig. 4. An instance with the optimal solution for a 3_5_10 JSSP

Furthermore, the instances of larger size are analyzed to test the approach. The characteristics of these large-size instances are described in Table 3. For each problem size, 5 test instances are randomly produced. The experimental results are summarized in Table 4 and it can save approximately 1%–4% of the average energy consumption and approximately 2.4% of the average maximum energy. It can be observed that the makespan of all jobs on machine tools are almost near to the optimal solution, but the potential of energy saving is not remarkable This is due to the one important fact that the load balancing between machine utilization and task allocation becomes effectively improved in large-size instances.

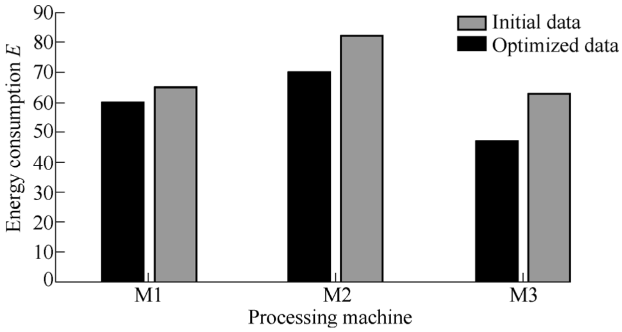

Fig. 5. The associated energy consumption of each machine tool

Table 3. Test instances with large size

Problem size	j	m	o	p
10_10_200	10	10	10	[1, 200]
15_15_200	15	15	15	[1, 200]
20_20_200	20	20	20	[1, 200]
20_20_200	50	20	20	[1, 200]
20_20_200	100	20	20	[1, 200]

Table 4. Data collection of the large instances

Problem size	Makespan t	Gap $\Delta/\%$	Initial energy consumption Ei	Optimized energy consumption Eo	Average energy saving ratio $\Delta Ea/\%$	Maximum energy saving ratio $\Delta Em/\%$
10_10_200	939.04	1.08	10 305.6	9873.2	4.18	6.95
15_15_200	1554.12	1.22	23 150.2	22 505.8	2.78	3.40
20_20_200	4778.07	2.33	82 381.3	80 577.2	2.19	2.69
20_20_200	7753.04	4.36	101 047.0	100 073.4	0.96	1.08
20_20_200	15 062.5	6.73	198 874.1	197 787.5	0.55	0.59

5 Conclusions

(1) An energy-aware approach to minimizing the energy consumption in an extended job-shop scheduling problem, where one given schedule is generated by a production planning and scheduling system and each machine tool can work at different cutting speeds, is explored to account for energy savings.

(2) To solve the optimization problem a mixed integer programming mathematical model is proposed, and a hybrid metaheuristic algorithm based on a genetic-simulated annealing algorithm is employed to obtain optimization results.

(3) The effectiveness of the approach is tested with small- and large-size instances. The experimental results show that the proposed method can deduce a more energy-efficient solution while ensuring the makespan is the best one in small-size instances. Due to some uncertain factors in large-size instances, the trend of energy savings is not obvious.

(4) In further research, the approach should be implemented on uncertain events such as the loading balance rate of machine tools to realize energy savings of larger instances.

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