Multi-objective Optimization Model for Flexible Job Shop Scheduling Problem Considering Transportation Constraints: A Comparative Study

Dongsheng Yang, Xianyu Zhou
Intelligent Electrical Science and Technology Research Institute
Northeastern University
Shenyang, China
ds_yang@126.com

Zhile Yang, Qiangqiang Jiang, Wei Feng
Shenzhen Institute of Advanced Technology
Chinese Academy of Sciences
Shenzhen, China
zl.yang@siat.ac.cn

Abstract—**Flexible job shop scheduling problem (FJSP) has long been a complex problem due to the resource flexibility and strong constraints, generating a mixed-integer non-linear optimization problem. The problem becomes more complex with the increasing demand of energy reduction and the corresponding environmental impacts. Proper production scheduling is of significant potential in saving energy in the manufacturing system. In this paper, a multi-objective FJSP model is formulated with the objectives of minimizing the makespan and energy consumption considering strong transportation constraints. Two popular multi-objective optimization solver including Non-dominated Sorting Genetic Algorithm-II (NSGA-II) and A Multiobjective Evolutionary Algorithm Based on Decomposition (MOEA/D) are employed and compared in a real-world instance of the FJSP, associated with novel coding schemes. The results show that the proposed model is well solved by the two solvers and NSGA-II get the better solutions.**

Index Terms—**Multi-objective flexible job shop scheduling, Energy consumption, Transportation time, NSGA-II, MOEA/D**

I. INTRODUCTION

In the recent years, manufacturing enterprises are facing strong pressure from both economic and environmental areas due to the increasing energy consumption and the corresponding environmental issues. In China, the electricity energy consumed by manufacturing system accounts for over 50% of the power consumption of the whole country, and the enterprise releases at least 26% of carbon dioxide [8]. It is of great importance to use energy-efficient mechanism to save energy costs [1], [10], [12].

FJSP is an extended formulation of the canonical job shop scheduling problem (JSP). It is an NP-hard problem includes operation, sequencing and processing flexibility. Many studies have been addressing on reducing energy consumption on machine and product, and improving the production management level. Liu et al. [7] proposed a multi-objective model with the objectives of minimizing makespan and product carbon footprints and used a new hybrid fruit fly optimization algorithm to solve the problem. Zhang et al. [14] utilized an efficient gene expression programming to make dispatching rules more energy-efficient and applied it to the new mixed-integer linear mathematical model. Mokhtari and Hasani [9] proposed an enhanced evolutionary algorithm to solve an energy-efficient FJSP with the objectives inluding makespan, energy consumption and total availability of the system. Gong et al. presented a hybrid genetic algorithm for the multi-objective FJSP considering green production and human factor [5].

However, very limited studies have considered the transportation operations between the operations of a job, which is a crucial constraint in the real-world manufacturing system. In the manufacturing job shop system, each job, once finished, needs to be transported by vehicles or tools such as automated guided vehicle (AGV) to the next machine, in which the operations also consume large amount of energy [4], [11]. Zhang et al. introduced JSP with transportation constraints [15]. Karimi et al. proposed a hybrid imperialist competitive algorithm for FJSP with transportation constraints [6]. Rossi and Dini proposed a approach for FJSP with set-up constraints, transportation constraints and alternative machine tools [13]. Dai et al. [2] proposed an enhanced genetic algorithm for solving the energy efficient FJSP considering transportation constraint. In this paper, the transportation constraint is considered in a multi-objective FJSP considering makespan and energy consumption objectives. The problem is solved by two featured optimizers e.g. NSGA-II and MOEA/D for comparative study, associated with proposed corresponding novel encoding and decoding methods.

The remainder of this paper is structured as follows: the problem formulation of FJSP with transportation constraints is discussed in Section 2, followed by that NSGA-II and MOEA/D are briefly introduced in Section 3, where the encoding and decoding methods are also given. Experimental studies and the corresponding discussion are reported in Section 4. Finally, Section 5 concludes the paper.

II. MULTI-OBJECTIVE OPTIMIZATION MODEL OF THE FJSP

A. Problem formulation

The formulation of FJSP with transportation constraints is described as follows: Assuming that there are m machine tools and n jobs in the overall time period. Each job is consisted

978-1-7281-6929-3/20/$31.00 ©2020 IEEE

of a series of operations allowed to be processed in the corresponding set of available machines. In addition, an AGV is used to convey one job when it is finished one operation on one machine and needed to be moved to another machine. In this transportation process, the AGV also consumes certain amount of energy. In this paper, the objectives are to minimize the maximal completion time, i.e. makespan (C_{max}) and energy consumption, of which the notations are presented in Table. I.

B. Formulation of the optimization model

In this paper, the objective functions which involves the two separate objectives are demonstrated as follows:

• Minimizing makespan C_{max};

• Minimizing energy consumption $E = SE + PE + IE + TE + AE$.

The corresponding energy consumption modules are showed as follows:

1) Energy consumption for set-up state (SE):

SE is the energy for preparation such as positioning, loading or unloading pieces, changing tools and so on. It can be calculated by multiplying the basic power demand by the preparation time as shown in Eq.1.

$$SE = \sum_{k=1}^{m} \sum_{j=1}^{O_k} BP_{jk} * t_{jk} \quad (1)$$

2) Energy consumption for processing state (PE):

PE is the energy for material removal, which can be described as a polynomial fitting curve. PE is expressed by Eq. 2 as follows:

$$PE = \sum_{k=1}^{m} CU_k * (\sum_{i=1}^{n} \sum_{j=1}^{N_i} P_{ijk}) + \sum_{i=1}^{n} \sum_{j=1}^{N_i} \sum_{k=1}^{m} (1 + \alpha) CU_{ijk} * P_{ijk} \quad (2)$$

where α is the coefficient of the fitting curve.

3) Energy consumption for idle state (IE):

IE is the energy for waiting the next operation when a machine is at the idle state, which is dependent on the machine selection, operation sequence, and transportation time. It can be described as multiplying the unload power by the total idle time in Eq.3.

$$IE = \sum_{k=1}^{m} CU_k * (\max_{i,j} F_{ijk} - \sum_{i=1}^{n} \sum_{j=1}^{N_i} (F_{ijk} - B_{ijk})) \quad (3)$$

4) Energy consumption for transportation state (TE):

TE is the energy of the transportation resource. The transportation time is dependent on machine selection of two successive operations for the same job.

$$TE = \sum_{i=1}^{n} \sum_{j=2}^{N_i} \sum_{k=1}^{m} \sum_{w=1}^{m} TP * T_{i(j-1)jwk} \quad (4)$$

5) Auxiliary energy consumption (AE):

AE is the energy required to support the workshop environment like lighting, heating and so on, which can be described as Eq.5.

$$AE = e * \max_{1 \leq i \leq n} F_i \quad (5)$$

Constraints:

• All jobs are independent and any preemption or cancellation of jobs are not permitted.

$$B_{ijk} + P_{ijk} = F_{ijk} \quad (6)$$

$$\sum_k B_{ijk} \geq \sum_k F_{i(j-1)k} \quad (7)$$

• Every machine can at most process one job at a time.

$$B_{ik} + P_{ik} \leq B_{(i+1)k} \quad \forall j \quad (8)$$

• One operation can be processed by at most one machine at a time.

$$B_{ij} + P_{ij} \leq B_{i(j+1)} \quad \forall k \quad (9)$$

• Jobs and machines are available at time zero. Job can be transported to another machine immediately once completing processing one operation.

$$B_{ijk} \geq 0 \quad (10)$$

$$F_{ijk} \geq 0 \quad (11)$$

• Processing time is deterministic and includes set-up and inspection. The makespan is the maximal completion time of all jobs.

$$F_i \geq F_{ij} \quad \forall j \quad (12)$$

$$C_{max} \geq F_i \quad \forall i \quad (13)$$

III. Algorithm Introduction

In this paper, two most popular multi-objective solvers named NSGA-II and MOEA/D are adopted in solving the proposed problem for comparative study, both of the methods are illustrated in this section.

A. Non-dominated Sorting Genetic Algorithm-II

Non-dominated Sorting Genetic Algorithm-II is a multi-objective evolutionary algorithm proposed by Kalyanmoy Deb et al. in 2002 [3]. It has shown superior performance than the NSGA algorithm and the computational complexity is greatly reduced compared to NSGA. NSGA-II uses a fast non-dominated sorting scheme and a crowded-comparison operator instead of the sharing radius, and crowded-comparison operator is used as the winning criterion after the fast sorting in the same counterpart, making the individuals in the quasi-Pareto domain be extended to the entire Pareto domain and maintain the diversity of the population. The elite strategy is employed to expand the sampling space and prevent the loss of the best individual, which improves the efficiency and robustness of the algorithm. The calculation of sharing radius and the crowded-comparison operator are showed as follows:

TABLE I
NOTATIONS FOR THE FORMULATION

$i, i*$	Number of jobs
$j, j*$	Operations of the jobs
k, w	Number of machines
q	Position
O_{ij}	The j^{th} operation of job i
M_{ij}	Machine tools for operation O_{ij}
F_i	Completion time of job i
B_{ij}	Starting time of operation O_{ij}
P_{ij}	Processing time of operation O_{ij}
B_{ijk}	Starting time of operation O_{ij} on machine k
F_{ijk}	Completion time of operation O_{ij} on machine k
BP_{jk}	Basic power of machine M_k for its j^{th} operation
CU_{ijk}	Cutting power of operation O_{ij} on machine k
TP	Transportation power of AGV
$T_{i(j-1)jwk}$	Transportation time of operation $O_{i(j-1)}$ on machine w to operation $O_{i(j)}$ on machine k of job i

Imagine that there are n_m individuals on the first non-dominated front, and the distance between individual i and j on the same non-dominated front is:

$$d(i,j) = \sqrt{\sum_{l=1}^{L} (\frac{x_l^i - x_l^j}{x_l^u - x_l^d})^2} \tag{14}$$

where L is the variable number in the space, x_l^u and x_l^d are the upperbound and lowerbound of x_l relatively.

The sharing function s represents the relationship between x_j and other individuals in the niche are showed as follows:

$$s(d(i,j)) = \begin{cases} 1 - (\frac{d(i,j)}{\sigma_{share}})^\gamma & d(i,j) < \sigma_{share} \\ 0 & other \end{cases} \tag{15}$$

where σ_{share} is the sharing radius, γ is a constant.

Then the number of niche is:

$$c_i = \sum_{j=1}^{n_m} s(d(i,j)) \tag{16}$$

Thus the sharing fitness value can be obtained as follows:

$$f_m^{'} = \frac{f_m}{c_i} \tag{17}$$

After getting all the sharing fitness value of all the individuals, the crowding distance can be calculated as follows:

$$n_d = n_d + (f_m(i+1) - f_m(i-1)) \tag{18}$$

B. Multi-objective Evolutionary Algorithm Based on Decomposition

Multi-objective Evolutionary Algorithm Based on Decomposition (MOEA/D) is an algorithm proposed by Zhang and Li in 2007 [16]. It transforms the multi-objective problem into a series of single-objective sub-problems, and then uses the evolutionary algorithm to optimize these sub-problems simultaneously. Given that a solution on the Pareto front corresponds to the optimal solution of each single-objective sub-problem, a set of Pareto optimal solutions can eventually be obtained. Due to the elegance of decomposition, this algorithm has great advantages in maintaining the diversity of the solution and avoids the individuals from falling into a local optimum by analyzing the information of adjacent problems.

In the algorithm implementation, the most popular decomposition approach is Tchebycheff approach, which can be presented as follows:

$$\min g(x|\lambda, z^*) = \max_{1 \le i \le m} \{\lambda_i | f_i(x) - z_i^*\} \tag{19}$$

where $z^* = (z_1^*, ..., z_m^*)$ is the reference point and $z_i^* = \max\{f_i(x)|x\} \in \Omega$, λ is the weight vector, $f_i(x)$ is the fitness value of individual x, m is the number of individuals.

C. Encoding and decoding

In the model formulation, the decision variable should be well encoded for highly efficient implementation. The proper encoding scheme is crucial in algorithm performance. In this paper, a novel encoding and decoding scheme which fits for the both two algorithms are proposed.

The way of encoding is represented as follows:

• There are two kinds of individuals P and M representing the total operations of all the jobs and the machines used for all the operations. They are both vectors of n columns. The i^{th} occurrences of the same number in one individual P or M represents the i^{th} operation of the job or machine.

• Each element in the individual P and M corresponds to each other.

• Initialize the individuals by randomly ranking the operation and selecting the machines from the alternative machine sets.

The procedure of decoding is showed as follows:

Step 1: Obtain the best individuals P_best and M_best.

Step 2: According to all the constraints mentioned above, decode P_best, M_best with the processing time, transportation

TABLE II
THE PARAMETERS SETTINGS OF NSGA-II AND MOEA/D

Parameters	Value
Size of the population	100
Total number of generations	250
Crossover constant	0.8
Mutation rate	0.1

time and other factors to formulate the time set every operation processes.

Step 3: Calculate the completion time of each operation, e.g. the sum of starting time, processing time and transportation time.

Step 4: Calculate the energy consumption of each operation.

Step 5: Determine and composite the final solutions.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section, the aforementioned NSGA-II and MOEA/D are used to optimize a real-world case with transportation time. Both algorithms terminate when the number of iteration achieves the maximum iteration value. The parameters for the two experiments are shown in Table. II.

A. Case introduction

The case is about a flexible job shop in Nanjing with 10 jobs and 32 operations in all, which should be processed on 10 machines [2]. There are several AGVs to transport these jobs, in which time the power consumption is about 3.5 kW. Moreover, the power for AE is about 1 kW. The information of all the jobs is showed in Table. III. The transportation time between machines and the related power are relatively presented in Table. IV and Table. V.

B. Optimization results

From the information given above, we can obtain the solutions for FJSP considering transportation time. Fig. 1 and Fig. 2 show the Gantt chart and the fitness value obtained by NSGA-II respectively. Fig. 3 and 4 show the fitness value obtained by MOEA/D. Fig. 5 and 6 show the Gantt chart obtained by MOEA/D. Fig. 1 and 6 show the case when makespan is at its minimum value. Fig. 3 and 5 show the case when energy consumption is at its minimum value. The value of makespan and energy consumption are also showed in the figures. $p(i, j) = t$ in Gantt chart means the processing time for the j^{th} operation of the i^{th} job is t.

From the results showed above, it could be observed that NSGA-II gets both better makespan value and energy consumption value than MOEA/D. There can not be seen a law in the fitness value figure of NSGA-II, but for MOEA/D, the fitness values are whether the makespan value is small or the energy consumption value is small.

TABLE III
THE INFORMATION OF ALL THE JOBS

Job	Operation	Machine candidates	Processing time (min)	Set-up time (min)
J1	O11	M1,M2,M3,M7	18,20,40,45	2,2,3,3
	O12	M9,M10	20,14	3,2.5
	O13	M1,M2,M3,M7	17,20,30,28	3,2,3.5,3
J2	O21	M1,M2,M3,M7	12,10,20,15	2,1.5,3,2
	O22	M1,M2,M8	15,20,30	2,2,3
	O23	M9,M10	20,25	3,2.5
J3	O31	M1,M2,M3,M7	30,33,40,40	3,4,4,3.5
	O32	M9,M10	20,15	2.5,3
J4	O41	M1,M2,M3,M7	11,10,10,25	1.5,1.5,2,3
	O42	M9,M10	15,16	2,2
	O43	M1,M2,M3,M7	15,17,29,30	2,2.5,4,4
	O44	M1,M2,M3,M7	21,15,20,20	2.5,2,3,2
J5	O51	M1,M2,M3,M7	20,17,16,25	2,3,2.5,3
	O52	M9,M10	20,20	3,4
	O53	M1,M2,M3,M7	25,28,37,40	3,3,4,5
J6	O61	M4,M5,M6	15,25,30	1.5,2,2
	O62	M4,M5,M6	25,20,30	3,2.5,4
	O63	M1,M2,M3,M7	20,10,10,35	2,1,1,3
J7	O71	M4,M5,M6	10,20,30	1.5,1.5,2
	O72	M4,M5,M6	15,15,20	2,3,2.5
	O73	M1,M2,M3,M7	15,15,30,30	2,3,3,4
J8	O81	M4,M5,M6	20,25,30	1.5,2,2,5
	O82	M1,M2,M3,M7	15,20,30,40	2.5,3,3,4
J9	O91	M4,M5,M6	10,18,23	1,2,2
	O92	M4,M5,M6	15,20,20	1.5,3,2.5
	O93	M1,M2,M3,M7	5,5,7,11	1,1.5,2,2
	O94	M1,M2,M3,M7	10,12,17,15	1.5,1.5,2,2.5
J10	O101	M4,M5,M6	10,10,20	2,2.5,3
	O102	M4,M5,M6	15,10,25	1.5,2,2
	O103	M1,M2,M3,M7	10,10,25,30	1,1.5,3,3.5
	O104	M1,M2,M3,M7	20,15,30,40	3.5,2,2,4
	O105	M9,M10	22,20	3,3

C. Evaluation of the results

The 30 times results of NSGA-II consisting of makespan value and energy consumption value are showed in Table.VI.

From the table above, decision makers could get the most satisfying results according to the preference using analytic hierarchy process (AHP). Set the relative comparison decision matrix D as Eq.20, therefore the weight vector can be obtained: $W = (0.333, 0.667)^T$. The decision matrix X can also be obtained according to Table.VI.

$$D = \begin{pmatrix} 1 & 1/2 \\ 2 & 1 \end{pmatrix} \quad (20)$$

$$X = \begin{pmatrix} 110.03 & 110.03 & ... & 94.00 & 110.03 \\ 97.52 & 97.52 & ... & 97.71 & 97.15 \end{pmatrix}^T \quad (21)$$

TABLE IV
THE TRANSPORTATION TIME BETWEEN MACHINES

Machine	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
M1	0	152	170	193	100	112	173	165	142	133
M2	152	0	131	138	152	169	120	170	162	143
M3	170	131	0	160	151	140	132	171	122	140
M4	193	138	160	0	140	140	165	170	140	198
M5	100	152	151	140	0	103	142	140	148	150
M6	112	169	140	140	103	0	142	140	148	150
M7	173	120	132	165	102	142	0	150	162	160
M8	165	170	171	170	170	140	150	0	141	120
M9	142	162	122	140	180	148	162	141	0	153
M10	133	143	140	198	192	150	160	120	153	0

TABLE V
THE TRANSPORTATION TIME BETWEEN MACHINES

Machine	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Rated power (kW)	20	15	6	12	10	5.5	7.5	3	5.5	10
Unload power (kW)	3.45	2.82	0.84	1.58	1.41	0.55	1.02	0.37	1.16	1.8

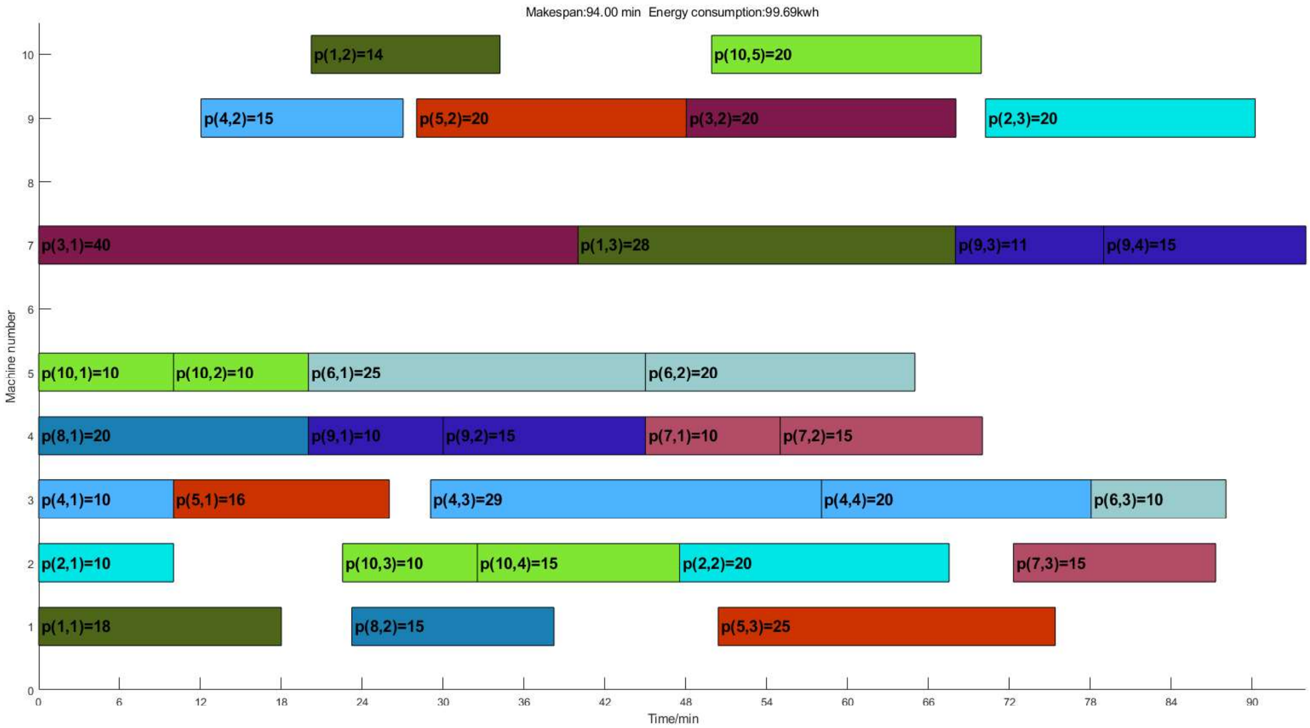

Fig. 1. Gantt chart of a featured result with minimum makespan obtained by NSGA-II

Then normalize X to Y according to Eq.22. The matrix Y is showed in Eq.23.

$$y_{ij} = \frac{\max\{x_{i1}, x_{i2}, ...x_{i30}\} - x_{ij}}{\max\{x_{i1}, x_{i2}, ...x_{i30}\} - \min\{x_{i1}, x_{i2}, ...xi30\}} \tag{22}$$

$$Y = \begin{pmatrix} 0.5344 & 0.5344 & ... & 1 & 0.5344 \\ 0.8614 & 0.8614 & ... & 0.7903 & 1 \end{pmatrix}^T \tag{23}$$

It can be seen that the evaluation value of solution 29 is 0.8601, which means solution 29 is the most satisfying result according to the relative comparison decision matrix.

V. CONCLUSION

In this paper, NSGA-II and MOEA/D are used for solving FJSP considering transportation constraint, which is more complicated than conventional JSP. The novel encoding and

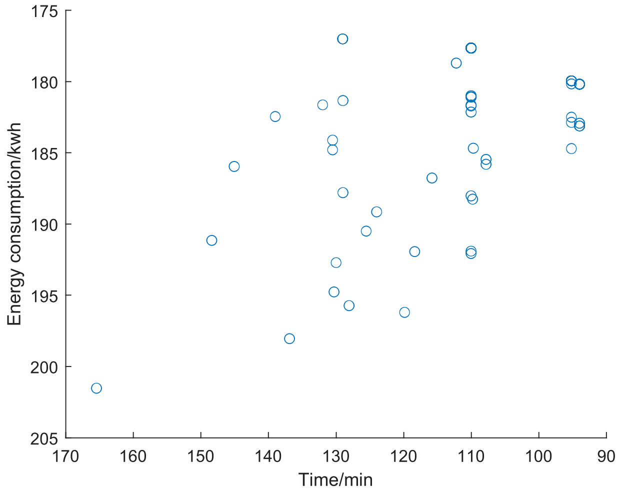

Fig. 2. Fitness value of a featured result with minimum makespan obtained by NSGA-II

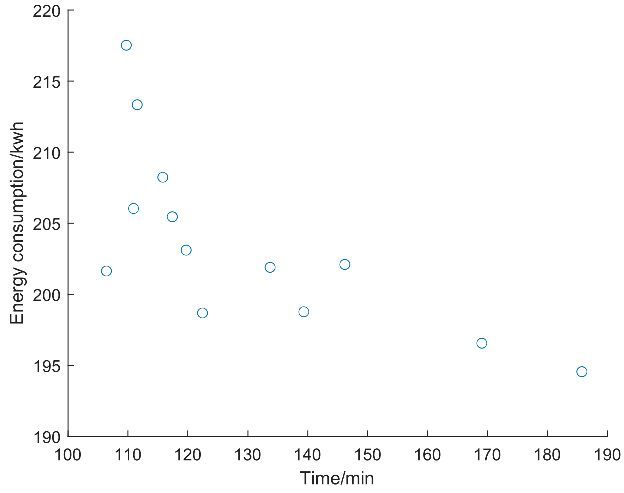

Fig. 4. Fitness value of a featured result with minimum makespan obtained by MOEA/D

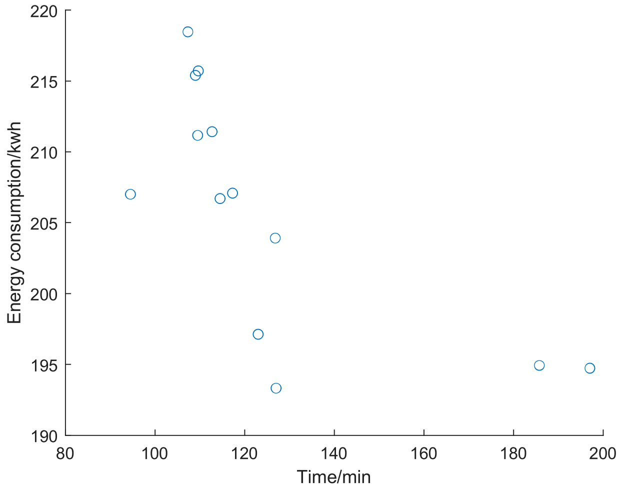

Fig. 3. Fitness value of a featured result with minimum energy consumption obtained by MOEA/D

TABLE VI
THE PARETO SOLUTIONS OF NSGA-II

Number	Makespan (min)	Energy consumption (kWh)	Evaluation
1	110.03	97.52	0.7525
2	110.03	97.52	0.7525
3	97.52	98.37	0.6612
4	95.20	99.82	0.3214
5	110.03	97.52	0.7525
6	110.03	97.52	0.7525
7	110.03	97.52	0.7525
8	95.20	99.82	0.3214
9	110.03	97.52	0.7525
10	97.52	98.37	0.6612
11	110.03	97.52	0.7525
12	97.52	98.37	0.6612
13	110.03	97.15	0.8450
14	97.52	98.01	0.7511
15	95.20	99.45	0.4138
16	95.20	99.45	0.4138
17	110.03	97.15	0.8450
18	95.20	99.45	0.4138
19	110.03	97.15	0.8450
20	97.52	98.01	0.7511
21	110.03	97.15	0.8450
22	110.03	97.15	0.8450
23	95.20	99.45	0.4138
24	94.00	99.69	0.3655
25	128.43	96.60	0.8044
26	110.03	97.15	0.8450
27	110.03	97.15	0.8450
28	110.03	97.15	0.8450
29	94.00	97.71	0.8601
30	110.03	97.15	0.8450

decoding methods are prosed in this paper associating the two solvers and a real-world FJSP instance is introduced to make the comparison. Through comprehensive case study, NSGA-II get both better makespan and energy consumption value. Finally, AHP is used to evaluate the results according to the decision makers. Future work will be addressing more real-world objectives and constraints in the model formulation and solving.

ACKNOWLEDGEMENT

This research work is supported by the National Key Research and Development Project under Grant 2018YFB1700503, National Natural Science Foundation of Guangdong (No. 2018A030310671, 2016A030313177), Guangdong Frontier and Key Technological Innovation (No. 2017B090910013), Science and Technology Innovation Commission of Shenzhen (No. JCYJ20170818153048647, JCYJ20180507182239617, JCYJ2018050718223961 and

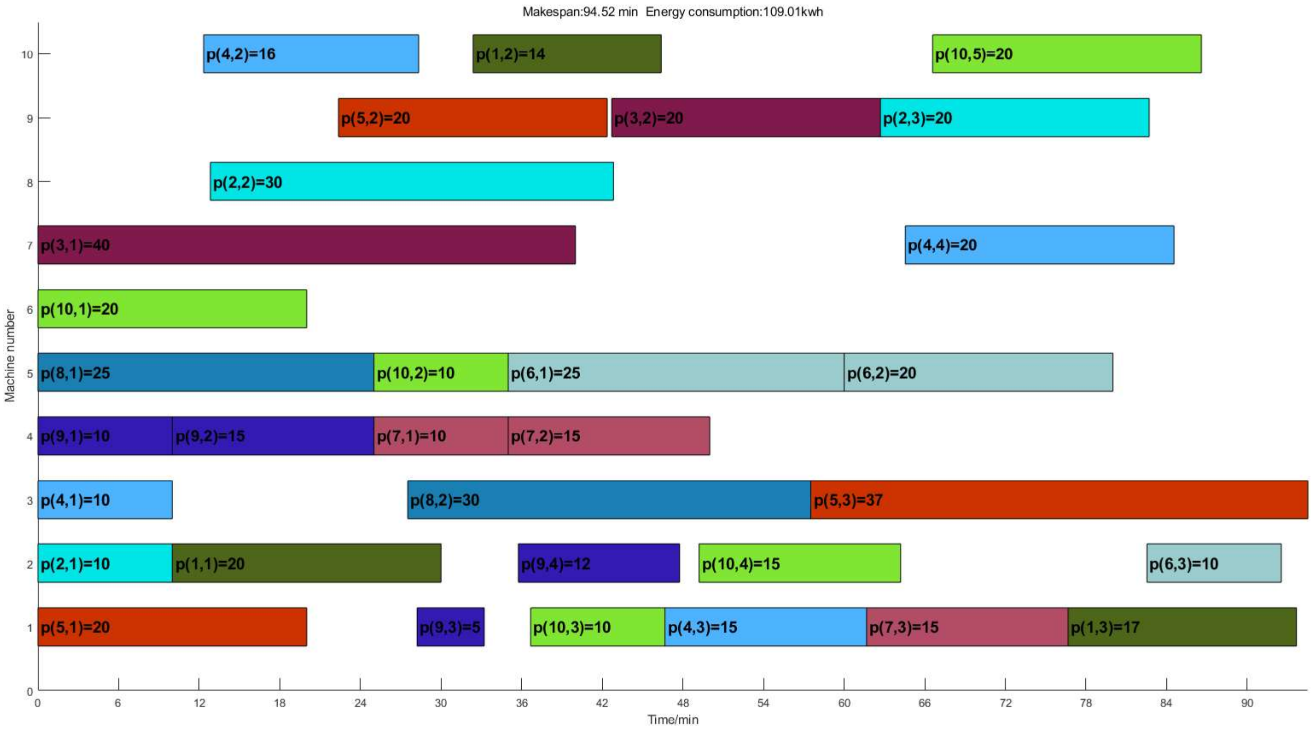

Fig. 5. Gantt chart of a featured result with minimum obtained energy consumption by MOEA/D

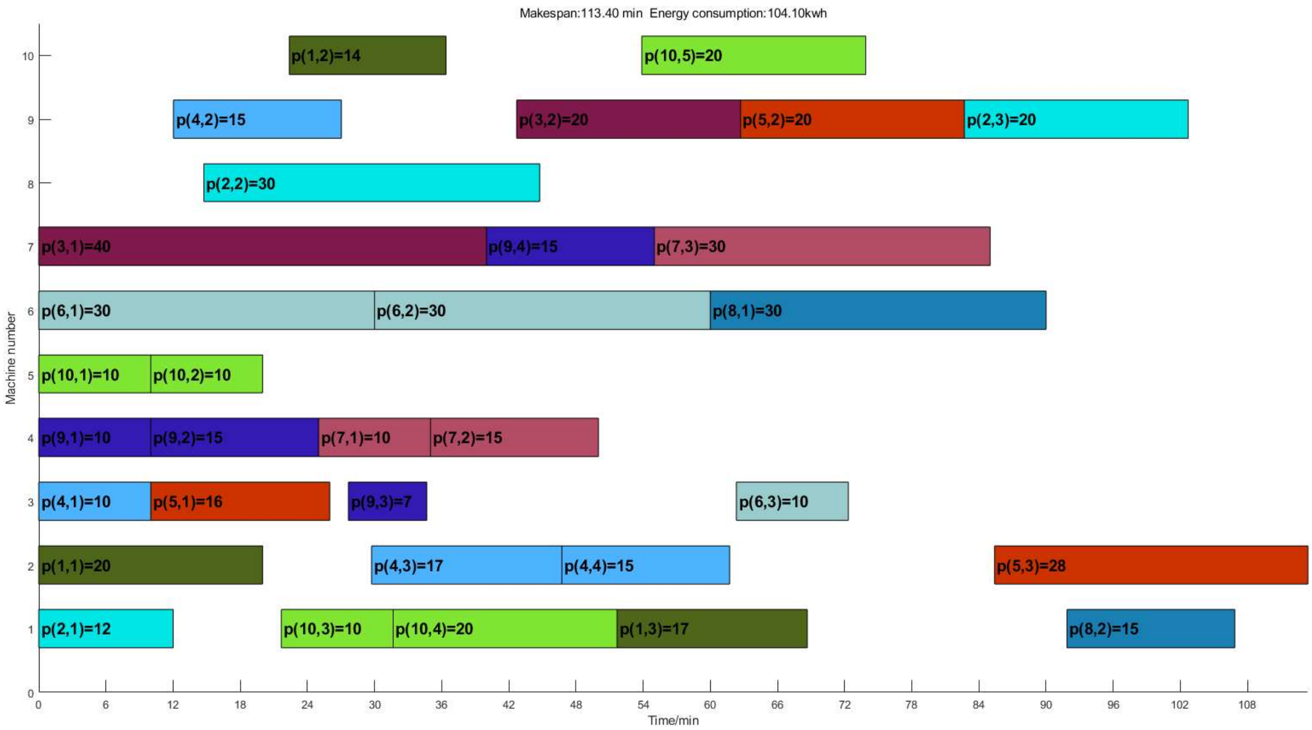

Fig. 6. Gantt chart of a featured result with minimum makespan obtained by MOEA/D

ZDSYS20190902093209795), and Outstanding Young Researcher Innovation Fund of Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences (201822).

REFERENCES

[1] Apostolos, F., Alexios, P., Georgios, P., Panagiotis, S., George, C.: Energy efficiency of manufacturing processes: A critical review. Procedia Cirp 7, 628–633

[2] Dai, M., Tang, D., Giret, A., Salido, M.A.: Multi-objective optimization for energy-efficient flexible job shop scheduling problem with transportation constraints. Robotics and Computer-Integrated Manufacturing 59, 143–157 (2019)

[3] Deb, K., Pratap, A., Agarwal, S., Meyarivan, T.: A fast and elitist multiobjective genetic algorithm: Nsga-ii. IEEE Transactions on Evolutionary Computation 6(2), 182–197 (2002)

[4] Gadaleta, M., Pellicciari, M., Berselli, G.: Optimization of the energy consumption of industrial robots for automatic code generation. Robotics and Computer-Integrated Manufacturing 57, 452–464

[5] Gong, G., Deng, Q., Gong, X., Liu, W., Ren, Q.: A new double flexible job-shop scheduling problem integrating processing time, green production, and human factor indicators. Journal of Cleaner Production 174, 560–576 (2018)

[6] Karimi, S., Ardalan, Z., Naderi, B., Mohammadi, M.: Scheduling flexible job-shops with transportation times: Mathematical models and a hybrid imperialist competitive algorithm. Applied Mathematical Modelling 41, 667–682 (2017)

[7] Liu, Q., Zhan, M., Chekem, F.O., Shao, X., Ying, B., Sutherland, J.W.: A hybrid fruit fly algorithm for solving flexible job-shop scheduling to reduce manufacturing carbon footprint. Journal of Cleaner Production 168, 668–678 (2017)

[8] Liu, Y., Dong, H., Lohse, N., Petrovic, S., Gindy, N.: An investigation into minimising total energy consumption and total weighted tardiness in job shops. Journal of Cleaner Production 65, 87–96

[9] Mokhtari, H., Hasani, A.: An energy-efficient multi-objective optimization for flexible job-shop scheduling problem. Computers & Chemical Engineering 104, 339–352 (2017)

[10] Moreira, L., Li, W., Lu, X., Fitzpatrick, M.: Energy-efficient machining process analysis and optimisation based on bs en24t alloy steel as case studies. Robotics and Computer-Integrated Manufacturing 58, 1–12

[11] Pastras, G., Fysikopoulos, A., Chryssolouris, G.: A theoretical investigation on the potential energy savings by optimization of the robotic motion profiles. Robotics and Computer-Integrated Manufacturing 58, 55–68

[12] Peng, T., Xu, X.: Energy-efficient machining systems: a critical review. International Journal of Advanced Manufacturing Technology 72(9-12), 1389–1406

[13] Rossi, A., Dini, G.: Flexible job-shop scheduling with routing flexibility and separable setup times using ant colony optimisation method. Robotics and Computer-integrated Manufacturing 23(5), 503–516 (2007)

[14] Zhang, L., Tang, Q., Wu, Z., Wang, F.: Mathematical modeling and evolutionary generation of rule sets for energy-efficient flexible job shops. Energy 138, 210–227 (2017)

[15] Zhang, Q., Manier, H., Manier, M.: A modified shifting bottleneck heuristic and disjunctive graph for job shop scheduling problems with transportation constraints. International Journal of Production Research 52(4), 985–1002 (2014)

[16] Zhang, Q., Li, H.: Moea/d: A multiobjective evolutionary algorithm based on decomposition. IEEE Transactions on Evolutionary Computation 11(6), 712–731 (2007)