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A basic study on scheduling method for electric power saving of production machine

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Abstract. At present, energy consumption all over the world is increasing, and various approaches to energy issues such as the Sustainable Development Goals (SDGs) are in progress. In Japanese manufacturing industry, the introduction of factory Energy Management System (EMS) and the improvement of production equipment are being carried out in order to reduce energy consumption. Accordingly similar considerations are also important issues for production scheduling. In this paper, based on the assumption that renewable energy and EMS will eventually be introduced in the future, we focus on factories and utility companies, and at the same time, try to realize a scheduling method that improves energy efficiency with keeping production performance, and evaluate it by computational experiments.

Keywords: flexible flow shop scheduling · power saving · optimization · production machine.

1 Introduction

As energy demand in the world increases with the development of the economy, problems such as the depletion of fossil fuels due to the increase of energy consumption and increase of CO_2 emissions causing global warming becomes more serious. Therefore, various countries around the world collaborate altogether for Sustainable Development Goals (SDGs), and work on energy issues with the aim of realizing a sustainable society [1]. The industrial sector, including the manufacturing sector, accounts for more than 50% of the total energy consumption, and in today's era of rapid electrification, power saving in the industrial sector is considered an important initiative [2]. In the manufacturing industry, energy saving is promoted by introducing an Energy Management System (EMS) with energy-efficient equipment, and by scheduling in consideration

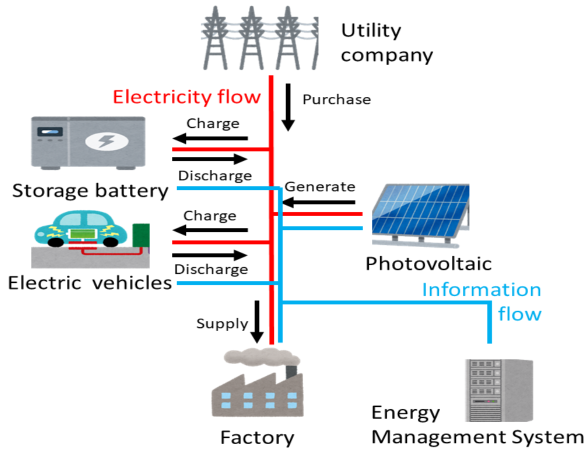

Fig. 1. Target model

of power consumption. Among them, research on scheduling aimed at improving production efficiency and energy efficiency has attracted attention because it could be realized at a lower investment cost than such as purchasing a new system or equipment[3].

In the target model (Fig. 1), electricity used in the factory is supplied by purchasing from a utility company or by generating electricity from renewable energy such as PhotoVoltaic(PV). A storage battery stores electricity from a utility company during the time when the electricity charge is low, and discharges the electricity to factory during the time when the electricity charge is high. In addition, efficient use of renewable energy is realized by positioning multiple Electric Vehicles (EVs) as moving batteries. Furthermore EMS predicts power demand and PV power generation, and determines the operation plan of each power generation facility and the EV charging and discharging schedule.

In this paper, we first focus on two models, utility company and factory, and perform scheduling for power saving and production efficiency.

2 Problem statement

In this paper, the problem is formulated based on the reference [4]. A Flexible Flow Shop (FFS) covered in this paper (Fig. 2) is described as follows: J jobs must be processed in the I stages, and all jobs are processed in the same order. There are L machines in each stage, and each machine has difference in ability. No machine failure occurs. All jobs and machines are available from the start of production. Each job is assigned to only one machine in each stage, and each machine can process at most one job at a time. No interruption occurs during job processing. Setup occurs when processing different jobs. Each machine belongs to

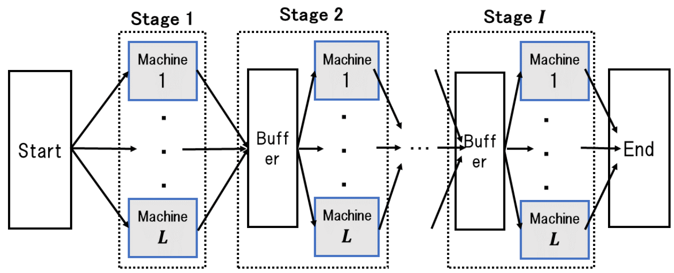

Fig. 2. An example of flexible flow shop

one of the three states of processing, idle, and setup, and the power consumption differs depending on each state.

2.1 Notation

The definition of the characters used in the formulation is as follows:

- Index
  - j, k, h: job number
  - i: stage number
  - l: machine number
- Parameters
  - J: total number of jobs
  - I: total number of stages
  - L: number of machines in each stage
  - P_{ilj}: processing time of job j at machine l on stage i
  - ST_{iljk}: setup time from job j to job k at machine l on stage i
  - PE_{il}: energy consumption per Time Slot (TS) at machine l on stage i during processing
  - IE_{il}: energy consumption per TS at machine l on stage i during idle
  - SE_{il}: energy consumption per TS at machine l on stage i during setup
  - $SOTEC$: total energy consumption value when solving the total energy consumption minimization scheduling problem
  - SOC_{max}: makespan value when solving the makespan minimization scheduling problem
  - α: weighting parameter of the objective function
- Variables
  - TEC: total energy consumption
  - C_{max}: makespan (the completion time of the last job on the last machine)
  - pe_{il}: total energy consumption during processing at machine l on stage i
  - ie_{il}: total energy consumption during idle at machine l on stage i
  - se_{il}: total energy consumption during setup at machine l on stage i
  - pt_{il}: total processing time at machine l on stage i

- it_{il}: total idle time at machine l on stage i
- st_{il}: total setup time at machine l on stage i
- $t1_{il}$: work start time at machine l on stage i
- $t2_{il}$: work end time at machine l on stage i
- c_{ij}: completion time of job j in stage i
- $x_{iljk} = \begin{cases} 1 \text{ if job } j \text{ precedes job } k \text{ at machine } l \text{ on stage } i \\ 0 \text{ otherwise} \end{cases}$

2.2 Formulation

The formulation of this paper is shown below.

$$\text{Min.} \quad \alpha * \frac{TEC}{SOTEC} + (1-\alpha) * \frac{C_{max}}{SOC_{max}} \tag{1}$$

$$\text{where} \quad TEC = \sum_{i \in I} \sum_{l \in L} (pe_{il} + se_{il} + ie_{il}) \tag{2}$$

$$C_{max} = \max\{c_{ij}\}, \quad \{\forall i \in I, \forall j \in J\} \tag{3}$$

$$pe_{il} = pt_{il} * PE_{il}, \quad \{\forall i \in I, \forall l \in L\} \tag{4}$$

$$se_{il} = st_{il} * SE_{il}, \quad \{\forall i \in I, \forall l \in L\} \tag{5}$$

$$ie_{il} = it_{il} * IE_{il}, \quad \{\forall i \in I, \forall l \in L\} \tag{6}$$

$$pt_{il} = \sum_{j \in \{0,J\}} \sum_{k \in J, k \neq j} x_{iljk} * P_{ilk}, \quad \{\forall i \in I, \forall l \in L\} \tag{7}$$

$$st_{il} = \sum_{j \in J} \sum_{k \in J, k \neq j} x_{iljk} * ST_{iljk}, \quad \{\forall i \in I, \forall l \in L\} \tag{8}$$

$$it_{il} = t2_{il} - t1_{il} - pt_{il} - st_{il}, \quad \{\forall i \in I, \forall l \in L\} \tag{9}$$

$$t1_{il} = 0, \quad \{\forall i \in I, \forall l \in L\} \tag{10}$$

$$t2_{il} = C_{max}, \quad \{\forall i \in I, \forall l \in L\} \tag{11}$$

$$\text{sub.to} \quad \sum_{j \in \{0,J\}, j \neq k} \sum_{l \in L} x_{iljk} = 1, \quad \{\forall i \in I, \forall k \in J\} \tag{12}$$

$$\sum_{j \in J, j \neq k} \sum_{l \in L} x_{ilkj} \leq 1, \quad \{\forall i \in I, \forall k \in J\} \tag{13}$$

$$\sum_{h \in \{0,J\}, h \neq j, h \neq k} x_{ilhj} \geq x_{iljk}, \quad \{\forall i \in I, \forall l \in L, \forall j, k \in J, j \neq k\} \tag{14}$$

$$\sum_{l \in L} (x_{iljk} + x_{ilkj}) \leq 1, \quad \{\forall i \in I, \forall j \in J, k = j+1, ..., Job, j \neq k\} \tag{15}$$

$$\sum_{k \in J} x_{il0k} \leq 1, \quad \{\forall i \in I, \forall l \in L\} \tag{16}$$

$$c_{i0} = 0, \quad \{\forall i \in I\} \tag{17}$$

$$c_{ik} + BigM(1 - x_{iljk}) \geq c_{ij} + ST_{iljk} + P_{ilk}, \quad \{\forall i \in I, \forall l \in L, \forall j \in \{0, J\}, \forall k \in J(k \neq j)\} \tag{18}$$

$$c_{ik} + BigM(1 - x_{iljk}) \geq c_{(i-1)j} + P_{ilk}, \quad \{\forall i \in I, \forall l \in L, \forall j \in \{0, J\}, \forall k \in J(k \neq j)\} \tag{19}$$

$$x_{iljk} \in \{0, 1\}, \quad \{\forall i \in I, \forall l \in L, \forall j \in \{0, J\}, \forall k \in J(k \neq j)\} \tag{20}$$

$$c_{ij} \geq 0, \quad \{\forall i \in I, \forall j \in J\} \tag{21}$$

x_{iljk} and c_{ij} are the decision variables. When x_{iljk} is 1, job j precedes job k at machine l on stage i, otherwise, x_{iljk} is 0. c_{ij} is integer decision variable that indicates completion time of job j on stage i.

Objective function (1) is intended for minimizing the weighted sum of the total energy consumption of equation (2) and the makespan of equation (3). The reason for using these two as an evaluation index is that to change the degree of consideration of total energy consumption and makespan in scheduling by changing the value of a weight parameter α. $SOTEC$ and SOC_{max} are obtained by setting the objective function to TEC or C_{max} for the same formulation. Equation (2) is sum of the total energy consumption in each state (processing, idle, setup). Equation (3) is the completion time of the last job on the last machine. Equations (4)-(6) calculate the power consumption in each state(processing, idle and setup) of machine l on stage i. Equations (7)-(9) calculate the time in each state (processing, idle and setup) of machine l on stage i. Equations (10) and (11) set the work start time and work end time of machine l on stage i. Equations (12)-(19) are constraint equations and have the same meanings as the constraint equations (2) to (9) in the formulation in chapter 5 in reference [4]. In this paper, constraint (18) considers only setup time between different jobs. Constraint (19) considers only the completion time of the previous stage of the job.

3 Computational experiment

In order to evaluate the influence of the weight parameter α of the objective function, the computational experiments are performed. In the experiments, we perform the sensitivity analysis for α which is the weighting factor of the total energy consumption and makespan. CPLEX12.9 [5] is used to solve the scheduling problem. The evaluation criteria are as follows:

- TEC: total energy consumption
- C_{max}: makespan

3.1 Experimental condition

The initial setup conditions are hypothetically determined. In general higher speed machine with powerful actuators requires more electric energy. We consider this assumption is commonly observed in real shop floor. Therefore, this experiment assumes that each stage has two type machines: Machine 1 in each stage has a high job processing speed but high power consumption. Machine 2 in each stage has a slower job processing speed than Machine 1, but consumes less power than Machine 1. The experimental conditions are as follows. [ ] indicates a uniform random number.

- I: total number of stages = 2
- L: number of machines in each stage = 2
- J: total number of jobs = 8
- P_{i1j}: processing time of job j at machine 1 on stage i = [10, 20]
- PE_{i1}: power consumption per TS at machine 1 on stage i during processing = 80
- IE_{i1}: power consumption per TS at machine 1 on stage i during idle = 8
- P_{i2j}: processing time of job j at machine 2 on stage i = [30, 40]
- PE_{i2}: power consumption per TS at machine 2 on stage i during processing = 10
- IE_{i2}: power consumption per TS at machine 2 on stage i during idle = 1
- ST_{iljk}: setup time from job j to job k at machine l on stage i l = 5
- SE_{il}: power consumption per TS at machine l on stage i during setup = 5

3.2 Experimental result

In the experiment, the parameter α used for the weighted sum of the objective function is changed between 0 and 1. When α is increased, the weight for minimizing the total energy comsumption in the objective function increases. Whereas if it is decreased, the weight of the minimization of the makespan increases. Table 1 shows the results of total energy consumption and makespan when α is changed. Considering the results in Table 1, when the weight of the total energy consumption increased, total energy consumption is reduced and makespan is increased. And when we increased the weight of makespan, total energy consumption is increased and makespan is reduced. So, there is a trade-off relationship between total energy consumption and makespan under this experimental conditions, and a decision maker can decide the priority degree of total energy consumption and makespan in a scheduling by deciding α. However, when α exceeds 0.7, the values of total energy consumption and makespan change significantly, so it is difficult to finely adjust the α value close to the total energy consumption and makespan schedule assumed by decision makers.

Table 1. Results of experiment

α		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
TEC	Avg.	14790.7	14357.4	14155.5	14084.3	13974.4	13923.9	13730.2	13681.5	13126.0	11725.2	11364.6
	S.D.	337.22	482.01	550.60	552.73	531.65	505.70	552.07	556.72	473.18	398.17	182.71
C_{max}	Avg.	119.9	119.9	120.2	120.5	121.1	121.5	123.8	124.9	145.7	233.6	290.0
	S.D.	4.18	4.18	4.13	3.81	4.23	4.14	4.66	4.38	25.87	41.96	18.38

4 Conclusion

In this paper, we proposed a scheduling method aiming at productivity improvement and power saving for a flexible flow shop type production line. In this method, it is assumed that more detailed and specific energy management can be provided by dividing the state of the machine into three states: processing, idle, and setup. And we solved the optimization problem related to both productivity and energy efficiency in our hypothetical target production line as basic research. In the computer experiment, scheduling that saves total energy was possible by deciding the value of α, and changing the degree of consideration of makespan and total energy consumption. However, it is not clear how to set the value of α so that the decision maker can create a schedule of total energy consumption in this experiment. Therefore, as the next step, it is necessary to clearify the relationship between the degree of consideration of makespan and the degree of consideration of total energy consumption, for each value of α, by scheduling with experimental conditions set according to a more realistic factory model.

In addition, it is also important to reduce the cost in the manufacturing industry, so we aim to reduce not only the power consumption but also the power cost in this research. Therefore, we assume that the long-term goal is to propose not only factory scheduling but also an energy allocation plan that reduces the power cost according to the power demand of the factory resulting from the scheduling. The installation of renewable energy system, batteries, or EVs, is now spreading into factory operation. Therefore, in factories including those systems, the analysis between production performance and energy saving with sophisticated scheduling methodology becomes more important issues, and it is our obvious next step.

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