A control method to save machine energy in production

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Abstract. Nowadays, energy saving is one of the most talked about issues in our life, it is also increasingly important in the manufacturing industry. This research considers the dynamic flexible flow shop scheduling (DFFS) problem, which is an extended version of the classical flow-shop scheduling problem. A flexible flow shop has multiple stages with multiple machines at each stage for processing multiple products. Previous research on DFFS aimed to achieve just-in-time production, or reducing difference between the actual completion time and the due date of each job. However, little research has been made on energy saving of machines in production. To address such a need, this paper proposes a method that dynamically turns on and off machines so as to reduce energy consumption while achieving JIT production. The proposed method has been tested on different environments, and the results show that it is high performing for both JIT production and energy saving.

1. Introduction
Energy and environmental issues are one of the most talked about issues in the 21st century. As a result of climate change, regulation of carbon dioxide emissions has been imposed globally, which has put much pressure on the manufacturing industry to reduce energy (particularly electric energy) [1]. Environmental protection, solar, wind and other new energy sources are being widely used in life and production. Sustainable development is becoming a trend to promote energy saving. With the need for energy efficiency and low-carbon production, it is a big challenge for high energy consumption enterprises to reduce energy use [2]. Therefore, effective energy and utility management is a key factor to enhance the competitive advantage of organizations, and to promote green and sustainable practices [3]. The factory as a major energy consumer, energy conservation is particularly important.

Current studies have been highlighting the importance of energy efficiency on the environmental impact of manufacturing processes. They primarily focus on the evaluation of manufacturing processes based on operating state and components of machine tools [4], thermodynamics approaches [5], and empirical modelling [6].

What’s more, cutting parameters optimization for material removal processes is also one of the important energy-saving strategies using by most research. Anderberg et al. analyzed the relationship between cutting parameters, machining costs, and energy consumption in a CNC machining environment [7]. Diaz et al. analyzed the effect of material removal rate and workpiece material on cutting power and energy consumption [8]. Mativenga and Rajemi proposed a method for selecting optimum cutting parameters for minimum energy consumption in turning a cylindrical steel billet [9]. These methods have been developed which enable consideration of energy consumption for the selection of optimal cutting parameters. Based on machine level, this paper presents a method called...
dynamic machine on/off method which can dynamic turn on and turn off machines when needed in order to save energy consumption of machines.

Similar to machine level, at shop floor level, most of the research related to energy efficient shop floor scheduling have shown improvements in reducing energy consumption for manufacturing. Multi-objective scheduling models have been proposed to optimize both makespan and energy consumption [10, 11] presented a general multi-objective mixed-integer programming formulation for flow shop scheduling problem that considers makespan, peak power demand, and carbon footprint. The proposed scheduling problem considers the operation speed as an independent variable, which can be changed to affect the peak load and energy consumption. Bruzzone et al. [12] presented an energy-efficient scheduling method to modify the original timetable of the jobs in FFS in order to reduce the shop floor's peak power demand while some level of tardiness and makespan increase are accepted.

The just-in-time (JIT) production and flexible flow shop (FFS) type of manufacturing system are selected as the research object for the following reasons:

With the increase in inventory costs, more and more factories tend to JIT production rather than reduce the maximum completion time of all jobs. The objective of JIT production is to reduce both inventory costs of jobs completed before due dates and delay costs of jobs completed after due dates. The due date is the date that the factory expects to deliver the product to the customer. There is a complex manufacturing environment called FFS which is a further development of the classical flow-shop scheduling. FFS has multiple stages with multiple machines at each stage for processing multiple products. All jobs must go through all the stages to become finished products, which means that there are many different flow lines (routes) available for each job to go through the system. There is a previous study [13] concentrating on JIT production for FFS problem. It detailed three distributed-intelligence approaches to achieve the JIT objective. We add the proposed dynamic machine on/off method in the best-performing approach among the previous study, which is named stage to stage (S2S) feedback approach. This research intends to minimize both total inventory costs and delay costs of all jobs and total energy consumption of all machines.

The remainder of this paper is organized as follows. We give the problem description in chapter 2. After that, we present the dynamic machine on/off method proposed in this paper in chapter 3, and give the computational simulation results and the conclusions in chapters 4 and chapter 5 respectively.

2. Problem description

This paper considers the dynamic FFS problem in which the manufacturing environment consists of multiple stages with multiple machines at each stage. All jobs must go through all stages in sequence in order to become a product. If job $j$ is finished before its due date $D_j$, it has an earliness $E_j$. On the other hand, if job $j$ is finished after its due date $D_j$, it has a tardiness $T_j$. Let $C_j$ denote the completion time of job $j$, then the earliness of a job completed before its due date is given as $E_j = \max(0, D_j - C_j)$, and the tardiness of a job completed after its due date is given as $T_j = \max(C_j - D_j, 0)$. Both early jobs and tardy jobs have penalties but earliness penalties are always smaller than tardiness penalties. Each stage has a waiting queue before it, with jobs inside the queue processed in an Earliest-Due-Date (EDD) sequence.

The objective function is equation (1)

$$
\text{Min} \left[ \sum_{j=1}^{J} (E_j \times EP_{p(j)} + T_j \times TP_{p(j)}) + \sum_{m=1}^{M} (tp_m \times MP_m + t_l_m \times M_l_m + nt_m \times MS_m) \right]
$$

(1)

where $p(j)$ is product type of job $j$ and $J$ is the total number of jobs, $E_j$ is earliness of job $j$ and $EP_{p(j)}$ is unit penalty of earliness, $T_j$ is tardiness of job $j$ and $TP_{p(j)}$ is unit penalty of tardiness, $tp_m$ is sum of processing time of jobs operated on machine $m$, $MP_m$ is energy cost per unit time for machine $m$ in processing mode, $t_l_m$ is sum of idling time for machine $m$, $M_l_m$ is energy cost per unit time for
machine $m$ in idle mode, $n_{tm}$ is number of times for turning on and turning off machine $m$, $MS_m$ is energy cost for turning on or turning off machine $m$.

Besides, the following conditions are assumed in this paper:
1. One machine can only process one job at a time.
2. The processing of each job is nonpreemptive.
3. Machines do not break down.
4. Machines have the same energy cost per unit time when they are in the same mode.
5. The processing time for each product on each machine is different but fast machines process all types of products faster than slow machines.
6. The waiting queue of each stage is unlimited.

3. Proposed method
We propose a method that dynamically turns off some machines without causing jobs to be tardy in order to save energy and turns on them again when they need to be used for reducing job tardiness.

We assume that each machine has three modes: processing mode, idle mode and off mode [14]. Machines are in the processing mode when they are processing jobs and will switch to the idle mode automatically after they finish the jobs. The energy cost per unit time for the processing mode is bigger than that for the idle mode. There is also an energy cost for either turning on or turning off a machine. The proposed method aims to reduce the total energy consumption by dynamically turning on and off machines. In the following, we introduce how to dynamically turn off and turn on machines respectively.

3.1. Design of turning off machines
As mentioned before, machines are in the processing mode when they are processing jobs and will switch to the idle mode automatically after they finish the jobs. Since jobs come dynamically, the system does not always need all the machines to work when the system is not busy. We focus on these idle machines when trying to turn off a machine. The procedure of turning off the machines is shown in figure 1.

At each stage, when a machine in the processing mode finishes a job, we use the estimated completion time of each job provided in the S2S feedback approach to check if any job in the waiting queue will be tardy if we turn off the machine. If no job is found to be tardy, we will compare idle energy consumption with machine on/off energy consumption, if the idle energy consumption is greater, we will compare the average processing time of the last job in the stage waiting queue with the waiting time of the last job in queue of current stage. The average processing time (APT) is calculated by equation (2)

$$APT = \frac{\sum_{j=1}^{M_s} P(j,m)}{M_s},$$

(2)

where $M_s$ is the number of machines of each stage, $P(j,m)$ is the processing time of job $j$ operated on machine $m$. The waiting time of a job means the time duration from this job enters the waiting queue of current stage to it is processed by machine. If the former is larger than the latter, the idle machine will be turned off. Each stage repeats this procedure until it finds at least one condition in figure 1 is not satisfied.

3.2. Design of turning on machines
The procedure of turning on the machines is shown in figure 2. When a new job enters the waiting queue of a stage, if there are some machines that are turned off at the stage and any of the waiting jobs is found to be tardy based on the estimated completion time provided by S2S in the stage, we will compare the average processing time of the last job in waiting queue of current stage with the waiting time of the last job in queue of current stage. After comparison, we will turn on the fastest off machine using the procedure shown in figure 2. Since jobs arrive dynamically, machines are turned off and on dynamically at each stage.
4. Computational simulations

4.1. Simulation environment
Table 1 describes parameters design of simulation environment. The type of products is designed to be 1 and 5, the number of stages is designed to be 3, 5 and 10. The total number of machines in the system is designed to be 5, 10 and 20. Since each factor has more than one design, the number of combinations is equal to 18 \((2*3*3=18)\). Then we let the problem instance for each feasible combination equals to 3, so the total number of problem instances is 48. When there are 10 stages, the number of machines must be at least 10, so there are 6 infeasible instances because the number of machine is 5 in system is unacceptable.
In order to evaluate the results in a fair way, each instance has 2200 jobs, of which the first 200 jobs are used to warm up the system to a stable state, so we focus on only the remaining 2000 jobs for getting the results.

Table 1. Design of simulation environment.

| Type of Products: | 1, 5 |
|-------------------|------|
| Number of Stages: | 3, 5, 10 |
| Number of Machines: | 5, 10, 20 |
| Number of combinations: | 18 |
| Problem instance for each feasible combination: | 3 |
| Total number of problem instances: | 48 |

These designs are intended to test whether the proposed dynamic machine on/off method can work well under all kinds of situations. In addition, we set the energy costs as follows after refer to a previous paper [9]:

- Energy cost per unit time for a machine in processing mode: 1;
- Energy cost per unit time for a machine in idle mode: 0.4;
- Energy consumption for turning on or turning off a machine: 0.6.

4.2. Simulation results

In order to show the effect of this dynamic machine on/off method, Tables 2-4 give the average results of all instances in different designs.

In the tables, Total Cost is sum of Power Consumption Cost and Earliness & Tardiness Cost, which means the total penalty including energy consumption, earliness and tardiness of all jobs. The data of tables are calculated by equation \( r = \frac{r_r}{r_0} \times 100\% \), where \( r \) is the result calculated by using machine on/off method and \( r_0 \) is the result without using method.

Table 2. Average results of different products.

| P | Power Consumption Cost | Earliness & Tardiness Cost | Total Cost |
|---|------------------------|-----------------------------|-----------|
| 1 | -31.57%                | -0.05%                      | -18.39%   |
| 5 | -24.10%                | -0.08%                      | -15.67%   |

Table 3. Average results of different stages.

| S | Power Consumption Cost | Earliness & Tardiness Cost | Total Cost |
|---|------------------------|-----------------------------|-----------|
| 3 | -38.65%                | -0.07%                      | -20.96%   |
| 5 | -25.58%                | -0.05%                      | -15.20%   |
| 10 | -25.48%              | -0.07%                      | -16.90%   |

Table 4. Average results of different machines.

| M | Power Consumption Cost | Earliness & Tardiness Cost | Total Cost |
|---|------------------------|-----------------------------|-----------|
| 5 | -12.54%                | -0.03%                      | -6.30%    |
| 10 | -20.12%               | -0.06%                      | -12.42%   |
| 20 | -41.27%               | -0.07%                      | -27.54%   |

4.3. Result analysis

As revealed by tables 2-4, both energy consumption and total earliness and tardiness of all jobs are becoming better after we use dynamic machine on/off method, regardless of different factors or different types, so does the Total Cost, which means the total penalty including energy consumption, earliness and tardiness of all jobs.

Table 2 shows the results become better when \( P \) increases from 1 to 5. It is probably because the dynamic machine on/off method can effectively reduce both job earliness and tardiness, the total cost will become better with the increase in the number of products. Table 3 shows that when \( S \) increase, the results become worse. The reason is that a job need more time to be processed to a product when
the number of stage increase. When new order comes constantly, the number of waiting jobs will increase rapidly, which lead to the increase number of tardy jobs. Table 4 shows that the results become better when $M$ increases. This is because there are more machines that can process jobs and machines are turned off from slow to fast, jobs have more chances to be assigned to faster machine.

5. Conclusions
This research aims at saving energy consumption for JIT production by using a dynamic machine on/off method based on a previously proposed S2S feedback approach. The results show that all problem instances’ objective function values become better, thereby proving the effectiveness of the proposed method.

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