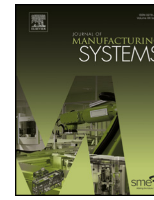
Journal of Manufacturing Systems 38 (2016) 98–106

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys



Technical Paper

Parallel machine scheduling problems in green manufacturing industry

Kai Li[a,b], Xun Zhang[a], Joseph Y.-T. Leung[a,b,c,*], Shan-Lin Yang[a,b]

[a] School of Management, Hefei University of Technology, Hefei 230009, PR China
[b] Key Laboratory of Process Optimization and Intelligent Decision-making, Ministry of Education, Hefei 230009, PR China
[c] Department of Computer Science, New Jersey Institute of Technology, Newark, NJ 07102, USA

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form
29 September 2015
Accepted 23 November 2015
Available online 23 December 2015

Keywords:
Green manufacturing
Scheduling
Identical and parallel machines
Makespan
Total completion time
Heuristics

ABSTRACT

Manufacturing companies are now more conscious about the environment. As such, there are more concerns in reducing the consumption of energy and the production of pollutants. Reduced consumption of energy will save cost, while reduction of pollutants will decrease the cost of cleaning up the environment. This paper considers scheduling problems that arise in green manufacturing companies. Suppose the manufacturing company has a set of parallel machines. Each machine has a cost per unit time that differs from machine to machine. The cost here is the sum of the energy cost and the clean up cost. A set of jobs is to be processed by these machines. Our goal is to find a schedule that minimizes the makespan (schedule length) or the total completion time, subject to the constraint that the total cost is not more than a given threshold value. We propose efficient heuristics and show, by computational experiments, that they perform very well in practice.

1. Introduction

Many manufacturing companies consume a lot of energy such as coal or electricity. As well, they use a lot of chemicals and toxic materials in the manufacturing process. Consequently, a large amount of pollutants will be discharged during the manufacturing process. Without effective management, it can cause great damage to the environment. With increasing awareness of environment protection, more and more companies are now paying attention to protect the environment. The government also plays an important role in setting up regulations and penalties for damaging the environment. In recent years, green manufacturing has attracted a lot of attention. Green manufacturing, also known as environmentally conscious manufacturing, is a modern manufacturing mode. It gives a comprehensive consideration of the environment influences and resource efficiency. In green manufacturing, the hope is that the impact on the environment is minimal and the resource utilization is maximal. Through this effort, the company can benefit economically and socially. Green manufacturing reflects sustainable development strategy in the history of modern manufacturing industry.

Modern green manufacturing industry mainly deals with green design, process planning, material selection, product packaging, recycling, green management, and equipment utilization. Green manufacturing fully considers the product's entire life cycle. In this paper we consider two aspects of this life cycle, namely, the machine scheduling and the equipment utilization.

In a manufacturing enterprise, machines are usually bought at various times. Some machines are bought recently while other machines were bought long time ago. Because of technological advance, the new machines usually consume less energy and discharge less pollutants, even though they are functionally the same as the older machines. The older machines, on the other hand, consume more energy and produce more pollutants. Usually, a company keeps both types of machines around, as the older machines can be used as a back-up. For example, when the newer machine needs to do maintenance, the older machine can replace the newer machine so that there is continuity in the manufacturing process. Therefore, at any moment of time, the manufacturing company will have a mixture of newer and older machines.

In this paper, we consider scheduling problems in this kind of environment. We assume that the company has m parallel machines that are functionally the same; i.e. the machines have the

* Corresponding author at: Department of Computer Science, New Jersey Institute of Technology, Newark, NJ 07102, USA. Tel.: +1 973 596 3387; fax: +1 973 596 5777.

http://dx.doi.org/10.1016/j.jmsy.2015.11.006
0278-6125/

same functionality and speed. However, they differ in the energy consumption and the pollutants discharged. Let the machine set be denoted by $\mathcal{M} = \{M_i | i = 1, 2, \ldots, m\}$. For each machine M_i, we have an estimate of the energy cost and the clean-up (of pollutants) cost per unit time. Let l_i denote the cost per unit time for machine M_i. If M_i operates for t time units, then the cost will be $l_i \cdot t$. Without loss of generality, we may assume that $0 < l_1 \le l_2 \le \cdots \le l_m$. Clearly, the newer machine has smaller cost, e.g. l_1, while the older machine has higher cost, e.g. l_m.

While there are many aspects in terms of environmental performance, we concentrate on just the energy and pollution cost in this paper. This is a natural objective since we are dealing with machine scheduling problems. We also assume that the cost of a machine is a linear function of the time spent on the machine. This assumption may not hold in some situations. As the first paper to study this problem, we make this simplified assumption. In the future, we hope to consider more complicated cost functions.

Suppose we have a set of n jobs, $\mathcal{J} = \{J_j | j = 1, 2, \ldots, n; \quad n \ge m\}$. Each job J_j, $1 \le j \le n$, can be processed by any machine M_i, $1 \le i \le m$, and its processing time is $p_j > 0$. A machine can process at most one job at a time, and a job can be processed by one machine at a time. If σ is a feasible schedule of the n jobs, then $C_j(\sigma)$ denotes the completion time of job J_j. The makespan of σ is defined as $C_{\max}(\sigma) = \max_{j=1}^{n}\{C_j(\sigma)\}$ and the total completion time of σ is defined as $\sum_{j=1}^{n} C_j(\sigma)$. Let $C^i_{\max}(\sigma)$, $1 \le i \le m$, denote the completion time of machine M_i; i.e. M_i is processing some jobs in the interval $\left[0, C^i_{\max}(\sigma)\right]$. Then the cost of M_i is $U_i(\sigma) = l_i \cdot C^i_{\max}(\sigma)$. The total cost of σ is $U(\sigma) = \sum_{i=1}^{m} U_i(\sigma)$. If there is no ambiguity, we will omit σ in the above notations. Our goal is to find a schedule that minimizes the makespan or the total completion time, subject to the constraint that the total cost of the schedule is not more than a given threshold $\hat{U}$.

We will be mainly concerned with non-preemptive scheduling discipline. Using the three-field notation proposed by Graham et al. [25], our problems can be denoted as $P_m | U \le \hat{U} | C_{\max}$ and $P_m | U \le \hat{U} | \sum C_j$. We will propose efficient heuristics to solve both problems. To evaluate the performance of the heuristics, we use Cplex to find an optimal non-preemptive solution for both problems. Our heuristic for the $C_{\max}$ problem is based on modifying an optimal solution for the preemptive problem; i.e. the $P_m | pmtn, U \le \hat{U} | C_{\max}$ problem. As it turns out, we are able to give a polynomial-time algorithm to solve the preemptive problem.

The remainder of the paper is organized as follows. In the next section we will study the problem $P_m | pmtn, U \le \hat{U} | C_{\max}$. We will give a polynomial-time algorithm to solve this problem; our algorithm is based on McNaughton's wrap-around rule. In Section 3 we will consider the problem $P_m | U \le \hat{U} | C_{\max}$. For this NP-hard problem, we propose a polynomial-time approximation algorithm to solve it; our algorithm is based on modifying the optimal preemptive schedule obtained in Section 2. We prove the worst-case performance ratio of the proposed algorithm. Moreover, we perform computational experiments to test the average performance of the algorithm, by comparing the solution obtained by the algorithm versus an optimal solution obtained by Cplex. In Section 4 we consider the problem $P_m | U \le \hat{U} | \sum C_j$. A simple heuristic is proposed to solve this problem. Its performance is evaluated through computational studies, by comparing the solution obtained by the heuristic versus an optimal solution obtained by Cplex. Finally, we draw some concluding remarks in Section 5.

2. Literature review

In the past few years, green manufacturing has attracted the attention of many researchers. This research field is very broad. As early as 1997, Zhang et al. [1] have given a survey about environmentally conscious design and manufacturing (ECD&M). They consider the social and technological aspects of the design, synthesis, processing, and the use of products in continuous or discrete manufacturing industries. This paper also provides general information, guidelines, and references for research and implementation, as well as clear definitions of related terms used in the ECD&M area. However, research on reducing environmental pollutants through scheduling has been quite limited. As an important part of green manufacturing, disassembly scheduling is the scheduling of the ordering and disassembly of EOL (end-of-life) products to fulfill the demand for the parts or components over a planning horizon. Gupta and Taleb [2] propose an MRP (materials-requirement-planning) algorithm for disassembly scheduling of a discrete and well-defined product structure. Kim et al. [3] propose a heuristic algorithm based on the linear programming (LP) relaxation for the case of multiple product types with parts commonality with the goal of minimizing the sum of setup, disassembly operation and inventory holding costs. Lee and Xirouchakis [4] suggest a two-phase heuristic algorithm for the objective of minimizing the various costs related with the disassembly process. Kim et al. [5] propose a branch-and-bound algorithm for the case of single product type without parts commonality.

The topics covered in the above papers are not close to the current paper. More relevant work can be found in the paper by Yildirim and Gilles [6], where energy consumption and total completion time are considered. A genetic algorithm is proposed to obtain an approximate set of non-dominated alternatives. Furthermore, dominance rules and a heuristic are proposed to increase the speed of the proposed genetic algorithm. Fang et al. [7] present a new mathematical programming model for the flow shop scheduling problem that considers peak power load, energy consumption, and associated carbon footprint in addition to the cycle time. However, it is difficult to obtain optimal schedule by directly applying commercial software to this multi-objective scheduling problem, since it requires significant computation time. Yu [8] is the first one to put forward green scheduling problems. The difference between traditional scheduling and green scheduling is noted, and the environmental effect and resource consumptions are synthetically taken into account. The resolution strategy with two steps is put forward in green scheduling. Pareto solution set is first obtained, then Pareto solutions are evaluated and determined with the standardization and the entropy weight. Finally, feasible solutions are searched out.

There are a number of papers in the field of production scheduling that consider machine cost. Imreh and Noga [9] are the first to suggest scheduling problems with machine cost. They assume that all the machines costs are one unit. They show that the classical list scheduling (LS) algorithm has a competitive ratio of $(1+\sqrt{5})/2$ when used for solving the online makespan minimization problem, and it has a competitive ratio of $(6+\sqrt{205})/12$ when the jobs have different release times. He and Cai [10] and Jiang and He [11,12] consider the semi-online scheduling problems. Unlike online scheduling, semi-online scheduling assumes that the sum of the processing time or the maximum of the processing time of the jobs are known before any job is scheduled. Dosa and He [13], Seiden [14], Dosa and Tan [15], Nagy-Gyorgy and Imreh [16] assume that all machine costs are one unit, but they expand their research in different directions.

Imreh [17] considers two kinds of machine cost, in which one kind is cheaper than the other. He uses the cheaper machine as much as possible and occasionally uses the expensive machine in the process of scheduling. Jiang and He [18] assume that the machine cost is a linear function of the number of machines used. Cao et al. [19] also make the same assumption and study