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Hybrid flow shop scheduling considering machine electricity consumption cost

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A B S T R A C T

Hybrid flow shop (HFS) scheduling has been extensively examined and the main objective has been to improve production efficiency. However, limited attention has been paid to the consideration of energy consumption with the advent of green manufacturing. This paper proposes a new ant colony optimization (MOACO) meta-heuristic considering not only production efficiency but also electric power cost (EPC) with the presence of time-of-use (TOU) electricity prices. The solution is encoded as a permutation of jobs. A list schedule algorithm is applied to construct the sequence by artificial ants and generate a complete schedule. A right-shift procedure is then used to adjust the start time of operations aiming to minimize the EPC for the schedule. In terms of theoretical research aspect, the results from computational experiments indicate that the efficiency and effectiveness of the proposed MOACO are comparable to NSGA-II and SPEA2. In terms of practical application aspect, the guideline about how to set preference over multiple objectives has been studied. This result has significant managerial implications in real life production. The parameter analysis also shows that durations of TOU periods and processing speed of machines have great influence on scheduling results as longer off-peak period and use of faster machines provide more flexibility for shifting high-energy operations to off-peak periods.

1. Introduction

Hybrid flow shop scheduling (HFS) problems are commonly encountered in manufacturing environments. They are extensions of classical flow shop scheduling problems in which a set of jobs need to be processed in a group of machines following the same route. In a HFS problem, there are a series of production stages in place of machines, and each stage consists of several parallel machines. Machines at each stage can be identical, somewhat related, or unrelated at all. Jobs have to be processed by one of the machines at each stage, and the flow of jobs through the shop is unidirectional (Linn and Zhang, 1999).

HFS has received significant research efforts and some advances have been achieved. However, some significant aspects of HFS have not yet been sufficiently explored. To begin with, most previous work aimed at improving production efficiency; that is, objective functions used in HFS studies are usually to minimize makespan, total completion time of jobs, total tardiness, or other criteria related to production efficiency (Ribas et al., 2010). Although production efficiency is essential, by no means should it be the only factor to be considered in manufacturing operations. In recent years, it has been increasingly recognized that economic development without environmental considerations may cause irreversible damage to the world environment. Statistical data shows the Germany industrial sector was responsible for approximately 47% of the total national electricity consumption, and the corresponding amount of CO_2 emissions generated by this electricity summed up to 18–20% (BMWi, 2009). Thus, the concept of green manufacturing has therefore been brought up to achieve economic growth while reducing negative environmental impacts.

Recently there has been a growing research interest in green manufacturing with considering energy saving due to a serial of environmental impacts and the rising energy costs. Research on minimizing the energy consumption of manufacturing systems has been conducted in different perspectives. From the machine-level perspective, research efforts focus on developing and designing more energy-efficient machines and equipment to reduce power and energy demands of machine components (Li et al., 2011, Mori et al., 2011, Neugebauer et al., 2011). From the product-level perspective, emphases have been put on modelling embodied product energy framework from the viewpoint of product design (Rahimifard et al., 2010). However, both the machine redesign and product redesign

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require enormous financial investments. The benefits could not be easily enjoyed by most of manufacturing companies, especially those small and medium sized enterprises.

This research attempts to reduce energy cost in the manufacturing system-level perspective. Thanks to the decision models and optimization technique applied in production planning and scheduling, it is feasible to achieve a significant reduction of energy consumption without any process or equipment reengineering.

This research has been indeed motivated by the research and development activities in our industrial collaborators with their shopfloor management systems. The collaborating company in metalworking industry runs a typical hybrid flow shop. In this case, the preheating and rolling stage are extremely energy intensive as the heating and rolling processes require high temperature and machine power. Electric power costs of these two stages account for a noticeable proportion of the total cost. Another feature in this company is that some stages contain multiple machines with different energy efficiency. For instance, the blanking stage has manual machines and automatic machines. Although both of them work in parallel and process the same blanking operation, the speed and the energy consumption are totally different.

In addition, time-of-use (TOU) electricity prices are offered by power grids with different time periods (see Fig. 1). The changes in electricity prices offer the possibility of cost savings for manufacturing enterprises if demand can be reduced during hours of high prices (on-peak periods) and shifted to hours of lower prices (off-peak periods). Operations with high electricity consumption may be processed on more energy-efficient machines during on-peak periods, whereas less energy-efficient machines are used during off-peak periods to fully utilize the capacities. Such arrangements will reduce the EPC, while maintaining production efficiency.

Research in HFS area during the past decades has focused on more realistic problems such as problems with sequence-dependent setup times, machine availability, and precedence constraints of jobs (Ribas et al., 2010). However, machine characteristics have been oversimplified. Machines are usually considered different from each other only in processing speed, or exactly the same in a uniform parallel machine environment. In a real world situation, however, it is common to see advanced machines running next to the older ones. In addition, these machines may have different rates of power consumptions. These features should be considered when assigning jobs to machines at each stage.

This paper addresses HFS problems by considering both production efficiency and electric power consumption (EPC). A new multi-objective solution is proposed, in which the objectives are to minimize the makespan and the EPC with Time-of-Use prices. As the two objectives are often in conflict with each other, a multi-objective ant colony optimization (MOACO) algorithm is developed for this problem. By means of computational experiments and parameter analysis, following research questions will be addressed:

- How different would schedules be when considering machine energy consumption cost?
- How to set preference over multiple objectives?
- How do TOU electricity prices periods affect scheduling?
- How do parallel machines with differing energy consumption rates affect scheduling?

The remainder of the paper is organized as follows. In Section 2, recent studies related to HFS are briefly reviewed. The problem is described and the mathematical model is constructed in Section 3. Section 4 details our ACO based Pareto optimal approach. The effectiveness of the proposed approach and the impact of parameters are studied through extensive experiments in Section 5. A summary and discussion of future research directions concludes the paper in Section 6.

2. Related work

HFS problems are important issues in manufacturing industry in terms of both theoretical research and practical application. On the one hand, HFS problems are complex and difficult to deal with. They are, in most cases, NP-hard (Ruiz and Vazquez-Rodriguez, 2010). For instance, even a two-stage HFS problem for makespan minimization with identical parallel machines at each stage is NP-hard in the strong sense (Gupta, 1988). On the other hand, real-world implementations of HFS have been emerging in recent years. HFS applications can be found in many industries, such as the iron and steel industry (Tang and Wang, 2010), the semiconductor manufacturing (Wittrock, 1988; Jin et al., 2002), the packaging industry (Adler et al., 1993), and the pharmaceutical sector (Guinet and Solomon, 1996). Therefore, in the past four decades, extensive work has been done in the field of HFS, and a large number of exact algorithms, heuristics and meta-heuristics have been proposed for different HFS applications. Comprehensive reviews on HFS have been given by Linn and Zhang (1999), Quadt and Kuhn, (2007), Ribas et al.(2010), and Ruiz and Vazquez-Rodriguez (2010).

The most commonly used objective in the literature is makespan. Gupta et al. (1997) considered a two-stage hybrid flow shop problem in which the first stage contains several identical machines, and the second stage contains a single machine. The problem was shown to be strongly NP-hard, and several constructive heuristics were presented. Allaoui and Artiba (2006) studied a similar problem, but considered some unavailability periods due to maintenance activities. Another special real-life case was given by Tseng et al. (2008). They investigated the production system in a stainless steel factory and found there were some missing operations in HFS. Huang and Li (1998) studied a two-stage HFS scheduling problem with uniform machines at the second stage,

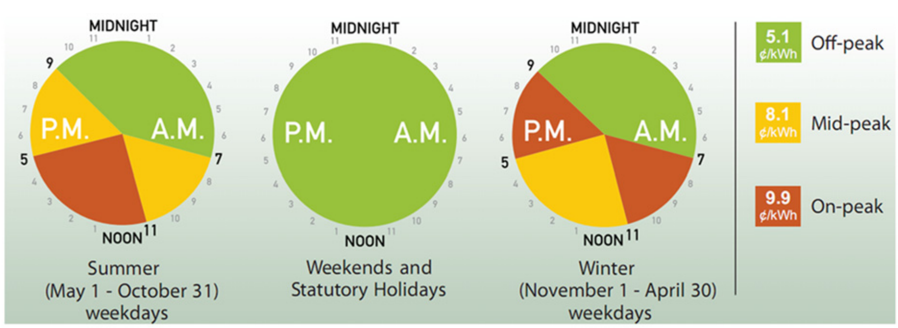

Fig. 1. An example of Time-of-Use electricity prices.
Source: Ontario Energy Board

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