Computers & Industrial Engineering 112 (2017) 721–734

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Bi-criteria single-machine batch scheduling with machine on/off switching under time-of-use tariffs

Junheng Cheng [a,b], Feng Chu [b,c,*], Ming Liu [d], Peng Wu [e], Weili Xia [a]

[a] School of Management, Northwestern Polytechnical University, 710072 Xi'an, China
[b] Laboratory IBISC, University of Evry-Val d'Essonne, 91020 Evry, France
[c] Management Engineering Research Center, Xihua University, Chengdu 610039, China
[d] School of Economics & Management, Tongji University, Shanghai 710049, China
[e] School of Economics & Management, Fuzhou University, Fuzhou 350116, China

ARTICLE INFO

Article history:
Available online 21 April 2017

Keywords:
Single-machine batch scheduling
Time-of-use tariffs
Bi-criteria optimization
Mixed-integer programming
Heuristic

ABSTRACT

The industrial sector is the largest consumer of the world's total energy and most of its consumption is in form of electricity. In recent years, to strengthen the peak load regulation capability, time-of-use (TOU) pricing has been implemented in many countries to encourage consumers to shift their use from peak to mid- and off-peak periods such that their energy bills can be reduced. In this paper, we study a new single-machine batch scheduling problem with machine on/off switching under TOU tariffs, which aims to simultaneously minimize total electricity cost and makespan. For the problem, we first develop a bi-objective mixed-integer linear programming model. Based on optimal batch rule analysis, an improved model is further provided which greatly reduces Pareto optimal solution search space. To efficiently solve large-size problems, we propose a heuristic based ε-constraint method. The results from extensive computational experiments confirm the effectiveness and efficiency of the proposed model and the algorithm.

1. Introduction

Globally, the industrial sector is the largest energy consumer. It contributes about 50% of the world's total energy consumption (Fang, Uhan, Zhao, & Sutherland, 2011), of which a major proportion is in form of electricity (Wang & Li, 2013). For example, the electricity consumption accounts for approximately 30% of the total industrial energy consumption in the APEC area (APERC, 2013). However, electricity cannot be efficiently stored such that it has to be generated, transmitted and consumed instantly. In the meantime, electricity demand generally varies dramatically over time. Thus the electricity supply and demand are in imbalance in real time. To meet the customer demand during peak periods, the electricity suppliers have to construct and enable costly backup facilities that are usually less efficient such that more greenhouse gases can be generated (Wang & Li, 2013). To reduce the backup facilities investments as well as carbon emissions, electricity suppliers have increasingly paid attention to the inexpensive and flexible demand response (DR) strategy that targets at regulating the imbalance between supply and demand by flexible electricity price management.

The DR strategy has been broadly implemented in many countries such as the United States, France, Canada and China (David Kathan, 2012). Time-of-use (TOU) pricing (see Fig. 1, a typical TOU pricing scheme) is among the most popular DR strategies. It aims to offer variable electricity prices over time reflecting demand changes to promote the balance between supply and demand and improve the grid's reliability, so that the demand during peak periods can be satisfied. Such pricing mechanism can encourage manufacturing industries, especially electricity-intensive ones, to shift their electricity usage from peak (with higher prices) to mid- and off-peak (with lower prices) periods, such that their electricity cost can be saved. Certainly, under TOU policy, appropriately taking energy cost into account in production scheduling becomes important and necessary because it can lead to significant energy cost savings without excessively deteriorating the traditional scheduling objectives such as makespan or weighted tardiness.

In recent years, there has been a growing number of studies on optimizing production scheduling to save energy cost under time-sensitive energy prices. Shrouf, Ordieres-Meré, García-Sánchez, and Ortega-Mier (2014) addressed a single machine scheduling problem considering variable electricity prices in a day to mini-

* Corresponding author at: Laboratory IBISC, University of Evry-Val d'Essonne, 91020 Evry, France.
E-mail address: feng.chu@ibisc.fr (F. Chu).

http://dx.doi.org/10.1016/j.cie.2017.04.026
0360-8352/

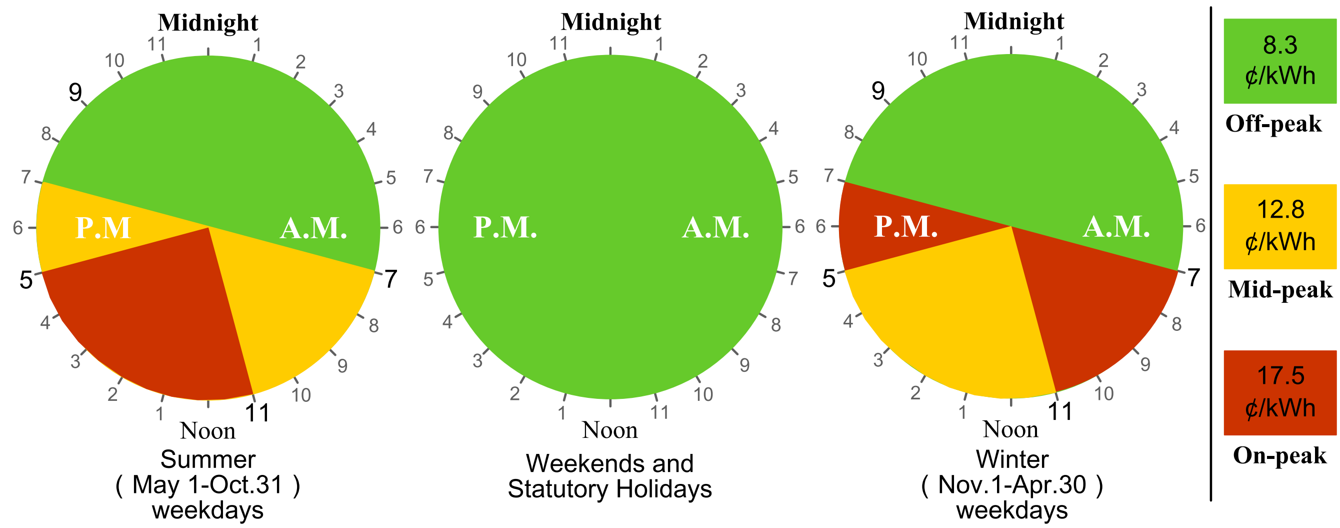

Fig. 1. An example of TOU pricing scheme. *Source:* Ontario Energy Board.

mize the total energy consumption cost under work shifts. They proposed a genetic algorithm (GA) to solve it. Later, Fang, Uhan, Zhao, and Sutherland (2016) considered scheduling jobs on a single machine under uniform-speed and speed-scalable scenarios with the same optimization objective under TOU pricing. Different heuristics were suggested to obtain their near-optimal solutions. Moon, Shin, and Park (2013) focused on scheduling jobs on unrelated parallel machines to minimize the weighted sum of makespan and time-dependent electricity cost. A hybrid inserted GA was proposed for solving it. Recently, Ding, Song, Zhang, Chiong, and Wu (2016) presented a mixed-integer linear programming (MILP) model for unrelated parallel machine scheduling under TOU tariffs with the objective of minimizing the total electricity cost respecting given makespan. A column generation based heuristic was suggested to yield near-optimal solutions. Besides, Luo, Du, Huang, Chen, and Li (2013) examined a bi-criteria hybrid flow shop scheduling problem under TOU policy to minimize both electricity cost and makespan. The authors developed a novel ant colony optimization based meta-heuristic to obtain a set of Pareto optimal solutions. Zhang, Zhao, Fang, and Sutherland (2014) also addressed a bi-criteria flow shop scheduling problem under TOU policy to minimize the total electricity cost and carbon emissions, while ensuring the production throughput at the same time. They formulated a time-indexed MILP model for the problem. It can be concluded that the existing research about production scheduling taking into account TOU pricing is mainly concerned with classical shop scheduling, e.g., single machine (Fang et al., 2016; Shrouf et al., 2014), parallel machine (Ding et al., 2016; Moon et al., 2013), and flow shop (Luo et al., 2013; Zhang et al., 2014), and most of them mainly focus on single-criteria optimization, i.e., minimizing the total energy cost.

Batch processing manufacturing system representing a typical production environment has been widely encountered in modern manufacturing industries, such as steel manufacturing (Tang, Liu, Rong, & Yang, 2001), semiconductor manufacturing (Uzsoy, Lee, & Martin-Vega, 1992, 1994), and aircraft industry (Van De Rzee, Van Harten, & Schuur, 1997). Notably, most of them are energy-intensive ones and the electricity expenditure can account for a large proportion of the final cost of products (Hadera & Harjunkoski, 2013). A remarkable feature of batch processing is that the processing machine can process multiple jobs at a time. As a result, to perform batch scheduling is usually more complex than classical production scheduling, as the former needs to first appropriately group the jobs into batches and then optimally schedule the formed batches. Majority of batch scheduling problems have been proved to be NP-hard, even under most single-machine environments. The existing research on a batch scheduling problem (BSP) is mainly concerned with improving production efficiency by optimizing the makespan, weighted completion time, weighted or maximum tardiness (Bilyk, Mönch, & Almeder, 2014; Li, Chen, Xu, & Li, 2015; Potts & Kovalyov, 2000; Uzsoy et al., 1992, Uzsoy, Lee, & Martin-Vega, 1994), while energy cost optimization is usually ignored.

To the best of our knowledge, no work in the literature has considered batch scheduling under TOU pricing except our previous work (Cheng, Chu, Chu, & Xia, 2016). We previously formulated an MILP model for a single-machine batch scheduling problem under a TOU pricing scheme to simultaneously optimize the total electricity cost and the makespan under the assumption that turning on the machine does not consume energy. Consequently, the machine is always turned off when finishing processing in each period and is restarted when needed. However, turning on machines can consume a great amount of energy in some manufacturing environments, e.g., steel manufacturing. As indicated by Mouzon, Yildirim, and Twomey (2007), the resulted non-processing energy (NPE) consumption related to machine turn-on, turn-off and idling constitutes a significant part (over 30%) of the total energy consumption for certain scheduling environments. Remarkably, it has been shown in Mouzon et al. (2007), Mouzon and Yildirim (2008), and Yildirim and Mouzon (2012), the NPE consumption can be significantly reduced by rationalized machine turn-on/turn-off. This work is motivated by optimizing the whole electricity consumption cost considering machine on/off switching under TOU tariffs and it is a natural extension of our previous work. A small part of the work for the problem was included in CIE 45 conference (Cheng, Chu, Ming, & Xia, 2015), in which a preliminary model was presented and small-size instances were solved with the model. In the present paper, we complete and improve the work of Cheng et al. (2015) as follows:

(1) An improved model is further proposed based on optimal batch rule analysis, which greatly reduces Pareto optimal solution space. Then the complexity of the studied problem is demonstrated.
(2) A heuristic based ε-constraint method is developed to effectively and fast solve the problem, especially large-size instances.