Journal of Cleaner Production 147 (2017) 470–484

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Minimizing energy consumption and tardiness penalty for fuzzy flow shop scheduling with state-dependent setup time

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ARTICLE INFO

Article history:
Received 3 December 2015
Received in revised form
5 December 2016
Accepted 11 December 2016
Available online 11 January 2017

Keywords:
Flow shop scheduling
Energy consumption
Setup time
Fuzzy processing time
Genetic algorithm

ABSTRACT

This paper addresses a flow shop scheduling problem in a production system where the machine setup times depend on their prior states. State-dependent setup times exist widely in thermal facilities such as boilers and furnaces. The fuzzy set theory is introduced to describe the uncertainty of processing times and due dates in this study. The goal of the proposed fuzzy flow shop scheduling problem is to dispatch jobs to the machines and to determine the job sequence and state transition of each machine to minimize energy consumption and tardiness. To most efficiently determine the impact of uncertainty, the problem is formulated based on accurate operations of fuzzy numbers, which differ from approximate calculations in the existing literature on scheduling. To solve the problem, two common pattern matching schemes and heuristics are proposed to be combined with the classical genetic algorithm. Computational experiments show that the proposed GA performs better than the random key GA method, especially for large problems. The numerical results also provide practical implications for the proposed problem. The state-dependent setup time constraint significantly influences the scheduling results. In addition, the objective can be improved by reducing the uncertainty of processing times and due dates.

1. Introduction

BP statistical review shows that the global primary energy consumption increased by a below-average 0.9% in 2014, which is the slowest rate of growth since 1988 other than the decline in the aftermath of the financial crisis (BP Statistical Review of World Energy, 2015). However, from overall historical data, world energy consumption is projected to increase by 35% over the next two decades, from 12.93 Btoe currently to 17.45 Btoe in 2035 (BP Energy outlook, 2014). Following the rapid and sustained growth of energy use, public and industrial concerns regarding energy efficiency and environmental sustainability have increased considerably over the last decade. Particularly in the manufacturing sector, energy efficiency has become even more important given that manufacturing accounts for 31% of primary energy consumption and 36% of CO_2 emissions (International Energy Agency, 2007). The US Department of Energy conducted a comprehensive survey on manufacturing energy use and carbon emissions for the year 2010 (US Department of Energy, 2014). Some of the key results from the report are summarized and illustrated in Fig. 1. The onsite energy efficiency is approximately 48.8%, far below the ideal scenario. Compared to machine drives, the majority of onsite energy is used for process-supporting functions that are not directly related to production. According to the statistical data, heating has taken the largest share, consuming 69.6% of the process energy. Although most studies have focused on developing more electrical energy efficient machines or machining processes (Duflou et al., 2012; Fang et al., 2011), the vital battlefield of energy reduction is undoubtedly improving thermal energy efficiency in manufacturing processes.

It is natural that how to achieve energy efficient production is also part of the operational scheduling problem, especially at most situations production paces and collaborating with function-supported facilities can significantly affect the manufacturing energy efficiency. Energy efficient scheduling (EES) is considered as one of the most important means for manufacturing enterprises to achieve sustainable production and improve their sustainable competitive advantage. With the rapid development of information technology, it is also now technically possible to integrate Internet of Things (IoT) technique, smart sensors, and enhanced data

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http://dx.doi.org/10.1016/j.jclepro.2016.12.044

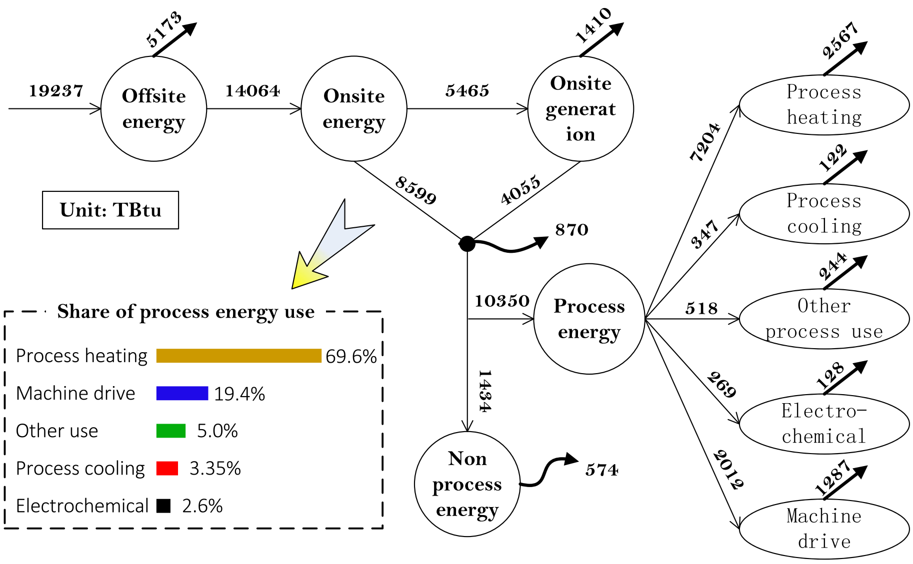

Fig. 1. Energy use from supply to end use in U.S. manufacturing sectors in 2010.

analytics tools with energy efficient scheduling (Zhang et al., 2014, 2017). Compared to equipment innovation or process redesign, improvement of energy efficiency by production scheduling requires only a modest capital investment and can be easily applied to existing production environment (Fang et al., 2011).

Generally speaking, two critical features must be considered to schedule a real-life production system with thermal devices: (1) A thermal device typically needs to warm up before actual work, and this warm-up (setup) time depends on its prior temperature (state) and (2) The human experience of operating thermal devices results in production uncertainty (such as fuzzy processing times). We will discuss these two features in detail using the example of tire curing in Section 3. According to this real-life case, we propose a fuzzy flow shop scheduling problem with state-dependent setup times. An improved hybrid genetic algorithm (GA) is developed for solving this problem, and further discussions are given by numerical experiments.

The remainder of this paper is organized as follows: In Section 2, we present a brief literature review of three categories, namely, energy efficient scheduling, fuzzy operations, and setup time constraints. In Section 3, we provide a detailed description and present a mathematical model for the studied problem. Section 4 constructs two common pattern matching methods along with heuristics to enhance the solvability of the genetic algorithm. The effectiveness of the proposed algorithm and parameter sensitivity are studied through numerical experiments in Section 5. A summary and discussion of our studies concludes the paper in Section 6. In addition, relative concepts on fuzzy numbers and operations are given in the Appendices.

2. Literature review

The scheduling problem considered in this paper can be described by dividing the literature into three categories: (1) energy efficient scheduling; (2) fuzzy operations; and (3) setup time constraints.

2.1. Energy efficient scheduling

Energy efficient scheduling, also referred to as energy aware or energy-oriented scheduling, considers energy or environmental issues in traditional operational studies. The goal is to increase efficiency, lower cost, or improve robustness in the industrial energy consumption process. This emerging type of scheduling problem has attracted considerable attention over the last decade. Shrouf et al. (2014) consider the scheduling problem of a single machine with the aim of minimizing total energy cost. In their model, energy price is variable in the production period, and energy consumption arises in the machine processing, idle, turn-on, and turn-off operations. Fang and Lin (2013) investigate an unrelated parallel machine scheduling problem with the objective of minimizing the weighted summation of tardiness and power cost. In their model, power cost is related to machine processing speeds, where fast processing speed is considered to require additional energy but to reduce processing time. Bruzzone et al. (2012) impose a peak power load of a flexible flow shop not to exceed a given upper limit. Rager et al. (2015) state that the systematic energy efficiency in industries could be dramatically improved by minimizing the deviation of the cumulated applied energy source demand (AESD). They also enhance the smoothness of energy consumption in the planning horizon, not just applying a peak load limitation as in (Bruzzone et al., 2012). Fang et al. (2011) propose an integer linear programming with multi-objective optimization, namely, makespan, peak load, and carbon footprint. Merkert et al. (2015) summarize the main challenges and potential opportunities related to energy efficient scheduling and management in industrial sectors.

As surveyed above, energy efficient scheduling problems often consider optimizing a single objective or multiple objectives that combine productivity and energy-related objectives. However, most of the existing studies focus on optimizing electrical energy use. It is necessary to discuss the impact of thermal energy on scheduling problems. This paper is motivated by the rubber tire curing process, and the feature of state-dependent setup time in this type of thermal process is discussed.

2.2. Fuzzy scheduling and fuzzy operations

In real-life cases, production parameters may not be crisp due to man-made factors or uncertainty of market demands. Stochastic theory or fuzzy set theory is usually adopted to address this uncertainty. Because the former requires the knowledge of a prior probabilistic distribution, fuzzy scheduling has received