Journal of Cleaner Production 168 (2017) 239–253

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Integrating labor awareness to energy-efficient production scheduling under real-time electricity pricing: An empirical study

Xu Gong*, Marlies Van der Wee, Toon De Pessemier, Sofie Verbrugge, Didier Colle, Luc Martens, Wout Joseph

Department of Information Technology, Ghent University/imec, Technologiepark 15, 9052, Ghent, Belgium

ARTICLE INFO

Article history:
Received 11 January 2017
Received in revised form
19 August 2017
Accepted 30 August 2017
Available online 4 September 2017

Handling Editor: Yutao Wang

Keywords:
Sustainable production
Production scheduling
Optimization
Demand response
Case study
Sensitivity analysis

ABSTRACT

With the penetration of smart grid into factories, energy-efficient production scheduling has emerged as a promising method for industrial demand response. It shifts flexible production loads to lower-priced periods to reduce energy cost for the same production task. However, the existing methods only focus on integrating energy awareness to conventional production scheduling models. They ignore the labor cost which is shift-based and follows an opposite trend of energy cost. For instance, the energy cost is lower during nights while the labor cost is higher. Therefore, this paper proposes a method for energy-efficient and labor-aware production scheduling at the unit process level. This integrated scheduling model is mathematically formulated. Besides the state-based energy model and genetic algorithm-based optimization, a continuous-time shift accumulation heuristic is proposed to synchronize power states and labor shifts. In a case study of a Belgian plastic bottle manufacturer, a set of empirical sensitivity analyses were performed to investigate the impact of energy and labor awareness, as well as the production-related factors that influence the economic performance of a schedule. Furthermore, the demonstration was performed in 9 large-scale test instances, which encompass the cases where energy cost is minor, moderate, and major compared to the joint energy and labor cost. The results have proven that the ignorance of labor in existing energy-efficient production scheduling studies increases the joint energy and labor cost, although the energy cost can be minimized. To achieve effective production cost reduction, energy and labor awareness are recommended to be jointly considered in production scheduling.

1. Introduction

Sustainability is a crucial factor in future production systems for manufacturing enterprises to stay competitive (May et al., 2016). It is the "development that meets the needs of the present, without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1987). When it is integrated to manufacturing enterprises, all dimensions of the triple bottom line should be followed: the economic, environmental and social dimension (Gimenez et al., 2012). Recently, production planning and scheduling have shown up as a promising industrial demand response approach for sustainable production (Giret et al., 2015).

Production scheduling is the allocation of available production resources to jobs/tasks, aiming to optimize one or more criterion, while satisfying production constraints, such as due date and operation sequence. Only recently, it has considered industrial energy consumption, which creates tangible added value.

From an economic perspective, energy-efficient production scheduling reduces the energy cost, under a volatile energy price from the deregulated electricity markets (Merkert et al., 2015). For many power-intensive industries, the electricity cost accounts for 10–50% of the final product cost (Hadera and Harjunkoski, 2013). Therefore, the potential to save energy cost remains considerable.

From an environmental perspective, energy-efficient production scheduling decreases greenhouse gas (GHG) emissions, of which manufacturing processes are known as the major source (Newman et al., 2012). Some of GHG emissions are caused by unnecessary machine idling (Liu et al., 2016) and peak power consumption in the electricity grid (Gong et al., 2016a), which are solvable by production scheduling.

From a societal perspective, energy-efficient production scheduling stabilizes the electricity grid by avoiding peak demand. This secures the power supply and delivery for local residents.

* Corresponding author.
E-mail address: xu.gong@ugent.be (X. Gong).

http://dx.doi.org/10.1016/j.jclepro.2017.08.223
0959-6526/

Moreover, optimal energy utilization and reduced GHG emissions help enterprises meet sustainability compliance and regulations, improving an enterprise's reputation for public responsibility.

Among these added values, the economic implication is the chief decision driver in manufacturing (Diaz-Elsayed et al., 2015). The potential of energy efficiency for cost reduction remains more than significant for manufacturing processes (Zavanella et al., 2015). Therefore, this paper focuses on the economic perspective.

Despite the ongoing automation in manufacturing and the appealing economic impact of energy-efficient production scheduling described above, labor cost is still a major part of production cost and follows the opposite trend of energy cost. For instance, labor compensation is higher at night and on weekends, while energy price is lower during these periods. Consequently, simple production load shifting to lower-priced periods in literature may increase the labor cost and rise the overall production cost, going against the expected sustainability. Therefore, it is indispensable to integrate labor awareness to energy-efficient production scheduling.

Compared to our previous work (Gong et al., 2016a), this paper has threefold contributions. (1) The energy-efficient scheduling model is enhanced by introducing labor shifts and cost, machine changeovers, as well as multiple idle modes. (2) A continuous-time shift accumulation heuristic is proposed to synchronize power states and labor shifts, as necessary part of the solution algorithm. (3) An empirical study is performed in a Belgian plastic bottle manufacturer. Extensive sensitivity analyses revealed a new understanding of energy-efficient production scheduling: energy and labor cost should be jointly considered to reduce the production cost.

The reminder of this paper is organized as follows. Section 2 gives the literature review and three research questions. Section 3 describes the energy-efficient and labor-aware production scheduling problem at the unit process level. Section 4 presents the solution algorithm. Section 5 introduces the empirical data from a Belgian plastic bottle manufacturer as case study. Section 6 explains the extensive sensitivity analysis results. Section 7 performs discussions. Section 8 draws conclusions.

2. Literature review

The shop floor configurations encompass single-machine, parallel-machine, (hybrid) flow-shop, and (flexible) job-shop (Branke et al., 2016). While each configuration has accumulated many production scheduling studies, energy efficiency has only been considered in recent years, with the emerging penetration of industrial demand response (Gahm et al., 2016).

2.1. Energy-efficient production scheduling

The powering-on/-off mechanism is an intuitive idea to enhance energy efficiency via production scheduling. It prevents machines from consuming energy when there are no active production jobs. This idea was first described in (Mouzon et al., 2007). Furthermore, a multi-objective genetic algorithm was utilized to minimize energy consumption and total completion time of a single machine (Yildirim and Mouzon, 2012). In addition to reducing non-cutting energy consumption, Hu et al. (2017) characterized the machining energy of machine tools. They minimized the joint non-cutting and cutting energy by sequencing the feature processing order of a part. Despite these efforts, the economic impact is vague, since energy consumption was not linked to the energy cost.

Shrouf et al. (2014) considered the volatile electricity price from the spot market in a single-machine scheduling model. Production loads were shifted to low-priced periods. However, a lack of job sequencing capability locks the energy cost saving potential of this idea. The authors further proposed to use Internet-of-Things (IoT) technologies for industrial energy management (Shrouf and Miragliotta, 2015), but gave no implication on how to link empirical energy data to the scheduling model.

Gong et al. (2016a) filled these gaps. Finite state machines (FSMs, or automata) were utilized to build an energy model whose power profiles were extracted from measurements. Job sequencing and reactive rescheduling upon disruptions during the execution of a schedule were also introduced in the scheduling model. The energy-cost-effectiveness was validated on a surface grinding process, and further demonstrated with various electricity pricing schemes (Gong et al., 2015), including time-of-use pricing (ToUP), real-time pricing (TRP), and critical peak pricing (CPP). Numerical experiments showed that a higher electricity cost saving ratio is contributed by prolongation of makespan. To specifically reduce the energy cost under ToUP, a greedy insertion heuristic was proposed in (Che et al., 2016) for a single machine scheduling model, such that it yielded high-quality solutions within 10 s even for the instance with 5000 jobs. Fang et al. (2016) further investigated the same scheduling problem under the cases of uniform and scalable machine speeds.

Energy-efficient production scheduling can be found in the other shop floor configurations, though most of them are not explicitly linked to the energy cost. A parallel machine scheduling problem was investigated in (Li et al., 2016). Machines differ in energy consumption and discharged pollutants. The energy cost and pollutant clean-up cost were modeled as hard constraints, while the objective was to minimize the makespan. Zhang et al. (2014) studied a flow shop scheduling problem under ToUP electricity tariffs. They revealed the trade-off between reducing electricity cost and decreasing CO_2 emissions. A hybrid flow shop floor configuration was involved in (Luo et al., 2013), where the ant colony-based scheduling method shifted loads under ToUP. The electricity cost was minimized considering the trade-off with the makespan. Liu et al. (2016) studied a job shop energy-efficient scheduling problem. Energy consumption was decreased by turning off underutilized machines, accounting for the trade-off with total weighted tardiness. A flexible job-shop scheduling problem was investigated in (Mokhtari and Hasani, 2017), where the optimization objective was to minimize the total completion time, maximize the total availability of the system, and minimize total energy cost of production and maintenance operations. He et al. (2015) proposed an energy saving method in flexible job shops. This method optimizes not only the operation sequence for reducing idle energy consumption, but also the machine tool selection for decreasing the energy consumption for machining operations. As alternative method to handle unforeseen events during the execution of a schedule (Gong et al., 2016b), a dynamic game theory based two-layer scheduling method was proposed for a flexible job shop (Zhang et al., 2017). Upon a machine's active request for processes during an idle period, the real-time scheduling task pool output a schedule, optimizing the makespan, total workload and energy consumption.

Furthermore, some recent studies are observed to perform economic benefit analysis of energy-aware production planning and scheduling. Wang and Li (2014) combined both electricity consumption (kWh) and peak demand (kW) to calculate the electricity cost of manufacturing systems. Although 24.8% of the per-product electricity cost was predicted, the additional consideration of the human factor was highlighted as outlook, since a time-shifted schedule with extended night hours must be paid for with a premium. The authors' preliminary case study revealed that although incorporation of labor increased the energy cost by 9%, it reduced the joint energy and labor cost by 12%, due to the minor proportion (3%) of energy cost in this joint cost (Gong et al., 2017). Salahi and Jafari (2016) proposed a two-dimensional energy