Journal of Cleaner Production 67 (2014) 197–207

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Optimizing the production scheduling of a single machine to minimize total energy consumption costs

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ARTICLE INFO

Article history:
Received 5 June 2013
Received in revised form
2 December 2013
Accepted 8 December 2013
Available online 17 December 2013

Keywords:
Minimizing energy consumption costs
Single-machine sustainable scheduling
Variable energy prices
Genetic algorithm
Demand side management

ABSTRACT

The rising cost of energy is one of the important factors associated with increased production costs at manufacturing facilities, which encourages decision-makers to tackle this problem in different manners. One important step in this trend is to reduce the energy consumption costs of production systems. Considering variable energy prices during one day, this paper proposes a mathematical model to minimize energy consumption costs for single machine production scheduling during production processes. By making decisions at machine level to determine the launch times for job processing, idle time, when the machine must be shut down, "turning on" time, and "turning off" time, this model enables the operations manager to implement the least expensive production scheduling during a production shift. To obtain 'near' optimal solutions, genetic algorithm technology has been utilized. Furthermore, to determine whether the heuristic solution provides the minimum cost and the best possible schedule for minimizing energy costs, an analytical solution has also been run to generate the optimal solution. Next, a comparison between the analytical solution and heuristic solutions is presented; for larger problems, the heuristic solution is preferable. The results indicate that significant reductions in energy costs can be achieved by avoiding high-energy price periods. This minimization process also has a positive environmental effect by reducing energy consumption during peak periods, which increases the possibility of reducing CO_2 emissions from power generator sites.

1. Introduction

Manufacturing plants are facing increasing pressure to reduce their carbon footprint, driven by concerns related to energy costs and climate change. The potential to reduce energy costs can lie in increasing the energy efficiency (EE) of production processes and management approaches (Weinert et al., 2011). In general, energy efficiency refers to achieving the identical output with less energy consumption, thereby utilizing economic efficiency (Patterson, 1996). Many studies about the policies (Bunse et al., 2011; Thollander et al., 2013) and the barriers of the implementation of energy efficiency programs in several countries have been conducted (Kostka et al., 2013; Trianni et al., 2012).

Reducing non-production modes (Soroush, 2010) is an example of improving energy efficiency. This improvement has a positive effect on ecological requirements (Herrmann and Thiede, 2009). It also has a significant effect on reducing total production costs (Hasanbeigi et al., 2009). Although this reduction is an important factor (He et al., 2012), it is certainly not the only factor involved. Hence, energy demand-side management (DSM) includes peak-reduction and load shifting, which involves moving load from on-peak to off-peak energy tariff rates (Michaloski et al., 2011); this is an area in which energy cost reduction can be achieved.

Demand-Side Management is an umbrella term that includes energy efficiency and Demand Response (DR). A report prepared by Charles River Associates (2005) for the World Bank defines DSM as the "systematic utility and government activities designed to change the amount and/or timing of the customer's use of electricity for the collective benefit of the society, the utility and its customers." According to the Federal Energy Regulatory (FERC, 2012), Demand Response is defined as "Changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive

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http://dx.doi.org/10.1016/j.jclepro.2013.12.024

payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."

Significant efforts in DSM have generated great economic and environmental benefits. In this direction, different strategies (Albadi and El-Saadany, 2008) have been adopted in some countries to achieve the desired effect such as adopting time-of-use pricing with large differences between on-peak and off-peak prices (Wang et al., 2010).

The continuous changes in energy prices have become an important factor in defining energy consumption costs. Therefore, this paper seeks to provide a mathematical model to minimize the total energy consumption costs for single-machine scheduling by making decisions that identify the launch time for job processing, when the machine must be idle or shut down, and when to start "turning on" and "turning off" times. This can be accomplished by reducing energy consumption during high price periods in shifts. Thus, the changes in energy prices as shown in Fig. 1 are the key factor in the proposed model.

The paper is structured as follows: Section 2 provides a literature review. After the presentation of the problem definition and the mathematical models in Section 3, Section 4 describes the implementation of the model. Finally, Section 5 presents the study's conclusions.

2. Literature review

Improving production efficiency, minimizing makespan, reducing production costs (Hoogeveen, 2005), and reducing energy consumption (Liu et al., 2013) are among the most important production scheduling problems in the job shop. Mathematical models and optimizing algorithms have been widely used for optimizing production scheduling processes. In this area, Méndez et al. (2006) have reviewed the state-of-the-art optimization methods for short-term production scheduling of batch processes. Other researchers such as Lin and Liao (2008) have used an optimal algorithm to minimize the makespan to solve the uniform parallel machine problem.

Production efficiency means producing without wasting resources. Although production efficiency is significant for economic development in factories, environmental considerations and related economic effects are essential. Thus, there has recently been growing research interest in sustainability in addition to productivity. Despeisse et al. (2012) analyzed industrial practices and environmental principles to develop a conceptual manufacturing ecosystem model as a basis on which to improve environmental performance. In addition, Heikkurinen and Bonnedahl (2013) "proposed a new sustainability-oriented business strategy to replace the traditional stakeholder or market-oriented ones."

Many methods and solutions have been used to solve the problems of energy waste during production processes. Operational methods have been utilized to reduce energy consumption and environmental effects. One of the most relevant studies was conducted by Mouzon et al. (2007). They investigated the scheduling problem of a single machine to minimize total energy consumption, indicating that instead of keeping the non-bottleneck machines idle, they could be turned off until needed. Particularly, they proposed operation dispatching rules as steps to minimizing energy consumption: the machine could be shut down if the energy consumption for turning it off or on was less than the idle energy consumption. To ensure enough time to turn the machine back on before the next job began, they tried to predict the time of the beginning of the next job.

Optimization methods have also been used to improve energy efficiency; for instance Yan et al. (2005) presented a model for minimizing energy consumption and the makespan for job-shop scheduling in machine systems based on an "Energy-Saving Job-Shop Scheduling" method. These researchers developed a heuristic algorithm to identify the optimal or nearly optimal solutions for the model based on the "Tabu search mechanism".

Furthermore Liu et al. (2008) proposed a mixed-integer nonlinear programming model for the hybrid flow shop-scheduling problem to minimize energy consumption. An improved genetic algorithm solved this efficiently. Although energy consumption was mainly considered and the makespan was a key constraint, they ignored on-peak times for energy use. They assumed the machine would not be turned off until all jobs were accomplished, which means wasting energy during changes of machine states (when the machine lies in an idle status for a long time). Some mathematical models have also been proposed for dynamic scheduling in flexible manufacturing systems (FMS) with energy consumption minimization (Zhanga et al., 2012), which depends on a rescheduling strategy that is triggered when a new job arrives. However, the researchers ignored the amount of energy consumption used during peak times. Yi et al. (2012) proposed an emission-aware multi-machine job shop-scheduling model for minimizing both carbon emissions and makespan; they used a multi-objective genetic algorithm to solve the optimization problem. They, too, considered only power consumption during

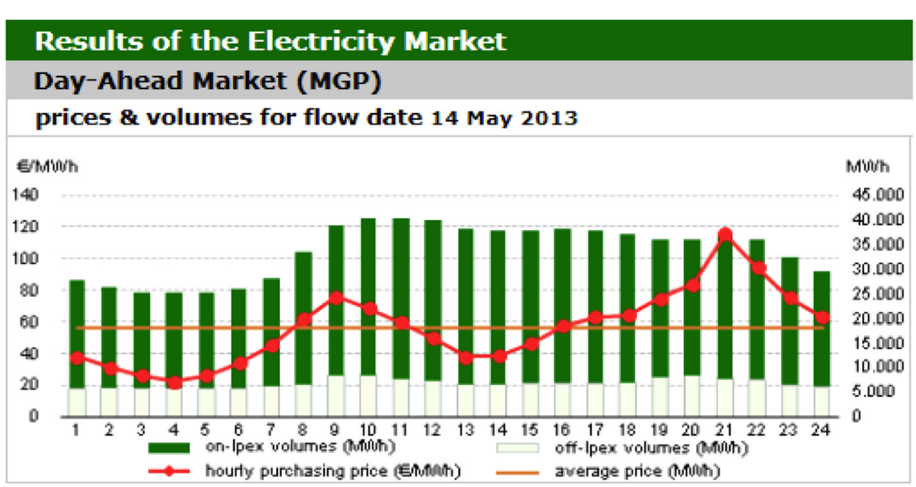

Fig. 1. An example of the hourly electricity price on a working day (GME, 2013).