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Econological scheduling of a manufacturing enterprise operating under a time-of-use electricity tariff

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ABSTRACT

A new ‘econological scheduling’ model combining the economic and ecological aspects of a multi-part multi-machine setup operating under a time-of-use tariff is presented. The operating speed of the machines and the frequency of operating speed change are allowed to vary, and the peak load and energy consumption during a shift is estimated using discrete event simulation. The electricity cost and environmental impact for a target production quota are simultaneously minimized using a multi-criterion meta-heuristic optimization. The proposed model is demonstrated via a case study on a manufacturing unit producing parts using machining and welding operations. A comparison among econological, economic, and ecological approaches and the underlying dynamics of scheduling under a time-varying electricity tariff are presented as one of several strategies for enabling a manufacturing system to be more eco-friendly without substantially increasing the electricity cost.

1. Introduction

Environmentally conscious manufacturing (ECM) has become more prevalent in today's world due to the significant increases in energy prices (Schlosser et al., 2011). The scope of the minimization of the environmental impact of manufacturing processes was initially limited to three principal methods: the modification of existing processes, replacement with alternative processes, and the development of new manufacturing processes (Munoz and Sheng, 1995). Subsequently, ECM was broadened to embrace a variety of other manufacturing issues, e.g., product design and development (Jackson et al., 1997) and systems planning (Sheng et al., 1998). The work of Munoz and Sheng (1995) and Dahmus and Gutowski (2004) addressed environmentally conscious machining. Basu and Sutherland (1999) introduced multi-variable multi-objective decision-making to simultaneously address cost, quality, and health hazard performance measures.

The current scope of the ECM is very broad and covers many different systems and scale levels, including unit processes, multiple machines, the factory, multiple facilities and even an entire supply chain (Duflou et al., 2012). Most of the work in the past focused on reducing the environmental impacts of manufacturing concentrated on smaller scales; for example, much of it was largely limited to unit processes or multi-machine approaches where a single product was the principal emphasis. The next highest level, that is, the factory level, involves multiple products that are simultaneously being produced using multiple machines. This scale invites a new challenge of reducing the non-productive time between operations. The non-productive time accounts for a significant portion of the cost and energy, as the utilities and supporting facilities continuously consume energy irrespective of production rate. As noted by Herrmann et al. (2011), the demand for higher productivity (cost, quality, and time) must be balanced with facility management and energy optimization because the cost of energy can be high enough to affect the plan for optimal facility operation.

Despite efforts to minimize peak loads and reduce the overall energy consumption within individual factories, power companies (electricity providers) are struggling to keep pace with growing electricity demands (this is especially true in the developing world).

As a consequence, energy shortages and peak demand deficits occur. Electric power companies apply different strategies for minimizing peak loads (Albadi and El-Saadany, 2008). Direct load control, interruptible load, and demand bidding are some of the

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incentive-based schemes in which energy saving provides a discount and overutilization a penalty. In contrast, price-based schemes are dynamic in the sense that the electricity rates change based on the real-time cost of electricity. These schemes are intended to smooth the demand pattern by charging a high price during peak periods and lower prices during off-peak periods. Time of use (TOU), extreme day pricing (EDP), and critical peak pricing (CPP) are some of the price-based schemes. Power companies around the world have introduced or are planning to introduce TOU tariffs to meet demand while balancing peak loads. A TOU tariff prescribes variable rates for electricity consumption during different times of day. A TOU tariff scheme, in principle, helps an electricity provider balance its load. The time-of-use tariff is based on the cost of producing the energy, which depends on the load seen by the electricity provider. The cost of production during a peak load period may be many times higher than that during off-peak periods; however, historically, power companies have not billed consumers based on the actual costs of production. A TOU tariff begins to align electricity charges with production costs. It encourages consumers to schedule their activities so that their electricity consumption (demand) is lower during the peak time. TOU tariffs are one of the most common demand-side management strategies, offering a means to lower electricity costs for consumers. However, a recent study by Jacopo (2012) showed that the under a TOU tariff, the average electricity consumption may sometimes increase, which translates into an increased carbon footprint.

A literature review suggests that no research has considered production scheduling based on electrical load tracking with the objective of the simultaneous minimization of the energy cost and carbon footprint for discrete manufacturing systems (DMSs). Dietrich (1991) provided a detailed discussion of classification, modeling, analysis, and optimization techniques for DMS. A DMS consists of many individual production machines/shops producing sub-parts or sub-assemblies, which are assembled to obtain the final product. The product can be disassembled at a later stage, and a sub-part may be replaced. The production of automobiles, electronic goods, and airplanes are examples of DMS. In contrast, continuous systems are concerned with the processing of raw materials and their blending into a final product in an irreversible fashion. Pharmaceuticals, fertilizers, and steel plants are examples of continuous systems. A continuous system of production is flexible and self-adjusting. Despite insufficient inventory, the production can continue with a smaller lot size (in terms of volume or weight), or a different formulation may be produced. This type of flexibility is not possible with DMS; the production needs to be halted in the absence of sufficient inventory required to assemble a product. Such halts in production are counterproductive and energy-consuming. Although no production takes place in this period, the basic amenities and utilities continue to consume energy. The conventional production scheduling practices have not addressed such issues. Thus, conscious efforts are essential for integrating the economic and ecologic (econologic) manufacturing scheduling models.

In the present work, we introduce a new ‘econological scheduling’ model for a discrete manufacturing system that aims to simultaneously optimize economic (energy cost) and ecological (carbon footprint) performance measures by the development of schedules that consider electrical load and the presence of a TOU tariff. The next section presents the background of the problem. This section is followed by the model formulation. Next, the proposed model is demonstrated using a case study on a manufacturing facility that uses a turning machine and a vertical machining center to produce sub-parts of a final product fabricated using a robotic welding machine.

2. Background

The scheduling problem in manufacturing has been widely investigated over the last 50 years. Extensive research has been conducted on various aspects of the scheduling problem, including job shop scheduling (e.g., Brucker et al., 1990; Gonçalves et al., 2005), flow shop scheduling (e.g., Osman and Potts, 1989; Tavakkoli at al. 2007), flexible job shop scheduling (e.g., Brandimarte, 1993; Pezzella et al., 2008), and open shop scheduling (e.g., Gonzalez and Sahni, 1976; Blum, C. 2005). Most of the research related to discrete manufacturing scheduling has adopted some simplifying assumptions. For example, although most real-life situations involve different types of unrelated machines, most of the modeling research has examined hybrid flow shop scheduling using identical machines (Marcus et al., 2011). Although some of the cases are related to real-life applications, the mathematical formulation is similar in the sense that either a single objective or mutually independent multiple objectives (usually only two objectives) have been considered. Efforts are continuously being made to solve scheduling problems using various techniques. For instance, over the last 10 years, meta-heuristic techniques such simulated annealing (Varadharajan and Rajendran, 2005), tabu search (Armentano and Arroyo, 2004), genetic optimization (Chang et al., 2007), particle swarm optimization (Chen, 2011), ant colony optimization (Leung et al., 2010), and a hybridization of the aforementioned techniques (Vallada et al., 2009; Zobolas, 2009; Sayadi et al., 2010; Mesmas et al., 2011; Yin-Yann et al., 2013) have been used to address scheduling problems.

Despite these enormous efforts, the outcomes of the scheduling investigations have largely centered on establishing a better algorithm that can yield a superior solution to the best known solution. In retrospect, considering the interdependencies of the machines, building, and facilities and associated complexities, simulation and optimization might be better applied to achieving the best operating environment and production plan. With such an approach, scheduling simulation would become an integral part of ECM at the factory level. Limited attempts relating to energy-conscious scheduling have been made in the past (Swaminathan and Chakrabarty, 2003; Subai and Baptiste, 2006; Mouzon and Yildirim, 2008; Róbert et al., 2008; Maria et al., 2008; He at al. 2008, He at al. 2012, Wang and Huang, 2009; Natasha et al., 2010; Yoon et al., 2013; Shrouf at al. 2014). Fang et al. (2011) presented a multi-machine level multi-objective scheduling simulation aimed at the simultaneous optimization of the makespan, the peak power load, and the carbon footprint for the first time. Unlike conventional scheduling aimed at maximizing machine/operation speed to maximize productivity, the formulation presented by Fang et al. (2011) allows the operational speed to vary to minimize the peak load and energy consumption, in addition to maximizing productivity. More recently, Fadi et al. (2014) proposed a mathematical model to minimize energy consumption costs for single-machine production scheduling by making decisions about job launch time, idle time, turning-on time, and turning-off time. Sun and Li (2014) presented an analytical model for the identification of the optimal energy control actions through changes in the system state of an assembly line.

It should be noted that recent efforts with the goal of minimizing the total operating cost and satisfying production targets through peak electrical load adjustment while operating under a TOU tariff (Ashok, 2006; Kristian and Manfred, 2010; Alain and Christian, 2011) have concentrated on scheduling continuous production systems, e.g., steel plants and electrolytic process systems.