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Simulation-based machine shop operations scheduling system for energy cost reduction

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ABSTRACT

Owing to the ever increasing requirements in sustainability, manufacturing firms are trying to reduce their energy consumption and cost. In this paper, we propose a simulation-based machine shop operations scheduling system for minimizing the energy cost without sacrificing the productivity. The proposed system consists of two major functions: (1) real-time energy consumption monitoring (through power meters, a database server, and mobile applications) and (2) simulation-based machine shop operations scheduling (through a machine shop operations simulator). First, the real-time energy consumption monitoring function is developed to collect energy consumption data and provide real-time energy consumption status monitoring/electrical load abnormality warnings. Second, the simulation-based machine shop operations scheduling function is devised to estimate the energy consumptions and cost of CNC machines. In addition, an additive regression algorithm is developed to formulate energy consumption models for each individual machine as simulation inputs. The proposed system is implemented at a manufacturing company located in Tucson, Arizona state of USA. The experiment results reveal the effectiveness of the proposed system in achieving energy cost savings without sacrificing the productivity under various scenarios of machine shop operations.

1. Introduction

In recent decades, as pollutions caused by the high industrial energy consumption are rapidly increased all over the world, the mitigation of energy consumptions has become a serious global concern. Under this background, both governments and international organizations (e.g., European Union and the Organization of Economic Co-operation and Development) have motivated the manufacturing industry to mitigate the pollution generation by levying an environmental charge (e.g., energy tax) on the energy consumption level of their manufacturing facilities [6]. Such efforts have brought significant impact on the manufacturing industry that consumes large amount of energy (i.e., electricity in this paper).

Moreover, utility companies are encouraging both residential and industrial customers to manage their electricity consumptions by offering various demand response (DR) programs. For the instances of time of use (TOU) program and real time pricing (RTP) program, the electricity price varies depending on the time or the overall load of the entire end user

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group. Specifically, manufacturing companies are encouraged to regulate their electricity usage via participating DR programs to reduce the electricity usage during the load on-peak period. After enrolled in a DR program, a manufacturing company may need to turn off some or even all their machines during the load on-peak period or to pay additional fees (normally higher than regular rate) if they use more electricity than a predefined threshold.

Meanwhile, manufacturing companies with machine shops have been seeking ways to reduce their energy costs (herein energy and electricity are used interchangeably). One way is to use energy efficient CNC machines. However, purchasing new equipment may not be practically viable due to the potential huge financial burden for manufacturing companies (especially, small and medium-sized company) with a large number of old model CNC machines. In addition to the capital investment and the corresponding training cost, adopting new equipment may also cause shop floor layout change, production line redesign, and other potential reliability and productivity issues. Alternatively, a more realistic way is to reduce the electricity cost by managing machine operations under a DR program. This is because a DR program provides the customer a way to change their normal electricity consumption behaviors in response to the changes in the electricity cost over time and overall electrical load [1]. In a DR program, since machine shops are able to handle the timing of electricity usage by adjusting their operations schedules, the total electricity cost can be reduced if machine shops shift their major electricity consuming operations from on-peak hours (e.g., day time) to off-peak hours (e.g., night time).

Another practical concern for shop floor managers is to mitigate the electricity cost without sacrificing the productivity or increasing other costs (e.g., labor cost). To achieve cost savings at the shop level, it is important for a shop floor manager to make operational decisions at both shop and individual machine levels. At the shop level, operations can be allocated among shifts according to a specific DR program. In addition, operations schedules need to be made considering the machining parameters of each job (idling, cutting, drilling, grinding, milling, and turning) at each individual CNC machine as the electrical load generated under different machining parameters varies significantly [2, 16]. However, it is challenging to make an appropriate schedule considering both levels simultaneously. Therefore, it is difficult to understand and estimate the electricity consumption patterns of a machine shop without having a dedicated system for collecting/analyzing electricity consumptions. In other words, it requires a system that not only collects real-time energy consumption data, but also provides decision support for shop level operations scheduling. To understand the electricity consumption patterns of a machine shop at both levels, Zampou et al. [24] proposed an energy-based management and intelligent decision support framework consisting of energy monitoring and energy-aware analytics functions. Based on the real-time electricity consumption data from both facility and individual machine levels, the framework helps shop floor managers to reduce the electricity cost by managing the machine operations. Nevertheless, their framework mainly focused on the real-time monitoring function, while the tools for managing the machine operations and reducing the electricity cost at the shop level are still in short.

To this end, we propose an integrated system that can automatically collect real-time energy consumption data from both shop and machine levels, detect and notify electrical load abnormality, and provide decision support for shop operations scheduling considering DR programs. The proposed system provides two major functions: (1) a real-time energy consumption monitoring function and (2) a simulation-based machine shop operations scheduling function. The real-time energy consumption monitoring function is to collect energy consumption data corresponding to different machining parameters (e.g., spindle speed) and notify the users (e.g., shop floor managers and machine operators) any abnormality in electrical loads (e.g., exceeding a predefined threshold). The proposed function is realized via multiple components involving power meters that collect electricity consumption data, a MySQL database server that stores the collected data and run programs (e.g., simulation and algorithms), and mobile applications (i.e., smart phone based clients) through which users can monitor the real-time energy consumption of each individual machine as well as the entire machine shop. Since a detailed computer simulation is capable of mimicking the dynamic behaviors of complex systems [23], we develop a simulation model to estimate the shop electricity consumptions and cost under various scenarios. The developed simulation model allows the users to perform what-if analysis on various scenarios and optimize operations schedules for minimizing the total electricity cost. As the simulation model is data-driven, it is adaptive to any operational change in terms of machining parameters, electricity cost, product line, and job sequence for each type of product. In other words, given the latest shop operation status, the simulation provides a desirable shop operations schedule in advance so that the machine shop is not only to save electricity costs but also to prevent potential production interruptions caused by facility load peaks. To estimate the energy consumptions of CNC machines via simulation, the data collected by the real-time energy consumption monitoring function is processed with the corresponding machining parameters via a developed additive regression algorithm (see Section 3.2.1). The algorithm formulates energy consumption models for each machine job in terms of machining parameters (feed rate, depth of cut, and spindle speed). Then the formulated energy consumption models are used as simulation inputs. The contributions of the proposed system are summarized as follows:

(1) A real-time energy consumption monitoring function is designed and implemented to track the real-time energy consumption status by the users and notify abnormal electrical loads via mobile applications (developed in both Android and iOS platforms).
(2) An additive regression algorithm is developed to formulate energy consumption models for each individual CNC machine, which has not been adopted for addressing shop operations scheduling problems before.
(3) A shop operation simulation model is developed to evaluate the electricity cost of operations schedules via what-if analysis and obtain near optimal operations schedules via simulation-based optimization. Though simulation has