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A dynamic control approach for energy-efficient production scheduling on a single machine under time-varying electricity pricing

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ABSTRACT

This paper proposes a dynamic control algorithm to enable an energy-aware single machine scheduling under the time-varying electricity pricing policy, in which price rates remain fixed day-to-day over the season. The key issue is to assign a set of jobs to available time periods where different electricity prices are assigned, while considering requested due dates of jobs so as to minimize total penalty costs for earliness and tardiness of jobs and total energy consumption costs, simultaneously. As the first contribution of this study, we develop a new mixed integer nonlinear programming (MINLP) model that aims at determining job arrival times and resulting earliness and tardiness of jobs and energy consumption costs for machine idle and normal processing. Second, an efficient heuristic approach based on continuous-time variable control models and algorithm is developed. The proposed heuristic adaptively changes job arrival times and due dates, which finally determine production sequence over the time periods of different electricity prices, machine turn-off, and machine idle with minimum energy consumption costs and just-in-time (JIT) penalty. Energy and JIT performance of the proposed approach is examined using real energy and machining parameters of a HAAS machine and compared to those of the metaheuristic approach. For relatively large size data groups, the proposed approach incurs about $4\sim11\%$ higher energy consumption costs on average, which are offset by up to 99% lower JIT costs, resulting in $10\sim94\%$ lower total costs on average compared to the metaheuristic approach. The proposed time-scaled heuristic algorithm yields extremely short computational time, which enables production managers to flexibly select proper production strategies and to implement them for different production environments.

1. Introduction

Concerns over air pollution and the associated dramatic climate change have led to increasing pressure to reduce energy consumption in manufacturing plants and to develop more advanced energy-aware production strategies. Various research trials have been performed to reduce energy consumption and cost at both the machining and facility levels taking into account time related production performance by implementing advanced machining technologies and operation methods. From a production operation point of view, in particular, energy-consumption reduction during machine processing could be achieved by several means; for example, production capacity can be adjusted considering production demand and power price variations to reduce energy consumption (Johansson et al., 2009). Machine capacity (i.e., machining speed) variation also contributes not only to keeping track of production time but also to possibly changing energy consumption levels during operation (Lee and Prabhu, 2015).

As an active energy-saving strategy and operation in production lines, turning machinery on and off to save energy rather than remaining idle for a certain time contributes to significant reduction in energy consumption, thereby cost. Such energy-aware machine state controlling with effective production scheduling has been studied and addressed by various heuristic and optimization approaches. Since Mouzon et al. (2007) proposed a machine scheduling problem combined with a machine power switch (i.e., turn-on and turn-off) strategy for machine idle while taking into

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account energy consumption cost, similar studies have been conducted considering different energy-related conditions and production performance.

The initial attempts to materialize the idea of switching machine power based on production demands and machine idle time distribution have focused on developing mathematical models and their solution approaches aiming at minimizing energy consumption costs with several performance measures such as total tardiness (Mouzon and Yildirim, 2008) and total completion time Yildirim and Mouzon (2012). Extending these research, Chen et al. (2013) discussed the trade-off between production performance and energy efficiency in different operations schedules considering Bernoulli serial lines with dynamic machine turn-on and turn-off strategies. Markovian analysis on machine state control showed marginal impacts of the machine power-switch strategy on system performance. Dai et al. (2013) applied the machine switch strategy to the flexible flow shop scheduling problem with the two objective functions of minimizing makespan and total energy consumption. They developed a genetic-simulated annealing algorithm to solve such a multi-objective scheduling problem, resulting in an effective set of Pareto optimal solutions.

Most of the studies around this time were conducted under the assumption that electricity prices were fixed over the planning horizon. This has proven to be an unrealistic conditions, and time-varying electricity prices and tariffs are commonly used today. Since Shrouf et al. (2014) proposed the single machine scheduling problem combined with a machine power switch strategy while taking into account time-varying energy prices, several studies have been recently conducted to provide the most effective production scheduling methods under the energy and production efficiency perspectives. They established a mathematical model for a single machine scheduling problem to minimize the total energy consumption costs. In the problem, the continuous changes in energy price, the energy consumption of each machine status, and the energy consumption of transitions between status are simultaneously considered. A genetic algorithm and an analytical solution are developed.

Aghelinejad et al. (2016) modified the basic models in Shrouf et al. (2014) by introducing a variable that defines job situations integrally rather than using separate variables in the basic model, resulting in alleviating the computational complexity. Unlike the basic model in which job sequences are input values and not changed, they were also optimized by removing several constraints in the basic model while guaranteeing low computational times.

Extending the models with dynamic electricity variations, Che et al. (2016) considered a single machine scheduling problem under dynamic electricity tariffs. The objective function in this study was to minimize the total electricity cost by effectively assigning a set of jobs to specific time periods in which different electricity prices are applied. The problem was formulated by a continuous-time mixed-integer linear programming (MILP) model, and a greedy insertion heuristic algorithm was implemented to guarantee a short computational time. Assuming the preemption of jobs, each job is inserted in non-increasing order of power consumption rate into any idle time slots enough to hold it, while considering electricity costs.

Fang et al. (2016) also studied a single machine scheduling problem aiming at minimizing electricity costs under time-varying tariffs. They considered two scheduling conditions such that jobs are processed at a constant speed as well as an exponential function of speed that is called uniform-speed and speed-scalable machine conditions, respectively. They analytically showed NP-hard and polynomial properties for the non-preemptive and preemptive machine conditions and suggested approximate and exact polynomial-time algorithms for each case.

While those previous studies focused on a single machine problem with only an energy-related objective, Wang et al. (2016) recently solved a bi-objective single machine batch scheduling problem with the objective function of minimizing the makespan and total energy consumption costs, which depends on the energy price variations. An exact $\varepsilon-$constraint method was implemented by solving the problems of constructing job batches and sequences. Overcoming computational complexity caused by NP-hardness of the problem, two constructive heuristic methods were also proposed to determine batch size and sequence separately and showed their algorithmic benefits in terms of production, energy and computational performance.

Gong et al. (2016) also studied a similar problem with the objective function of minimizing electricity costs considering three demand response programs in which different electricity pricing strategies are given. The problem was formulated by the MILP model considering the machine power switch strategy, and genetic algorithm was implemented to solve it. They showed trade-off between the electricity cost and the makespan by analyzing numerical experiment results within three Pareto frontiers.

Recent research like that described above tells us that no one addresses a scheduling problem with consideration for just-in-time (JIT) production needs, the machine power switch strategy, and energy consumption costs under the dynamic electricity pricing condition, simultaneously. Particularly with the increasing importance of time-based competition and corresponding JIT needs, production performance based on due-dates becomes more important, especially in small-volume large-variety production processes. Here, JIT needs can be materialized simply by minimizing both tardiness and earliness of jobs, which improve, for example, customer satisfaction by improving delivery reliability and minimizes the work-in-process inventory (Prabhu, 2000). Technically, however, the JIT considerations in the scheduling problem lead to much higher computational complexity compared to other conventional measures, such as makespan, completion time, and lateness (Baker and Scudder, 1990).

In this paper, we demonstrate how improvement in JIT can be incorporated with improvement in energy consumption costs in a single machine scheduling problem under time-varying electricity prices and the machine power switch strategy. To do this, first we analyze the relationship between the approximated energy consumption level and the machine idle time, which is a part of production schedules and can be effectively managed to lower the overall energy consumption level. In particular, time-varying electricity price is considered to estimate overall energy consumption costs for production, specifically based on the time-of-use (TOU) pricing policy. To overcome huge computational burdens expected by non-linearity of the objective function consisting of JIT and energy measures, a heuristic method based on a control theoretic approach is developed and its solution proximity, limitation, and effectiveness are discussed. We develop dynamic models in which dynamics of part-arrival and machine idle time are represented and controlled for energy-efficient production scheduling. Furthermore, these control models serve as a core control logic in the dynamic algorithm, called dynamic idle time and arrival time control (DIATC) algorithm, which aims for real-time production and machine vacation scheduling on a single machine in the consideration of TOU pricing, thereby simultaneously achieving better JIT production performance as well as less energy consumption cost. Finally, the performance of DIATC is compared to the metaheuristic called particle swam optimization (PSO).

The remainder of this paper is organized as follows. In section 2, the single machine scheduling and machine switch on-off problem with the consideration of energy consumption cost and JIT performance is defined, and its mixed integer nonlinear programming