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Energy-conscious flow shop scheduling under time-of-use electricity tariffs

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ABSTRACT

A time-indexed integer programming formulation is developed and used to identify manufacturing schedules that minimize electricity cost and the carbon footprint under time-of-use tariffs without compromising production throughput. The approach is demonstrated using a flow shop with 8 process steps operating on a typical summer day. Results suggest that shifting electricity usage from on-peak hours to mid-peak hours or off-peak hours, while reducing electricity cost may increase CO_2 emissions in regions where the grid base load is met with electricity from coal-fired power plants. The trade-off between minimizing electricity cost and reducing CO_2 emissions is shown via a Pareto frontier.

1. Introduction

Due to rising electricity prices in recent years, the issue of reducing electricity costs has become a focus for many factory managers. A considerable body of literature is starting to develop on electricity cost reductions in manufacturing. Most of the reported research has focused on reducing total electricity consumption, increasing the efficiency of facilities, etc. For example, Fang et al. [1] developed a new scheduling method to reduce peak power load and carbon footprints in manufacturing; jobs were processed at varying speeds with a trade-off between speed and energy consumption. Factories are using newer and higher efficiency equipment in place of older and lower efficiency ones [2]. A food manufacturer, Northern Foods, in the UK, achieved an annual energy savings of 769 MWh by using a variable speed drive (VSD) in a system, which produced an annual CO_2 reduction of 228 tons [3]. Although more efficient, switching to new and advanced equipment does require large capital investment.

Recently, many energy suppliers have begun to implement a so-called *time-of-use* (TOU) tariff, that is, retail electricity pricing that varies hourly to reflect changes in the wholesale electricity market. Such pricing represents a huge opportunity to reduce costs for electricity-intensive consumers by shifting electricity usage from on-peak hours to off-peak or mid-peak hours. Under time-of-use electricity tariffs, the electricity cost is based on consumed electricity over time, and takes into account that each period has a corresponding price per unit of electricity consumed. This presents an interesting challenge in terms of minimizing the total electricity cost in a scheduling problem. For example, Wan and Qi [4] considered a single machine scheduling problems in which each time period has an associated cost. The objectives in their paper were minimizing cost while considering traditional scheduling performance measures; they showed that such problems are NP-hard.

Due to the concerns about fossil fuel consumption and associated greenhouse gas emissions, carbon emissions or footprints have also received attention in the literature [5]. As mentioned above, manufacturing enterprises can reduce their electricity bills by exploiting changes in electricity pricing under TOU tariffs. However, carbon dioxide (CO_2) emissions from electricity generation may be increased due to electricity pricing and usage changes. This is because coal-fired generation plants normally have a greater carbon footprint per kWh of electricity produced than gas-fired generation plants. In some regions, the electricity providers start to use the gas-fired generation plants to supplement the coal-fired generation plants during peak hours [6]. In this context, shifting electricity usage from on-peak hours to off-peak hours or mid-peak hours can reduce the total electricity cost of manufacturing enterprises with a trade-off of an increased carbon footprint, assuming that the shift will not lead to additional use of gas-fired plants. This assumption is reasonable as there is excess capacity from coal-fired plants during mid-peak and off-peak periods. In this paper, the trade-off between electricity cost and carbon footprint emissions in flow shop scheduling with production throughput constraints under TOU tariffs will be examined.

2. Methodology

A time-indexed integer flow shop scheduling problem is considered that aims to minimize the total electricity cost and carbon footprint while not compromising production throughput. It may be termed an energy-conscious flow shop scheduling problem with production throughput constraints (or the EFSTC problem). In a typical flow shop, each part has to be processed in a

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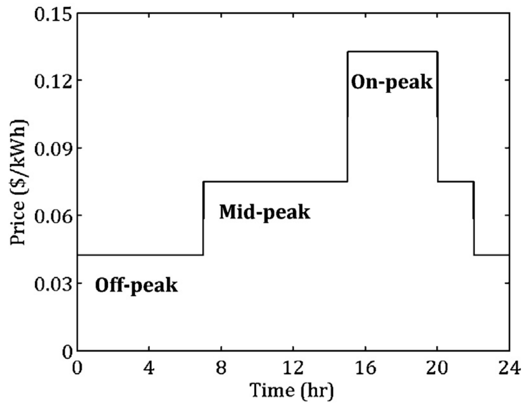

Fig. 1. Electricity price ($/kWh) over a 24-h time period.

defined order on a given set of machines, i.e., each part has to be processed first on machine 1, then on machine 2, and so on. In the EFSTC problem, the following assumptions are made: (a) all the machines have two modes, i.e., on mode and off mode; (b) each part must be processed continuously, that is, a machine cannot be switched from one mode to another during the processing of a part; (c) the buffer, or space for work-in-process, between any two successive machines is unlimited; (d) machines are automatically operated and labor is not included.

2.1. Electricity rate structures

Time-of-use (TOU) tariffs have emerged as one of the most common approaches adopted by utility companies to achieve more efficient and effective demand management. A TOU tariff establishes differing rates for electricity consumption during different time periods of the day. Generally, there are three periods during a day: on-peak hours, mid-peak hours, and off-peak hours (see Fig. 1).

For a given time period, the electricity cost is calculated based on the electricity consumption times the electricity price during the time period. Compared to flat electricity rates, TOU tariffs provide users with an opportunity to cut costs by shifting their consumption to hours with lower rates. However, such shifts may increase carbon emissions for regions that use coal-fired generation to meet the base load electricity demand.

2.2. CO_2 emissions in electricity generation

As noted above, the base electricity load is often provided by coal-based sources, and natural gas is used to handle peak demands. Generally, the CO_2 emissions per kWh from natural gas are less than that of coal [7]. Fig. 2 shows how the electricity demand throughout a typical day may be met with different power sources [8]. Fig. 3 displays the CO_2 emission per kWh based on this mix of power sources. As is evident, the CO_2 emission per kWh is lower during on-peak hours than during the other periods.

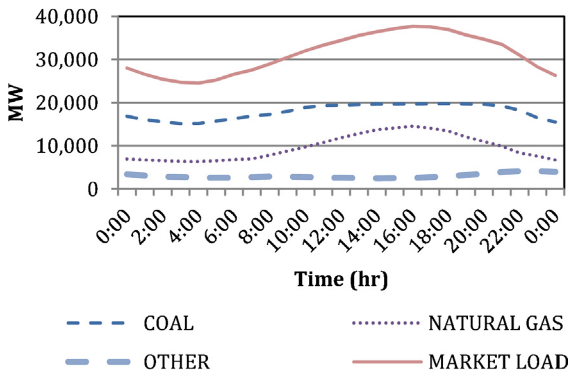

Fig. 2. Power generation being used in real time.

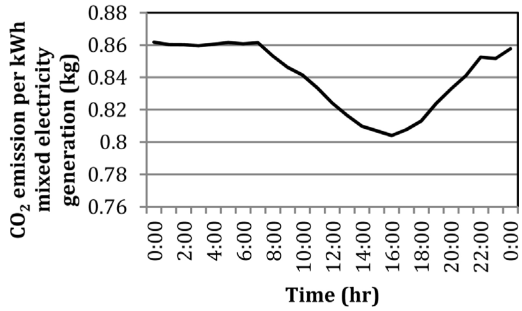

Fig. 3. CO_2 emission per kWh for a power grid mix.

2.3. Variables, parameters, and notation

In the EFSTC problem, a set of machines $M = \{1,2, \ldots, m\}$ and a set of products $J = \{1,2, \ldots, n\}$ are given. The required throughput for each product $j \in J$ is N_{j0}. When processing the *jth product* on machine i, its associated processing time is p_{ij} and its power consumption is q_{ij}. At time t, the electricity price is P_t and the corresponding carbon emission per unit of electricity consumption is C_t. The decision variables are defined as:

(a) x_{ijt} is equal to 1 if machine i is operating on *jth* product at time t, and 0 otherwise.
(b) y_{ijt} is equal to 1 if machine i starts processing the *jth* product at time t, and 0 otherwise.
(c) N_{ijt} is the number of products of the *jth* type that have been processed on machine i by time t.

2.4. Model

The following multi-objective, time-indexed mixed integer optimization model seeks to find a schedule that minimizes (1) the total electricity cost, and (2) the total carbon emissions (carbon footprint) for the EFSTC problem.

$$\min \sum_i \sum_j \sum_t P_t q_{ij} x_{ijt} \tag{1}$$

$$\min \sum_i \sum_j \sum_t C_t q_{ij} x_{ijt} \tag{2}$$

Subject to:

$$N_{ijt} = 0, \quad (t = 0, \ldots, p_{ij} - 1; i \in M; j \in J;) \tag{3}$$

$$N_{ijt} = \sum_{k=0}^{t-p_{ij}+1} y_{ijk}, \quad (t = p_{ij}, \ldots, T; i \in M; j \in J;) \tag{4}$$

$$N_{ijt} \geq N_{i+1,jt} + x_{i+1,jt}, \quad (i \in M \backslash \{m\}; j \in J; t \in T;) \tag{5}$$

$$N_{mjT} \geq N_{j0}, \quad (j \in J;) \tag{6}$$

$$x_{ijt} = \sum_{k=0}^{t} y_{ijk}, \quad (t = 1, \ldots, p_{ij} - 1; i \in M; j \in J;) \tag{7}$$

$$x_{ijt} = \sum_{k=t-p_{ij}+1}^{t} y_{ijk}, \quad (t = p_{ij}, \ldots, T; i \in M; j \in J;) \tag{8}$$

$$\sum_{k=t}^{t+p_{ij}-1} x_{ijk} \geq y_{ijt} p_{ij}, \quad (i \in M; t = 1, \ldots, T - p_{ij} + 1; j \in J;) \tag{9}$$

$$\sum_j x_{ijt} \leq 1, \quad (i \in M; t \in T;) \tag{10}$$