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ILP model for energy-efficient production scheduling of flake ice units in food retail stores

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ABSTRACT

This paper presents an integer linear programming (ILP) model to minimise the total energy-cost of a flake ice production unit in food retail stores. This work is based on a real problem in a Portuguese food retail company, where flake ice in necessary throughout the day in order to maintain fresh fish on the shelves at ideal temperature conditions and humidity levels. The proposed approach aims to provide an energy-efficient scheduling of the production to periods with a lower energy cost, as well as to reduce water consumption, by producing the exact quantities required at the right time, minimising waste. The model was tested on a set of real-world instances from the retail company, and on a set of randomly generated instances. The procedure used to create these instances is presented in the paper. For the sets of tested instances, the results show that the model is strong when compared to the lower bounds provided by the linear programming relaxation of the model. The results from the set of real instances show that it is possible to achieve an energy-efficient scheduling of the production which translates in an average annual cost savings of 34.3% for the stores.

1. Introduction

Energy prices tend to rise with demand. According to Mobil (2013), the global energy demand is likely to increase 35% by 2040, and this number can rise up to 140% if energy-efficiency measures are not adopted in the same time frame. The predicted increase in demand takes into account several factors such as an additional two billion in world population, the growth of the global middle class, particularly in developing nations, and the expansion of emerging economies, with non-OECD countries accounting for 70% of global energy demand. These scenarios represent huge challenges to companies, which not only have to continue to be profitable in an increasingly competitive global market, but have to accomplish their goals in a sustainable manner. An efficient use of energy is seen as a pressing challenge across the board.

In food retail stores, electricity is responsible for approximately 35% of the operating cost, which means that a good energy-efficiency policy can have a significant positive impact in the development of a sustainable business as well as in the global expenses. One way of achieving energy-efficiency is by producing the same output with lower energy consumption (Patterson, 1996). Another way is reducing energy costs by moving load from on-peak to off-peak energy tariff rates (Michaloski et al., 2011). In the first approach, efficiency is achieved independently of the energy grid to which the company belongs, while the latter efficiency is achieved by balancing the energy consumption of the members of the grid. One of the ways energy companies have to balance energy consumption is by offering variable prices for electricity depending on the time of day, to incentive customers to shift electricity consumption away from peak times. In the future there will be many more energy tariff rates and price variations as the on-demand fossil fuel generation is being replaced by the variable generation from renewable sources, which will make energy-efficiency measures much more complex and difficult to implement.

According to Méndez et al. (2006), scheduling is a critical issue in process operations and is crucial to improve the production performance. As a decision-making process, it allocates available resources to tasks and addresses the starting and completion times of the tasks to optimise one or multiple objectives. The objectives strongly influence the approaches to the problem and are mostly time-related. Examples include minimising the makespan or the flow time. Makespan is the total amount of time that elapses from

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the start to the conclusion of a group of jobs, and flow time is the time a job spends in the production system. Only recently has literature on scheduling focused on energy efficiency objectives, driven mainly by sustainability challenges facing companies. However, the amount of work on this topic is far from keeping up with the challenges posed by sustainability (Gahm et al., 2016).

This paper proposes an integer linear programming model to provide an energy-efficient scheduling of the production of flake ice production units in food retail stores by scheduling the beginning and end of production to the periods with the lower energy tariff rates, while guaranteeing that all needs are met at the right time and in the adequate quantities. This problem is referred to in the literature as the single machine scheduling problem under time-of-use (TOU) electricity tariffs.

The remainder of the paper is organised as follows. Section 2 presents an overview of related work. Section 3 describes the flake ice production process in detail. Section 4 presents an integer linear formulation of the problem. Section 5 presents the computational results and the tariff band prices, as well as the daily distribution generator. Section 6 describes the implementation of the model. Finally, Section 7 presents the conclusions.

2. Related work

In a recent study, Gahm et al. (2016) presented an extensive research review for energy-efficient scheduling in order to identify and structure different problems and the respective methods of production planning in manufacturing companies. The authors propose three different dimensions to classify energy-efficiency scheduling approaches:

- Energetic coverage - This dimension specifies the production system and the internal/external conversion systems used to improve energy efficiency by reducing the actual energy demand. It includes aspects such as the idle times of machines, the production planning of orders to avoid intensive setups, allocation of tasks to machines with fewer energy requirements or the adjustment of the processing speed.
- Energy supply - This dimension describes the characteristics of the final energy sources and applied energy sources. It is used in price-driven demand approaches where energy rates vary throughout the day to encourage companies to ration their energy consumption and avoid peak periods of energy consumption.
- Energy demand - This dimension describes the characteristics of the energy sources applied and can be divided into non-processing energy demand - which takes into consideration parameters like the time the machines are switched on, idle times, machine setups, times the machines are switched of and material storage - and processing energy demand, which takes into consideration the energy requirements and variations of each specific process and machine.

Examples of models for energy-efficiency scheduling problems can be found in the literature. Wang and Li (2013) propose a systems approach for time-of-use based electricity demand response for manufacturing systems with N machines and $N-1$ buffers connected in series. The goal is to control at what time each machine can be shut down temporarily to lower energy consumption and power demand. The authors propose two problems with different objectives: minimising of the total electricity consumption and the total electricity cost. Since the two proposed formulations are zero-one nonlinear programing problems, a binary particle swarm optimisation algorithm was used to find a near-optimal scheduling solution.

Yusta et al. (2010) presented a mathematical optimisation model which simulates cost and electricity demand of a machining process to find the optimum production schedule, which maximises the profit considering the hourly variation in electricity price. The power required by the machine tool is directly proportional to the feed and the cutting speed, which directly influence the number of parts produced in a day. On that basis, the optimisation process will obtain the number of parts to be produced each hour throughout the day, assuming a fixed price for each part, determined by the company.

Nolde and Morari (2010) propose a mixed integer linear programming (MILP) problem model to solve the load tracking scheduling problem in a steel plant. The model proposes the scheduling of all tasks to match a pre-specified periodic energy curve. The goal is to minimise the total energy-cost of transforming scrap metal into cast steel. In the MILP model, the authors use a continuous time representation, since using a model with discrete time representation would become computationally intractable.

Only recently researchers have started paying attention to the single machine scheduling problem with TOU electricity tariffs. Shrouf et al. (2014) proposed an integer linear programming model using a discrete time representation. Fore each machine, the authors identified different states and transitions with different energy consumption levels, which can be measured using sensors or smart meters. They identify three different states, “processing” (i.e., productive), “idle” (i.e., working but non-productive), and “shut down”. Using as input the duration of the production shift, energy prices at each time period, number, order and processing time of tasks, amount of power consumption per period at every machine status and transitions, and the respective time of each status and transition, the proposed model delivers three outputs: when to start processing each task; when the machine should be idle or shut down, all the transition times to minimise the total energy consumption costs for the machine.

Gong et al. (2015) proposed a mixed-integer linear programming model and a genetic algorithm for the single machine scheduling problem with arbitrary processing sequences of jobs, under three electricity tariff structures, “real time pricing”, “time-of-use pricing” and “critical peak pricing”. The genetic algorithm was applied to a real-life case of a surface grinder with five different states, “Off”, “Startup”, “Ready”, “Production” and “Shut down”. They compared the results against the as early as possible schedule, and for the ‘real time pricing”, “time-of-use pricing” and “critical peak pricing”electricity tariff structures they achieved electricity cost savings rates of 22%, 20%, and 69%.

Che et al. (2016) proposed a MILP problem model using a continuous time representation. Due to the number of variables and constraints of the proposed model, the authors developed a greedy insertion heuristic algorithm that was applied to a real-life case study of a CNC planer type horizontal milling and boring machine from a Chinese company, whose daily pricing scheme for electricity includes five periods with three types of electricity prices for on-peak, mid-peak and off-peak loads. As a result, the authors achieved 30% savings in the total electricity costs.

Scheduling problems have a wide application in different organisations and can lead to significant improvements in process efficiency and cost reduction. Although energy-efficiency is a well-known topic nowadays, and some studies have been conducted, no specific literature has been found that could be used to address flake ice production scheduling in food retail stores.

3. Description of the flake ice production process

This work is based on a real problem, which is, how to schedule the production of flake ice in a Portuguese food retail company. The