Int. J. Production Economics 146 (2013) 178–184

Contents lists available at ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

"Just-for-Peak" buffer inventory for peak electricity demand reduction of manufacturing systems

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ARTICLE INFO

Article history:
Received 18 November 2012
Accepted 20 June 2013
Available online 29 June 2013

Keywords:
"Just-for-Peak" buffer inventory
Peak electricity demand
Energy management

ABSTRACT

The reduction of the electricity demand during peak periods is considered a main objective of electricity load management. It can relieve the financial pressure of the investment on the capacity expansion for the power grid in the United States. Compared to a great deal of research on commercial and residential building sectors, few studies on the electricity demand reduction during peak periods for industrial manufacturing systems have been conducted due to the concern of system throughput variation and the complexity of modern manufacturing systems. This paper presents a novel "Just-for-Peak" buffer inventory methodology to reduce the electricity consumption without compromising system throughput during peak periods for typical manufacturing systems with multiple machines and buffers. Nonlinear Integer Programming (NIP) formulation is used to establish the mathematical model. The optimal buffer inventory management policies and corresponding load management actions for the whole system are identified by minimizing the holding cost of the "Just-for-Peak" buffer inventory and energy consumption cost under the system throughput constraint throughout the production horizon. A numerical case study based on an automotive assembly line is used to illustrate the effectiveness of the proposed method.

1. Introduction

The electricity demand in the United States will increase by 30% from 3873 billion kWh in 2008 to 5021 billion kWh in 2035 (EIA, 2010). In addition, due to the increasing cost of fossil fuels and new grid capacity investment, the electricity price is expected to increase from 8.6 cents per kilowatt-hour in 2011 to 10.9 cents per kWh in 2035 for the case of the high economic growth scenario (EIA, 2010).

The unbalanced distribution of the electricity demand in different periods exacerbates the situation, which leads to the huge financial pressure of the investment on new grid capacity to meet the growing peak demand. It is estimated that by 2030, about $697 billion investment for new generation capacities is required to satisfy the growing need. Considering transmission and distribution infrastructure, the investment will be approximately $2 trillion dollars (Chupka et al., 2008).

To reduce the growing financial cost and make the electricity generation more economically affordable and environmentally responsible, an unregulated electricity market model encouraging the competitiveness among the suppliers and marketers has been established to gradually replace the traditional regulatory market model where vertically integrated utilities retain functional control over the transmission and generation system (ESPA, 2013) and the end-use electricity rates are deterministic. The unregulated market model has been adopted by the Northeast, Mid-Atlantic, much of the Midwest, and California, where the market is organized and operated under an Independent System Operator (ISO) (ESPA, 2013). Under the unregulated market model, the end-use customers can choose to face stochastic pricing (real-time price based on the variable wholesale price) or deterministic pricing, e.g., average annual cost (Wikipedia, 2013). In fact, two-thirds of the electricity consumed in the United States is by the customers in the unregulated market that is operated by ISO (ESPA, 2013).

In addition, Demand Side Management (DSM) programs are also thought to be an effective strategy to reduce both economic and environmental impacts due to the increasing electricity demand in the near future. It covers multiple kinds of solutions for relocating or reducing the energy demand in residential, commercial and industrial sectors. These programs have attracted increasing attention from both supply and customer side of the electricity grid throughout the United States. DSM is defined by Federal Energy Regulatory Commission as "changes in electric usage by end-use customers from their normal consumption patterns in response to the changes in the price of electricity over time, or to the incentive payments designed to induce lower

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http://dx.doi.org/10.1016/j.ijpe.2013.06.020

electricity use at times of high wholesale market prices or when system reliability is jeopardized" (FERC, 2012).

Generally, there are two main forms of DSM, energy efficiency management and load management. The former focuses on achieving the same output with reduced energy usage and the latter, in contrast, concerns about curtailing or shifting the demand from peak periods with high financial cost to off-peak periods (Gellings, 1985). It is reported that the average energy saving ratio is approximately 65 kWh per kilowatt of peak demand reduction (Faruqui et al., 2007). Dynamic price systems, e.g., Time of Use (TOU) rate, are widely used in the retail market to encourage the end-use customers to shift or curtail their demand and relieve the unbalanced situation between the demand and the supply of the electricity during peak periods. It is estimated that in the commercial and industrial classes, load management programs are projected to reduce demand by 13% (Faruqui et al., 2007).

Compared to the research on energy efficiency improvement for either single machine manufacturing systems (Dietmair and Verl, 2009; Draganescu et al., 2003; Gutowski et al., 2006) or typical manufacturing systems with multiple machines and buffers (Li et al., 2012b; Li and Sun, in press; Sun and Li, 2013), most existing load management studies focus on the applications related to the commercial and residential building sectors. For example, Ghatikar et al. (2010) and Motegi et al. (2006) introduced the general strategy introduction and technology guidance of the load management for buildings. The thermal storage utilization methodologies were developed to reduce the power demand of buildings during peak periods (Braun, 1990; Houwing et al., 2011). The applications that integrate the building load management into the smart grid have also been studied (Corno and Razzak, 2012; Wang et al., 2012). The developed methodologies help the customers in building sector manage their consumptions of electricity in response to the dynamic prices. Either manual or automatic control strategies are introduced to effectively reduce the electricity demand of buildings during peak periods.

As for the load management research focusing on manufacturing systems, only a little literature with different limitations can be found. For example, Luo et al. (1998) established a mixed integer programming model to find an optimal load shed-restoration schedule for a coal mine by minimizing the production loss under the operational constraints. The production was not considered the first priority, which contradicts the principle of most manufacturing enterprises and thus the adoption is doubtful. Logenthiran et al. (2012) developed a heuristic-based evolutionary algorithm to solve the mathematical formulation of the implementation of day-ahead load shift by minimizing the difference between the actual load curve and the desired load curve for residential, commercial and industrial facilities. However, it assumed that the industrial devices were mutually independent, which is not applicable to the complex modern manufacturing systems with high interactions. Ashok and Banerjee (2001) developed a mathematical formulation for obtaining an optimal production schedule of a flour plant by minimizing the energy consumption cost ($/kWh) as well as other operation costs under the constraint of production target. However, it did not consider the cost of demand ($/kW) and thus the solution may not be necessarily the optimal one. Later, Ashok (2006) extended his previous work by adding the cost of energy demand ($/kW) to the objective function to model the operation of a small steel plant. Nevertheless, the production system modeled was a relatively simple batch process.

The difficulties in the research of load management for manufacturing systems come from the complexity of modern manufacturing systems and the concern of the system throughput variation. Firstly, modern manufacturing systems are usually in operation with high dynamics, which makes it intractable to obtain exactly optimal solutions for load management. Secondly, for most manufacturing enterprises, system throughput is considered the primary priority for profit and long-term survival. Therefore, it is desirable to perform load management to reduce electricity demand and overall cost during peak periods while the system throughput can be maintained at the same time.

Recently, Li et al. (2012a) systematically analyzed the research challenges of the load management for manufacturing systems and summarized that the state-of-the-art of the load management research for manufacturing systems is far less developed than the one in architecture (Li et al., 2012a), although the contribution of industrial sector to the total peak electricity demand is as high as about 20% in the United States (Faruqui et al., 2007). At the same time, it also introduced a heuristic buffer utilization method to reduce electricity demand for typical manufacturing systems without negative impacts on system throughput. It illustrated the feasibility and reduction potential of the load management implementation for manufacturing enterprises and also implied that more advanced methodologies are needed.

In this paper, a novel "Just-for-Peak" buffer inventory methodology is presented to implement power demand reduction for typical manufacturing systems with multiple machines and buffers during peak periods under the constraint of system throughput invariant. Both holding cost of the built-up buffer inventory and electricity bill cost are considered in the objective function. A Nonlinear Integer Programming (NIP) formulation is established and a numerical case study is conducted to illustrate the effectiveness of the proposed method. The rest of the paper is organized as follows. Section 2 demonstrates the proposed method in detail. Section 3 shows the results of a numerical case study by implementing the proposed method. Finally, the conclusion and future work are discussed in Section 4.

2. Proposed method

Consider a typical tandem production system with n machines and n-1 buffers as shown in Fig. 1. Buffer B_i, $i=1,\ldots,n-1$, is deployed between every two consecutive machines to relieve the throughput impacts caused by the random failures of the machines.

Besides the deployment of regular buffer B_i as shown in Fig. 1, referring to the method of buffer utilization for preventive maintenance developed by Salameh and Ghattas (2001), we define $n-1$ additional buffer locations that can be used to store the "Just-for-Peak" buffer inventory which is spared aside from regular buffer B_i during off-peak periods for the purpose of demand reduction during peak periods. Those additional locations are paired with each regular buffer B_i as shown in Fig. 2. Let J_i, $i=1,\ldots,n-1$, denote those additional buffers.

In addition, we define a production horizon as the sum of a scheduled off-peak period T and a follow-up scheduled peak period t_p, and assume the time length of T and t_p are both known. Before the end of period T, when the inventory level of specific B_i is high, we can spare and store products in corresponding J_i to build up "Just-for-Peak" buffer inventory as a source for the implementation of demand reduction during t_p. Hence, the corresponding upstream machines M_i can be turned off during the peak periods by utilizing the "Just-for-Peak" buffer inventory to maintain the production without being influenced. A typical cycle of the change of the "Just-for-Peak" buffer inventory in one production horizon is illustrated in Fig. 3. The "Just-for-Peak" inventory is built during off-peak periods and the demand reduction is implemented during peak periods. Let a_i be the assumed linear accumulation rate for "Just-for-Peak" inventory built up in J_i during the off-peak periods without the impact on system throughput

Fig. 1. Tandem production line with n machines and $n-1$ buffers.