**“Just-For-Peak” Buffer Inventory for Peak Electricity Demand Reduction of
Manufacturing Systems**

BY

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THESIS

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SUMMARY

The reduction of the electricity demand during peak periods is considered as an effective tool for load management to relieve the financial pressure of the investment on the capability expansion for the grid in the U.S. Compared to a great deal of research in the commercial and residential sectors, little work on the electricity demand reduction during peak periods for industrial manufacturing systems has been conducted due to the concern of the system throughput variation and the complexity of modern manufacturing systems.

This thesis presents a novel “Just-for-Peak” buffer inventory methodology to reduce the power demand during peak periods for typical manufacturing systems with multiple machines and buffers. The basic idea is to build up the “Just-for-Peak” buffer inventory during off-peak periods and thus the corresponding machines can be turned off during peak periods by using the accumulated “Just-for-Peak” buffer inventory.

Firstly, the model under the constraint of system throughput is developed using Nonlinear Integer Programming (NIP) for the mathematical formulation. The optimal building policy and control action are identified to minimize the holding cost of the “Just-for-Peak” buffer inventory and energy consumption cost under the system throughput constraint. Next, the system throughput constraint relaxed model is formulated with the objective function to minimize the holding cost of the “Just-for-Peak” buffer inventory, the energy consumption cost and the production shortage cost throughout the production horizon. The numerical case study based on the same section of an auto assembly line is developed for both models to illustrate the effectiveness of the methods.

1. INTRODUCTION

The electricity demand in the United States will increase by 30 percent from 3,873 billion kilowatt-hours in 2008 to 5,021 billion kilowatt-hours in 2035 (EIA, 2010), as we can see in Figure 1. 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 kilowatt-hour in 2035 (See Figure 1) for the case of high economic growth scenario (EIA, 2010).

Figure 1. Forecasting of the electricity demand and electricity cost.

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 two trillion dollars (Chupka et al., 2008).

To reduce the growing financial cost and make the electricity generation more economically affordable and environmentally responsible, 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). The structure of the unregulated model can be briefly described by Figure 2.

Under the unregulated market model, the end-use customers can choose whether or not 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).

Figure 2. Wholesale & Retail Electricity Market

(source:

http://www.nyiso.com/public/about_nyiso/understanding_the_markets/wholesale_retail/index.jsp)

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 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), as it is shown in Figure 3. It is reported that the average energy saving ratio is approximately 65 kWh per kW 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 percent (Faruqui et al., 2007).

Figure 3. Load Management Objectives

(source: <http://large.stanford.edu/courses/2010/ph240/malone1/>).

Compared to the research on energy efficiency improvement for either single machine manufacturing systems (Dietmair & Verl, 2009; Draganescu et al., 2003; Gutowski et al., 2006) or typical manufacturing systems with multiple machines and buffers (Li et al., 2012b; Li & Sun, 2013; Sun & 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 & 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 considered 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 percent 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 thesis, 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. The “Just-for-Peak” buffer inventory is built up during off-peak period and will be used during peak periods and thus the corresponding downstream machine can be turned off to reduce the energy consumption and power demand during the peak periods. We will first establish the model under the constraint of the system throughput to explore the feasibility and potential benefits of the method. Both holding cost of the built-up buffer inventory and electricity bill cost are considered in the objective function. After that, the system throughput constraint will be relaxed and the cost due to the potential production loss will be

integrated into the objective function. Mathematical formulation will be established for both models and the numerical case study is conducted on the same production system to illustrate the effectiveness of the proposed method and compare the results between the two models.

2. METHOD I: THROUGHPUT-CONSTRAINED MODEL

2.1 Motivation and Introduction

In this chapter, we will introduce the “Just-for-Peak” buffer inventory methodology under the constraint of the system throughput to initially explore the feasibility and potential benefits of the idea. The “Just-for-Peak” buffer inventory is built up during off-peak periods and will be used during peak periods and thus the corresponding upstream machine can be turned off to reduce the energy consumption and power demand during the peak periods. 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 will be established to identify the optimal building policy and energy control action during peak periods. A numerical case study is conducted to illustrate the effectiveness of the “throughput-constrained” model.

2.2 Problem Formulation

Consider a typical tandem production system with n machines and $n-1$ buffers as shown in Figure 4. Buffer B_i , $i=1,\dots,n-1$, is deployed between every two consecutive machines to relieve the throughput impacts caused by the random failures of the machines.

Figure 4. A tandem production line with n machines and $n-1$ buffers

Besides the deployment of regular buffer B_i 's as shown in Figure 4, referring to the method of buffer utilization for preventive maintenance developed by Salameh & 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 's 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 Figure 5. Let J_i , $i=1,\dots,n-1$, denote those additional buffers.

Figure 5. A tandem production line with $n-1$ additional “Just-for-Peak” buffer locations

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 's is high, we can spare and store products in corresponding J_i 's 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 's 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 Figure 6. 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 throughout the production horizon.

Figure 6. “Just-for-Peak” buffer inventory behavior during a production horizon

Let c_i be the consumption rate of “Just-for-Peak” inventory in J_i during the peak periods when demand reduction is implemented. Let J_i^T be the target unit of “Just-for-Peak” inventory

accumulated in J_i that can ensure the production of the corresponding downstream machine not to be influenced when the upstream machine is turned off for peak demand reduction.

In this thesis, a_i is assumed to be an average value that is obtained by an off-line simulation method which utilizes historical reliability data of the whole system. c_i is identified by the cycle time of the downstream machine. It was not considered the random failures during peak periods in this research, and thus c_i is actually a conservative minimal estimation (the cycle time will be longer when random failures are considered). Consequently, J_i^T can be obtained accordingly by equation (1).

$$J_i^T = c_i t_p \quad (1)$$

The average inventory level during the period $T + t_p$ can be obtained by equation (2).

$$I_i = \frac{\frac{J_i^T}{2}T + \frac{J_i^T}{2}t_p}{T + t_p} = \frac{\frac{J_i^T J_i^T}{2 a_i} + \frac{J_i^T J_i^T}{2 c_i}}{T + t_p} = \frac{\frac{(J_i^T)^2}{2 a_i} + \frac{(J_i^T)^2}{2 c_i}}{T + t_p} = \frac{(J_i^T)^2 (a_i + c_i)}{2 a_i c_i (T + t_p)} \quad (2)$$

Hence, the average holding cost of J_i per unit time during a production horizon can be obtained by equation (3).

$$H_i = \frac{h_i (J_i^T)^2 (a_i + c_i)}{2 a_i c_i (T + t_p)} \quad (3)$$

where h_i is the holding cost per unit held per unit time for the “Just-for-Peak” buffer inventory stored in J_i .

The energy cost per unit time throughout the whole production horizon includes the charge of energy consumption (\$/kWh) during off-peak period, and both consumption charge (\$/kWh) and demand charge (\$/kW) during peak period. Note that the deterministic pricing system for the end-use customers is used for calculating the electricity bill cost in this research since in many unregulated markets, customers do not pay based on stochastic real-time price (Wikipedia, 2013). In addition, during the preparation of the paper, the authors have surveyed different electricity rate schedules provided by the utilities (*e.g.*, see Pacific Gas & Electric, 2010) and talked to our industrial partners in the Midwest. To the best of our knowledge, most price systems for the end-users in unregulated market model are fixed with specific TOU rates. Therefore, It can be formulated by equation (4).

$$E_i = \frac{\varphi_i(T)(r_i)C_R + \varphi_i k_i(t_p)C_P + \varphi_i k_i C_D}{T + t_p} \quad (4)$$

where E_i is the total energy cost per unit time of machine i during a production horizon; φ_i is the rated power of machine i ; C_P is on-peak energy consumption charge rate (\$/kWh); C_R is off-peak energy consumption charge rate (\$/kWh); C_D is on-peak demand charge rate (\$/kW); k_i is a set of binary variables to denote the demand reduction decision for machine i during the peak periods, that is, $k_i = \begin{cases} 0, & \text{turn off machine } i \\ 1, & \text{keep machine } i \text{ on} \end{cases}$, and r_i is the availability of machine i which is obtained by equation (5),

$$r_i = \frac{MTBF_i}{MTTR_i + MTBF_i} \quad (5)$$

where $MTBF_i$ is mean time between failures of machine i , and $MTTR_i$ is mean time to repair of machine i . Please note that the transition energy between OFF state and ON state of machine is assumed to be relatively small and thus can be ignored.

The different combinations of pairs of k_i and k_{i+1} ($i=1, \dots, n-1$) imply the different building policies for “Just-for-Peak” buffer inventory. They are discussed as follows.

- 1) $k_i = 1$ and $k_{i+1} = 1$, the “Just-for-Peak” buffer inventory of buffer J_i does not need to be built during off-peak period T since both adjacent upstream machine and downstream machine of buffer B_i will be kept ON during the peak period.
- 2) $k_i = 0$ and $k_{i+1} = 1$, the “Just-for-Peak” buffer inventory of buffer J_i needs to be built during off-peak period T since the adjacent upstream machine of buffer B_i will be turned off and the adjacent downstream machine of buffer B_i has to utilize the “Just-for-Peak” inventory to maintain production during peak period.
- 3) $k_i = 0$ and $k_{i+1} = 0$, the “Just-for-Peak” buffer inventory of buffer J_i does not need to be built during off-peak period T since both adjacent upstream machine and downstream machine of buffer B_i will be turned off for energy consumption reduction during peak period.
- 4) $k_i = 1$ and $k_{i+1} = 0$, the “Just-for-Peak” buffer inventory of buffer J_i does not need to be built during off-peak period T since the adjacent upstream machine of buffer B_i will be

kept on and the adjacent downstream machine of buffer B_i will be turned off during peak period.

The objective of this method is to identify the optimal building policies of the “Just-for-Peak” buffer inventory and corresponding load management actions during the peak period, that is, the value of k_i , $i=1,\dots,n$, by minimizing the sum of the holding cost of “Just-for-Peak” inventory and energy consumption cost during a production horizon without compromising system throughput. In other words, before the production horizon, the building policy of “Just-for-Peak” buffer inventory needs to be determined to identify specific buffer locations B_i 's that are capable of building a paired “Just-for-Peak” inventory in J_i during off-peak period T . Therefore, the problem can be formulated as shown in equation (6).

$$\min TC(k_i) = \min(\sum_{i=1}^{n-1} h_i \left[\frac{(J_i^T)^2 (1-k_i) k_{i+1} (a_i + c_i)}{2a_i c_i (T+t_p)} \right] + \sum_{i=1}^n E_i) \quad (6)$$

where $TC(k_i)$ is the total cost per unit time throughout the production horizon.

Several constraints need be considered.

- 1) The power reduction during the peak periods has to be greater than or equal to the demand reduction requirement, that is,

$$\sum_{i=1}^n \varphi_i (1 - k_i) \geq P_{saving} \quad (7)$$

where P_{saving} is the power reduction requirement during the peak periods. The purpose of this constraint is to solve the problem based on a widely accepted reduction potential from literature to see if the system load management capability can satisfy the expected

potential or not. About 13% of the full load of the system will be used as reduction requirement in our case study based on the result from Faruqui et al (2007) (see Section 3 for details).

- 2) The total units of “Just-for-Peak” buffer inventory accumulated during the period T has to be no less than the target number J_i^T so that the production of the downstream machine will not be influenced and the system throughput can be maintained.

$$a_i T \geq J_i^T (1 - k_i) k_{i+1} \quad (8)$$

- 3) The target “Just-for-Peak” buffer inventory J_i^T has to be less than or equal to the “Just-for-Peak” buffer location capacity.

$$J_i^T (1 - k_i) k_{i+1} \leq J_{imax} \quad (9)$$

where the J_{imax} is capacity of J_i .

- 4) The last machine of the system cannot be turned off; otherwise, the production will be influenced during the peak periods.

$$k_n = 1 \quad (10)$$

By now, it can be formulate a Nonlinear Integer Programming (NIP) with nonlinearities in the objective function (6) and constraints (7)-(10). The classic algorithm for solving NIP formulation is the Branch and Bound approach. It starts with identifying an initial solution of the

relaxation of the original problem for the root node at the top level of an enumeration tree and continues to a separate root node into two or more candidate problems at the lower level if the result of the higher level node is not an integer solution (Floudas, 1995). The prune method is used to guide the direction of the tree by comparing the value of the node to the upper and lower bounds of the function during the process (Diwekar, 2003). Commercial software packages are mature and convenient for this kind of problem solving (Bussieck & Pruessner, 2003). In this research, GAMS (General Algebraic Modeling System) (GAMS, 2013a) platform with the solver Simple Branch & Bound (SBB) is used to solve the problem. SBB is a relatively new GAMS solver based on the combination of the standard Branch and Bound method and some of the standard nonlinear programming (NLP) solvers well known for GAMS. This method tries different solvers with different options before giving up on a node and losing part of the solution space (GAMS, 2013b).

Indeed, NIP problem is very difficult to solve when it is scaled up. In our case, the number of binary variables is equal to the number of the machines in system, which varies in different industries. For example, in a semiconductor fabrication factory, dozens of machines may be deployed (Bai & Gershwin, 1990). In many auto assembly plants, about 50-100 machines may be in one location (Ohno, 1988). In a metal processing plant, the manufacturing system may consist of 10-20 machines with different functionalities. Generally, 100 can be an upper bound of the number of the machines in a typical manufacturing system. Therefore, we set 100 as the upper bound of the number of the binary variables (correspondingly 199 constraints) of this problem to examine the computing time of our formulation. Due to the policy of confidentiality of the industrial partner, it cannot be obtained the complete data set of machine reliability and

buffer capacity of the whole production line with almost 100 machines (the case study in section 3 is only a section of auto assembly line).

However, several similar problems with larger size of variables and constraints (200 variables and 333 constraints) using the solver SBB on the platform GAMS within 12 hours have been solved in the research developed in the Sustainable Manufacturing System Research Laboratory . Therefore, we infer that the computing time for the proposed formulation with the largest layout setting (100 machines) is still acceptable in practice since the solution is not required to be obtained on a real-time basis.

2.3 Case Study

In order to illustrate the effectiveness of Method I, a section of an automotive assembly line with seven machines and six buffers is studied as shown in Figure 7.

Figure 7. A seven-machine and six-buffer serial production system

The basic settings of the machines in this manufacturing system, including cycle time, mean time between failures (MTBF), mean time to repair (MTTR), and rated power are recorded in Table I (Note that the cycle time, MTBF, and MTTR are the real data from our industrial partner, while the rated power is assumed).

TABLE I.
BASIC SETTING OF THE MACHINES

Machine	Cycle Time (min)	MTBF (min)	MTTR (min)	Power (kW)
1	0.455	100.0	4.95	14
2	0.492	45.6	11.7	24
3	0.473	98.8	16.0	14
4	0.489	217.5	27.3	15
5	0.483	109.4	18.4	25
6	0.469	107.7	15.6	25
7	0.482	127.5	19.98	13

The buffer related parameters, *i.e.*, buffer capacity for both regular and additional buffer locations, accumulation rate, consumption rate, initial content for regular buffers, and holding cost for additional buffers are shown in Table II (please note that the capacity and initial contents

of the regular buffer are the real data from our industrial partner, and the rest information is obtained by either assumption or simulation).

TABLE II.
PARAMETERS OF THE BUFFERS

Buffer	Capacity of B_i (unit)	Initial contents of B_i (unit)	Capacity of J_i (unit)	Accumulation rate, a_i (unit/hour)	Consumption rate, c_i (unit/hour)	Holding cost H_i (\$/unit/hour)
1	70	32	70	34.3	122	0.05
2	80	30	80	12.1	127	0.05
3	50	40	50	5.9	123	0.05
4	42	30	42	0.2	125	0.05
5	45	42	45	0.1	128	0.05
6	90	30	90	0.1	125	0.05

The information about the peak and off-peak periods is assumed and illustrated in Table III. The demand reduction requirement is set to be about 13 percent of the full load of the production system as shown in Table III. It is based on the estimation of the reduction potential of peak power demand due to the effective load management programs by Faruqi et al. (2007). In addition, the electricity rates from the actual bill of our industrial partner are shown in Table IV. The target units of “Just-for-Peak” inventory (J_i^T) are identified and shown in Table V.

TABLE III.
PRODUCTION HORIZON AND REDUCTION REQUIREMENT

Duration of off-peak period T (hour)	Duration of peak period t_p (hour)	Demand reduction requirement P_{saving} (kW)
7.5	0.5	16

TABLE IV.
ELECTRICITY RATE

On peak demand charge rate C_D (\$/kW)	On peak electricity consumption charge rate C_P (\$/kWh)	Off-peak electricity consumption charge rate C_R (\$/kWh)
9.58	0.029	0.016

TABLE V.
TARGET UNITS OF “JUST-FOR-PEAK” INVENTORY

Additional Buffer	Target of “Just-for- Peak” inventory $(J_i^T)(\text{unit})$
1	61
2	64
3	62
4	63
5	64
6	63

First, we examine the linear assumption of a_i by simulation. The Figure 8 shows the buffer accumulation curve of buffer 1, buffer 2, and buffer 3 (Note that the accumulation rate of buffer 4, buffer 5 and buffer 6 is so small that can be ignored). It can be seen that the mean of the simulation result of the accumulated buffer at the end of different time periods (diamond legends) can be approximately fitted into a straight line with high R-Square value. In addition, all the calculated results of accumulated buffer based on the linear assumption (triangle legends) fall into the 95% confidence interval of the simulation results.

Figure 8. Comparison between the assumed buffer accumulation and simulation results

Then GAMS with solver SBB is used to solve the NIP problem (6) with constraints (7)-(10) to obtain the optimal value of the objective function (6) and the corresponding decision

variables k_i 's denoting the status of each machine during peak periods as shown in Figure 9 and Table VI. Then, ProModel® is used to simulate the manufacturing system as shown in Figure 10,11 and 12 using the data in Table I and Table II with all the decision variables obtained by GAMS.

Final Thesis.gms Final Thesis.lst Part (2) Constant.gms Part (2) Constant.lst Untitled_6.gms Untitled_6.lst					
<div> <div> <div>Compilation</div> <div>Equation Listing</div> <div>Equation</div> <div>Column Listing</div> <div>Column</div> <div>Model Statistics</div> <div>Solution Report</div> <div>SolveEQ</div> <div>SolveVAR</div> <div>z</div> <div>k1</div> </div> <div> <div>SOLVE buffer Using MINLP From line 45</div> <div>SOLVE buffer Using MINLP From line 45</div> <div>SOLVE buffer Using MINLP From line 45</div> <div>SOLVE buffer Using MINLP From line 45</div> </div> </div>					
i1	-INF	.	0.487	.	
i2	-INF	.	0.480	.	
i3	-INF	-0.050	0.450	.	
i4	-INF	-0.080	0.420	.	
i5	-INF	-0.040	0.460	.	
i6	-INF	-0.060	0.440	.	
i7	-INF	-20.000	-19.500	.	
<div> <div>LOWER</div> <div>LEVEL</div> <div>UPPER</div> <div>MARGINAL</div> </div>					
----	VAR z	-INF	113.180	+INF	.
z Total cost					
----	VAR k1	status of machine i			
		LOWER	LEVEL	UPPER	MARGINAL
i1	.	.	1.000	16.790	
i2	.	.	1.000	28.059	
i3	.	1.000	1.000	15.815	
i4	.	1.000	1.000	-36.036	
i5	.	1.000	1.000	-98.117	
i6	.	1.000	1.000	-94.148	
i7	.	1.000	1.000	15.591	
<div> <div>**** REPORT SUMMARY :</div> <div>0 NONOPT</div> <div>0 INFEASIBLE</div> <div>0 UNBOUNDED</div> <div>0 ERRORS</div> </div>					

Figure 9. Snapshot of the case study results obtained by GAMS.

Figure 10. Snapshot of the case study simulation by ProModel®

Figure 11. Snapshot of the "Just-For-Peak" Buffer accumulation in ProModel®

Figure 12. Snapshot of the case study results obtained by ProModel®

TABLE VI.

OPTIMIZATION RESULTS OF THE WHOLE SYSTEM FOR METHOD I

Machine	Status during peak period, k_i	“Just-for-Peak” inventory (J_i)(units)	Total cost per unit of time (\$/hour)
1	0	0	113.18
2	0	64	
3	1	0	
4	1	0	
5	1	0	
6	1	0	
7	1	0	

Thirty replications of an eight-hour shift were studied in simulation. Both baseline model (no power reduction is implemented during peak period) and a model using Method I were

examined. Table VII shows the results of the throughput and the power demand during peak period for both models. Table VIII illustrates the electricity bill comparison between the two models. It can be observed that about 20.1% power demand can be reduced during peak periods and 20.1% saving of bill charge can be achieved. The difference of the throughput between the two models is negligible. Finally, Table IX shows the electricity, holding and total charge for both models.

TABLE VII.

COMPARISON OF THE THROUGHPUT AND POWER CONSUMPTION BETWEEN
BASELINE MODEL AND POWER METHOD I

Model	Throughput (unit) (95% C.I)	Power during peak period (kW) (95% C.I)	Demand reduction (kW) (95% C.I)	Average demand reduction (%)
Baseline Model	699.96 (673.96, 726.02)	116.62 (112.93, 120.32)	23.41 (19.63, 27.19)	20.1%
Method I	698.77 (666.99, 730.53)	93.21 (93.13, 93.30)		

TABLE VIII.

COMPARISON OF THE ELECTRICITY BILL BETWEEN BASELINE MODEL AND
METHOD I

Model	Energy consumption charge (\$) (95% C.I)	Demand charge (\$) (95% C.I)	Total charge(\$) (95% C.I)	Charge reduction (\$) (95% C.I)	Average charge reduction (%)
Baseline Model	1.69 (1.64, 1.74)	1117.22 (1081.87, 1152.67)	1118.91 (1083.51, 1154.41)	224.61 (188.34, 260.87)	20.1%
Method I	1.351 (1.350, 1.353)	892.95 (892.19, 893.81)	894.30 (893.54, 895.17)		

TABLE IX.

COMPARISON OF THE TOTAL COST BETWEEN BASELINE MODEL AND METHOD I

Model	Electricity charge(\$)	Holding Charge (\$)	Total Charge (\$)	Reduction (%)
Baseline Model	1118.91	0	1118.91	
Method I	894.30	9.26	903.57	19.2

2.4 Conclusions

The above methodology shows that the “Just-for-Peak” buffer philosophy can be successfully applied in typical manufacturing systems with multiple machines and buffers without influencing the system throughput. The case study in Section 2.3 illustrates that the total electricity charge and the overall cost can decrease by 20.1% and 19.2%, respectively.

METHOD II: THROUGHPUT CONSTRAINT RELAXED MODEL

3.1 Motivation and Introduction

In Chapter 2, the methodology to reduce the power demand during peak periods is proposed under the constraint of the system throughput. In section 2.3, it can be observed that machine 3, 4, 5, and 6 cannot be turned off during the peak periods to reduce the peak power due to the low accumulation rate of the downstream “Just-for-Peak” buffer. In other words, the constraint described in (8) cannot be satisfied. It can be seen that the method actually only considers turning off the machine during the whole peak-load periods. However, it would be much more promising to also allow machines off-time for only part of the peak-periods.

In this chapter, the methodology proposed in Chapter 2 will be further advanced by relaxing the constraint in (8). It allows the option of building a “Just-for-Peak” buffer inventory J_i with less units than its corresponding J_i^T , and thus J_i may run out before the ending of the peak periods. In that case, we may either resume the operation of the upstream machine i to maintain the production or keep the upstream machine i being off. The first option may increase the energy cost while maintain the throughput. It can be implemented under the condition that either additional “Just-for-Peak” buffer inventory is built in J_{i-1} or machine $i-1$ is determined to keep production during the peak periods and so the resumption of the operation of machine i can be ensured. The second option may decrease the energy cost while incurring production loss, and thus the cost due to the production loss need be integrated.

Therefore, the purpose of “Just-for-Peak” buffer inventory described in this chapter is expanded for either 1) turning off the upstream machine i and maintain the production of downstream machine $i+1$ at the beginning of the peak periods or 2) resuming the operation of the

downstream machine $i+1$ when the downstream “Just-for-Peak” buffer inventory J_{i+1} runs out and the upstream machine $i-1$ is turned off at the beginning of the peak period.

It can be seen that the problem is more complex than the model introduced in Chapter 2. Intuitively, we can see that more energy control actions will be available, however, the tradeoff between the potential production loss, the energy cost, and the additional holding cost of the buffer to ensure the production resumption, also need be carefully considered.

3.2 Problem Formulation

The basic configurations of the production system that will be modeled are same as the ones we introduce in Chapter 2. A typical n -machine- $n-1$ buffer tandem production system with $n-1$ “Just-for-Peak” buffer locations is considered (see Figure 4 and 5). The production horizon includes a scheduled off-peak period T and a follow-up scheduled peak period t_p with both known durations. The accumulation rate and consumption rate of the “Just-for-Peak” buffer J_i are a_i and c_i , respectively.

We begin with the focusing on the purpose for turning off the upstream machine m_i and maintain the production of downstream machine $i+1$ at the beginning of the peak periods. Let J_i^C be the maximum capable accumulated buffer inventory in “Just-for-Peak” buffer J_i during off peak period T . It can be formulated by (11)

$$J_i^C = a_i T \quad (11)$$

Define function $W(i)$ by (12) to describe the relationship between J_i^C and J_i^T .

$$W(i) = \begin{cases} 1, & \text{if } J_i^C < J_i^T \\ 0, & \text{if } J_i^C \geq J_i^T \end{cases} \quad (12)$$

Figure 13 illustrates the new cycle of the change of the “Just-for-Peak” buffer inventory when $W(i) = 1$.

Figure 13. “Just-for-Peak” buffer inventory behavior during a production horizon when $W(i) = 1$

Consider the relationship in (12), the average inventory level can be obtained by (13)

$$I_i^1 = \frac{\frac{\min(J_i^T, J_i^C)}{2} T + \frac{\min(J_i^T, J_i^C)}{2} T_c}{T + t_p} = \frac{\frac{(\min(J_i^T, J_i^C))^2}{2a_i} + \frac{(\min(J_i^T, J_i^C))^2}{2c_i}}{T + t_p} \quad (13)$$

where T_c is corresponding consumption time which may be less than t_p . Likewise, the average holding cost per unit time during a production horizon can be obtained by equation (14).

$$H_i^1 = h_i \left[\frac{\frac{(\min(J_i^T, J_i^C))^2}{2a_i} + \frac{(\min(J_i^T, J_i^C))^2}{2c_i}}{T + t_p} \right] \quad (14)$$

It can be seen from Figure 13 that the accumulated buffer J_i^C may run out before the ending of the peak periods and thus the upstream machine i will have the option to either resume operation or remain inactive. Let function $V(k_i)$ to describe these two scenarios:

$$V(k_i) = \begin{cases} 1, & \text{if } k_i=0, k_{i+1}=1, W(i)=1, \text{ machine } i \text{ resumes operation when } J_i \text{ runs out} \\ 0, & \text{otherwise} \end{cases} \quad (15)$$

To ensure the resumption of the operation of machine i , we consider two policies as follows: 1) “Just-for-Peak” buffer inventory in J_{i-1} need be built with the exact buffer level to ensure the production after operation resumption during peak periods; or 2) machine $i-1$ need be kept on throughout the whole peak periods (in other word, let k_{i-1} be equal to 1).

Let J_i^R be the exact buffer level built in “Just-for-Peak” buffer location J_i for the purpose of operation resumption of machine $i+1$. It can be formulated by (16)

$$J_i^R = a'_i \cdot T \quad (16)$$

where a'_i is the desired accumulation rate that can exactly build up the “Just-for-Peak” buffer inventory level in location J_i to ensure the production of machine $i+1$ during the period between the resumption of the operation and the end of the peak periods. It can be formulated by (17)

$$a'_i = \frac{c_i[t_p - \frac{\min(J_{i+1}^T, J_{i+1}^C)}{c_{i+1}}]}{T} \quad (17)$$

Figure 14. “Just-for-Peak” buffer inventory behavior during a production horizon for resuming operation.

Figure 14 describes the behavior of the “Just-for-Peak” buffer inventory J_i for the purpose of resuming operation of machine $i+1$.

The average inventory level associated with the buffer required for resuming machine operation can be obtained by (18)

$$I_i^2 = \frac{\frac{J_i^R}{2}T + J_i^R T_h + \frac{J_i^R}{2}T_c}{T + t_p} = \frac{\frac{J_i^R J_i^R}{2 a'_i} + J_i^R \left(t_p - \frac{J_i^R}{c_i} \right) + \frac{J_i^R J_i^R}{2 c_i}}{T + t_p} = \frac{\frac{(J_i^R)^2}{2 a'_i} + J_i^R \left(t_p - \frac{J_i^R}{c_i} \right) + \frac{(J_i^R)^2}{2 c_i}}{T + t_p} \quad (18)$$

where T_h is the time period of holding the built up inventory J_i^R and T_c is the duration when the built up inventory J_i^R is used. The average holding cost per unit time during a production horizon for J_i^R can be obtained by equation (19).

$$H_i^2 = h_i \frac{\frac{(J_i^R)^2}{2a_i} + J_i^R \left(t_p - \frac{J_i^R}{c_i} \right) + \frac{(J_i^R)^2}{2c_i}}{T + t_p} \quad (19)$$

In summary, consider the purposes altogether, the holding cost for the system can be formulated by (20)

$$H_i^T = h_i \frac{\frac{(\min(J_i^T, J_i^C))^2}{2a_i} + \frac{(\min(J_i^T, J_i^C))^2}{2c_i}}{T + t_p} (1 - k_i)k_{i+1} + h_i \frac{\frac{(J_i^R)^2}{2a_i} + J_i^R \left(t_p - \frac{J_i^R}{c_i} \right) + \frac{(J_i^R)^2}{2c_i}}{T + t_p} (1 - k_i)V(k_{i+1}) \quad (20)$$

In the same way, the energy cost per unit time throughout the whole production horizon can be formulated by the function of k_i , $W(i)$ and $V(i)$. Similarly to Method I, the energy cost includes the charge of energy consumption during off-peak period, and both consumption charge and demand charge during peak period as well. It can be formulated by (21).

$$E_i = \frac{\left(\varphi_i(T)(t_i)C_R + \varphi_i(t_p)C_P k_i + \varphi_i k_i C_D + (1 - k_i)k_{i+1}W(i)V(k_i) \left[\varphi_i(t_p - \frac{\min(J_i^T, J_i^C)}{c_i})C_P + [\varphi_i(t_p - \frac{\min(J_i^T, J_i^C)}{c_i})_i / t_p]C_D \right] \right)}{T + t_p}$$

(21)

It can be seen that the main difference is the inclusion of the energy cost for the machines that will resume operations during the peak period as shown in the fourth item of the numerator of (21).

Finally, we have to formulate an additional cost item to describe the possible production loss when $V(k_i)$ is equal to 0 and $W(i)$ is equal to 1. It can be formulated by (22)

$$P_i = W(i)[1-V(k_i)]\left[\frac{c_i g_i(t_p - \frac{\min(J_i^T, J_i^C)}{c_i})}{(T + t_p)}(1 - k_i)\right] \quad (22)$$

where g_i is the cost per unit production loss per unit time (\$/production loss per unit time). (Note that we assume that the resumption can only be implemented if either the upstream buffer is capable of supporting the resumption operation for the whole resumption period or the upstream machine keeps on during the peak periods, thus we need not consider the production loss due to the situation that the buffer accumulated cannot support the whole periods of the resumption.)

By now, Method II have different combinations of k_i , k_{i+1} ($i = 1, \dots, n-1$), and $V(k_i)$, the combinations of these variables will define the different building policies for “Just-for-Peak” buffer inventory, as we discussed as follows.

- 1) $k_i = 0$, $k_{i+1} = 1$, $W(i) = 0$, and $V(k_i) = 0$: the “Just-for-Peak” buffer inventory of buffer

J_i needs to be built during off-peak period T since the adjacent upstream machine i will be turned off for the whole peak period t_p and the adjacent downstream machine $i+1$

has to utilize the “Just-for-Peak” inventory to maintain production during peak period t_p . The buffer built during off-peak period T will be enough to maintain the consumption of the downstream machine during the peak period t_p without any harm to the throughput.

- 2) $k_i = 0$, $k_{i+1} = 1$, $W(i) = 1$, and $V(k_i) = 0$: the “Just-for-Peak” buffer inventory of buffer J_i needs to be built during off-peak period T since the adjacent upstream machine i will be turned off for the whole peak period t_p and the adjacent downstream machine $i+1$ has to utilize the “Just-for-Peak” inventory. The buffer built during off-peak period T will not be enough to maintain the consumption of the downstream machine $i+1$ during the whole peak period t_p , and the corresponding upstream machine i will not resume operation when the “Just-for-Peak” buffer inventory runs out. Consequently, the throughput will be affected.
- 3) $k_i = 0$, $k_{i+1} = 1$, $W(i) = 1$, and $V(k_i) = 1$: the “Just-for-Peak” buffer inventory of buffer J_i needs to be built during off-peak period T since the adjacent upstream machine i will be turned off and the adjacent downstream machine $i+1$ has to utilize the “Just-for-Peak” inventory. The buffer built during off-peak period will not be enough to maintain the consumption of the downstream machine $i+1$ during the whole peak period t_p , and the upstream machine i will resume operation. In this case the throughput will be maintained.

- 4) $k_i = 0$, $k_{i+1} = 0$, and $V(k_{i+1}) = 1$: the “Just-for-Peak” buffer inventory of buffer J_i needs to be built during off-peak period T to support the resumption of the operation of machine $i+1$.
- 5) $k_i = 1$, $k_{i+1} = 0$, and $V(k_{i+1}) = 1$: the “Just-for-Peak” buffer inventory of buffer J_i does not need to be built during off-peak period T since the resumption of the operation of machine $i+1$ can be supported by the operation of machine i .

For the rest of the possible cases, *e.g.*, $k_i = 1$ and $k_{i+1} = 0$, $k_i = 1$ and $k_{i+1} = 1$, the inventory building policies are same as the ones that have already been explained in Chapter 2.

At this point, the new objective function can be obtained by (23).

$$\min_{i=1, \dots, n-1} TC(k_i, V(k_i)) = \min \left(\sum_{i=1}^{n-1} H_i + \sum_{i=1}^n E_i + \sum_{i=1}^{n-1} P_i \right) \quad (23)$$

where $TC(k_i, V(k_i))$ is the total cost per unit time throughout the production horizon.

The objective function will identify the optimal building policies of the “Just-for-Peak” buffer inventory and the load management actions required for the peak period. It includes the decision variables of k_i and $V(k_i)$ to minimize the summation of the holding cost of the “Just-for-Peak” inventory, the energy consumption cost and the potential production loss cost during a production horizon. For each possible combination of the load management, we can obtain J_i as follows.

$$J_i = \begin{cases} \min(J_i^C, J_i^T), & \text{if } J_i \text{ is used for turning off upstream machine } i \\ J_i^R, & \text{if } J_i \text{ is used for resuming downstream machine } i+1 \end{cases} \quad (24)$$

Additionally, several constraints need to be considered as follows.

- 1) Similar to the throughput-onstrained model in Chapter 2, the power reduction during the peak period has to be greater than or equal to the demand reduction requirement. It is described by (25).

$$\sum_{i=1}^n \left(\varphi_i (1 - k_i) \frac{J_{i-1}}{c_{i-1}} + \varphi_i (1 - V(k_i)) (1 - k_i) \left(t_P - \frac{J_{i-1}}{c_{i-1}} \right) \right) \geq P_{saving} t_P \quad (25)$$

- 2) The target “Just-for-Peak” buffer inventory J_i has to be less than or equal to the “Just-for-Peak” buffer location capacity.

$$J_i \leq J_{i \max} \quad (26)$$

- 3) The following constraint states that machine $i+1$ can resume operation if either the upstream machine i keeps in operation during the peak periods or the capable accumulation of the upstream “Just-for-Peak” buffer inventory is equal or more than J_i^R

$$V(k_{i+1})(J_i^C - J_i^R)(1 - k_i) \geq 0 \quad (27)$$

By now, we can formulate a Nonlinear Integer Programming (NIP) with nonlinearities in the objective function and corresponding constraints, as in Method I. The Branch and Bound

approach is also used to solve this formulation (Floudas, 1995). Same as before, commercial software packages are mature and convenient for this type of formulations and we will use GAMS (General Algebraic Modeling System) (GAMS, 2013a) platform with the solver Simple Branch & Bound (SBB) to solve the NIP problem.

3.3 Case Study

To illustrate the effectiveness of the model proposed in Chapter 3, the same section of the automotive assembly line with seven machines and six buffers as we use in Chapter 2 is studied as shown in Figure 15.

Figure 15. A seven-machine and six-buffer serial production system

In Table X the same basic settings of the machines such as cycle time, mean time between failures (MTBF), mean time to repair (MTTR), and rated power are illustrated.

TABLE X.

BASIC SETTING OF THE MACHINES

Machine	Cycle Time (min)	MTBF (min)	MTTR (min)	Power (kW)
1	0.455	100.0	4.95	14
2	0.492	45.6	11.7	24
3	0.473	98.8	16.0	14
4	0.489	217.5	27.3	15
5	0.483	109.4	18.4	25
6	0.469	107.7	15.6	25
7	0.482	127.5	19.98	13

Table XI shows the buffer capacity for regular and additional buffer locations, accumulation rates, consumption rate, initial content for regular buffers, and holding cost for additional buffers. The accumulation rate to ensure the operation resumption a'_i is also included.

TABLE XI.
PARAMETERS OF THE BUFFERS

Buffer	Capacity of B_i (unit)	Initial contents of B_i (unit)	Capacity of J_i (unit)	Accumulation rate, a_i (unit/hour)	Resuming accumulation rate, a'_i (unit/hour)	Consumption rate, c_i (unit/hour)	Holding cost H_i (\$/unit/hour)
1	70	32	70	34.3	-	122	0.05
2	80	30	80	12.1	2.4	127	0.05
3	50	40	50	5.9	8.0	123	0.05
4	42	30	42	0.2	8.2	125	0.05
5	45	42	45	0.1	8.4	128	0.05
6	90	30	90	0.1	8.3	125	0.05

The peak information and the electricity rates from the actual bill of our industrial partner are also maintained as shown in Table XII and Table XIII respectively in order to compare results with the throughput-constrained model in Chapter 2. The property of different “Just-for-Peak” buffer inventories is shown in Table XIV.

TABLE XII.
PRODUCTION HORIZON AND REDUCTION REQUIREMENT

Duration of off-peak period T (hour)	Duration of peak period t_p (hour)	Demand reduction requirement P_{saving} (kW)
7.5	0.5	16

TABLE XIII.
ELECTRICITY RATE

On peak demand charge rate C_D (\$/kW)	On peak electricity consumption charge rate C_P (\$/kWh)	Off-peak electricity consumption charge rate C_R (\$/kWh)
9.58	0.029	0.016

TABLE XIV.
PROPERTY OF “JUST-FOR-PEAK” BUFFERS INVENTORIES

Additional Buffer	Target of “Just-for-Peak” inventory (U_i^T)(unit)	Capable “Just-for-Peak” inventory (U_i^C)(unit)	Resuming “Just-for-Peak” inventory (U_i^R)(unit)	$W(i)$
1	61	257	-	0
2	64	90	18	0
3	62	44	60	1
4	63	1	62	1
5	64	0	63	1
6	63	0	63	1

Finally, the costs per production loss per unit time for every machine are assumed as shown in Table XV.

TABLE XV.
COST RATE OF PRODUCTION LOSS

Machine	Production shortage cost per unit time (g_i)(\$/production loss per unit time)
1	10
2	20
3	80
4	20
5	20
6	20
7	50

Then GAMS with solver SBB is used again to solve the objective function (23) with its corresponding constraints to finally obtain the total cost per unit time, the binary variables k_i , $V(k_i)$ and the corresponding “Just-for-Peak” buffer inventories. The results are shown in Table XVI.

TABLE XVI.
OPTIMIZATION RESULTS OF THE METHOD II

Machine	k_i	$V(k_i)$	“Just-for-Peak” inventory (J_i)(unit)	Total cost per unit of time (\$/hour)
1	0	0	0	101.43
2	0	0	18	
3	0	1	44	
4	1	0	0	
5	1	0	0	
6	1	0	0	
7	1	0	0	

Then, the same simulation model in ProModel® is used to implement the new load management actions obtained by GAMS. In the same way, thirty replications of an eight-hour shift were studied. The comparison of the results of the throughput and the power demand during the peak period among the Baseline model, throughput-constrained model as described in Chapter 2 and the throughput constraint relaxed model proposed in this chapter are illustrated in Table XVII. The comparison of the electricity bill cost among the three models is shown in Table XVIII.

TABLE XVII.

COMPARISON OF THE THROUGHPUT AND POWER CONSUMPTION AMONG
BASELINE MODEL, METHOD I, AND METHOD II

Model	Throughput (unit) (95% C.I)	Power during peak period (kW) (95% C.I)	Demand reduction (kW) (95% C.I)	Average demand reduction (%)
Baseline Model	699.96 (673.96, 726.02)	116.62 (112.93, 120.32)	23.41 (19.63, 27.19)	20.1%
Method I	698.77 (666.99, 730.53)	93.21 (93.13, 93.30)		
Method II	688.90 (661.57, 715.69)	89.33 (89.22, 89.44)	27.29 (23.49, 31.10)	23.4%

TABLE XVIII.

COMPARISON OF THE ELECTRICITY BILL AMONG BASELINE MODEL, METHOD I,
AND METHOD II

Model	Energy consumption charge (\$) (95% C.I)	Demand charge (\$) (95% C.I)	Total charge (\$) (95% C.I)	Charge reduction (\$) (95% C.I)	Average charge reduction (%)
Baseline	1.69	1117.22	1118.91		
Model	(1.64, 1.74)	(1081.87, 1152.67)	(1083.51, 1154.41)	224.61 (188.34, 260.87)	20.1%
Method I	1.351 (1.350, 1.353)	892.95 (892.19, 893.81)	894.30 (893.54, 895.17)		
Method II	1.295 (1.293, 1.297)	855.78 (854.72, 856.83)	857.08 (856.02, 858.13)	261.83 (225.37, 298.39)	23.4%

It can be observed that compared with the baseline model about 23.4% power demand can be reduced during peak periods and 23.4% saving of bill charge can be achieved with the method developed in this chapter. The difference of the throughput among the three models is not

significant. Finally, Table IXX shows the comparison of the overall cost for all the models studied above. It can be seen that the method developed in this chapter can achieve about 22.6% cost reduction compared to the baseline model, which is 3.4 percentages better than the result of the method in Chapter 2.

TABLE XIX.

COMPARISON OF THE TOTAL COST AMONG BASELINE MODEL, METHOD I, AND METHOD II

Model	Electricity charge(\$)	Holding Charge (\$)	Production Shortage Charge (\$)	Total Charge (\$)	Reduction (%)
Baseline Model	1118.91	0	0	1118.91	
Method I	894.30	9.26	0	903.57	19.2
Method II	855.78	9.41	0	865.19	22.6

3.4 Conclusions

The case study for method developed in this chapter illustrates that 23.4% of power reduction and the bill charge saving can be achieved compared with the baseline model. As for the overall cost, 22.6% reduction can be achieved compared with the baseline model. It also can be seen that the performance is better than the method developed in chapter 2 due to its high flexibility of load management actions.

CONCLUSIONS AND FUTURE WORK

This thesis proposes a novel method to reduce power demand during peak periods for a typical manufacturing system with multiple machines and buffers by utilizing “Just-for-Peak” buffer inventory that is built up during off-peak periods. Two models, *i.e.*, throughput-constrained model, and the throughput constraint relaxed model are investigated. The optimal building policy of “Just-for-Peak” buffer inventory and load management actions are identified by minimizing the sum of the holding cost of “Just-for-Peak” buffer inventory and the energy consumption cost throughout the production horizon for the throughput-constrained model. The cost due to the potential production loss is further integrated into the objective function for the throughput constraint relaxed model.

Nonlinear Integer Programming framework is used to establish the mathematical model. The case study of the throughput-constrained model illustrates that 1) about 20% power demand reduction during peak periods and the bill charge saving can be achieved; 2) 19.2% reduction of overall cost can be achieved; and 3) the system throughput is well maintained. The case study of the throughput constraint relaxed model illustrates that 1) about 23.4% power demand reduction during peak periods and bill charge saving can be achieved; 2) 22.6% reduction of overall cost can be achieved; and 3) the system throughput is well maintained. The results illustrate the feasibility and potentials of the electricity load management for the manufacturing enterprises. Both economic and environmental benefits can be obtained by effective methodologies. It represents a pilot study of the electricity load management implementation from the manufacturer customer point of view.

In the future, the real time decision-making about the dynamic control of the machine energy state during peak periods can be considered. The state-based decision-making need be implemented and the stochastic factors including the random failures of the machines need be modeled. The analytical method to calculate the accumulation rate a_i 's for specific short periods on a real-time basis can be developed to identify the potential of the power demand reduction in specific load management program that the beginning time is usually issued with a short notice.

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