Cost-Effective Energy Integrated Production Scheduling in Sustainable Manufacturing Systems

BY

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THESIS

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TABLE OF CONTENTS

CHAPTER PAGE

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

LIST OF ABBREVIATIONS

AEMA	Advanced Energy Management Alliance
CPP	Clean Power Plan
CPP	Critical-peak period
EIA	Energy Information Administration
EnerNOC	Energy Network Operations Center
EPA	Environmental Protection Agency
GAMS	General Algebraic Modeling System
IPCC	Inter-governmental Panel on Climate Change
LTRA	Long Term Reliability Assessment
MINLP	Mixed Integer Nonlinear Programming
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
RTP	Real-Time pricing
TOU	Time-of-use

SUMMARY

The increasing temperature of the earth has been a major concern to scientist, and the world at large. This increase is the result of huge amount of greenhouse gas emission, which mainly consists of carbon dioxide. The manufacturing sector is considered a major contributor to the carbon dioxide emissions and energy consumption. In the manufacturing sector, many studies have been implemented to conduct energy management, analyze the cost, and optimize production schedule to reduce productivity related cost, energy cost and energy consumption. The related literature has been reviewed. However, these existing studies are usually conducted separately, while the interconnections among the three aspects have rarely been considered. There still lacks an overall cost-effective energy management model that considers minimizing both energy cost and productivity cost. In this thesis, a cost-effective energy-integrated production scheduling model is proposed for a typical manufacturing system with multiple machines and buffers. A mathematical model is developed using Mixed Integer Nonlinear Programming (MINLP). The objective function of the model is to determine the optimal production schedule that can minimize both energy and productivity-related costs in the production system under the constraint of fulfilling production target. A numerical case study is developed to illustrate the efficacy of the proposed model. The results of the model indicate that the energy-integrated production scheduling model can reduce both energy cost and productivity related cost from an overall perspective.

1. INTRODUCTION

The earth's climate is consistently changing. The Environmental Protection Agency (EPA) of the United States recorded that, " the earth's average temperature has risen by 1.4 degrees Fahrenheit in the past century and is projected to rise another 2 to 11.5 degrees Fahrenheit over the next hundred years" (EPA, 2014). The year of 2014 has been recognized as the warmest year of the earth since record-keeping began in 1880 by two separate analyses by National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) (NASA, 2015).

Approximately 97.5% of climatologists who have published research on climate change recently have acknowledged that the change in the earth temperature over the past century is mostly due to human activities (W. R. L. Anderegg et al., 2010). The Inter-governmental Panel on Climate Change (IPCC) also stated that with 95% confidence that humans are the main cause of current global warming (IPCC, 2014).

The major reason that leads to this global warming trend is the huge amount of greenhouse gas emissions. The predominant sources of the increase in greenhouse gases are carbon dioxide which is resulted from the combustion of fossil fuels and industrialization (EPA, 2014). Human activities like deforestation and fossil fuel combustion over the past century have emitted enormous amounts of carbon dioxide into the atmosphere. It leads to global warming and results in adverse effects on human welfare and ecosystems. Figure 1 illustrates the proportion of carbon dioxide emission compared with other greenhouse gases based on 2004 data from IPCC. As seen in Figure 1, 77%

of the gases emitted were carbon dioxide, 57% of which were emitted due to fossil fuel combustion.

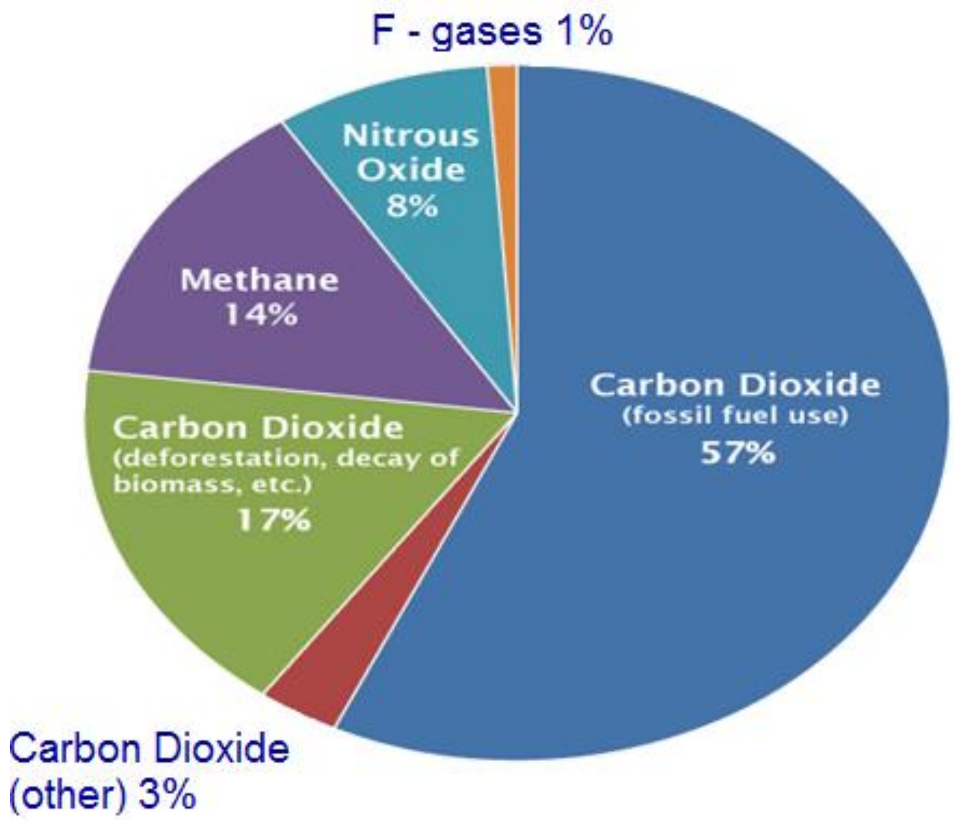


Figure 1: Chart Based on Global Emission of Greenhouse Gases from 2004

Source: http://www.epa.gov/climatechange/ghgemissions/global.html

Figure 2 illustrates the global emission of carbon dioxide from 1995 to 2013. As seen in Figure 2, a near constant increase can be observed, with emissions as high as 36.13 billion metric tons in 2013. Figure 3 illustrates the carbon emission from energy consumption in the United States between 1975 and 2014. It is seen from the chart that in 2013, the United States recorded carbon emission of approximately 5.4 billion metric tons as a result of energy use.

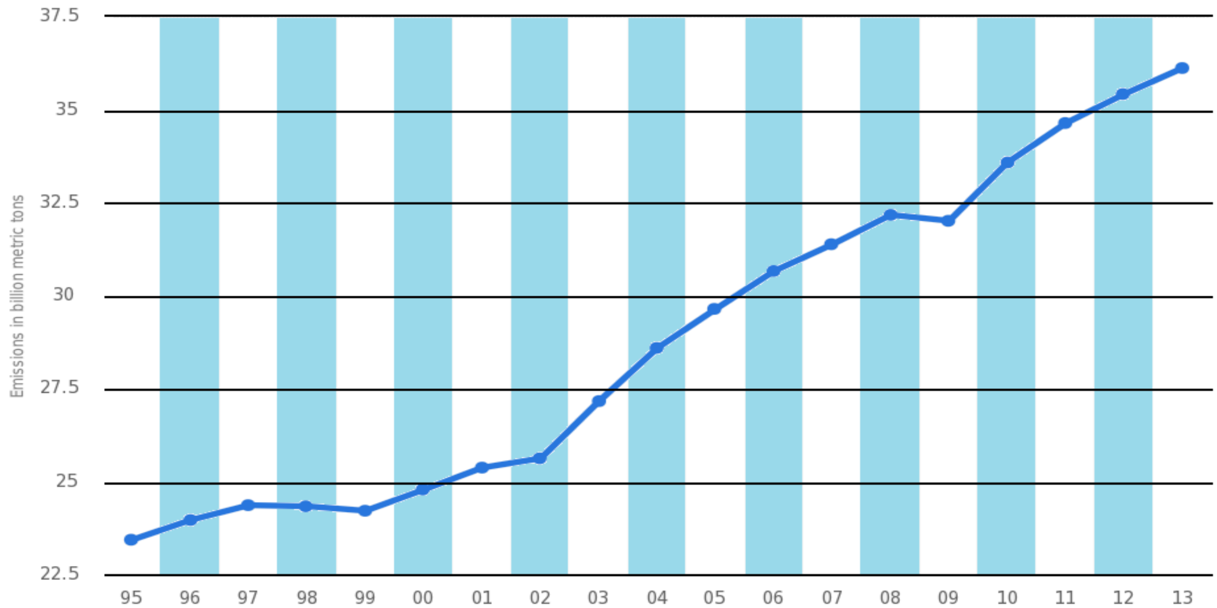


Figure 2: Global Carbon dioxide Emission from 1995 to 2013 (in billion metric tons)

Image source: http://www.statista.com/statistics/276629/global-co2-emissions/

Data source: Carbon dioxide Information Analysis Data (CDIA), 2014

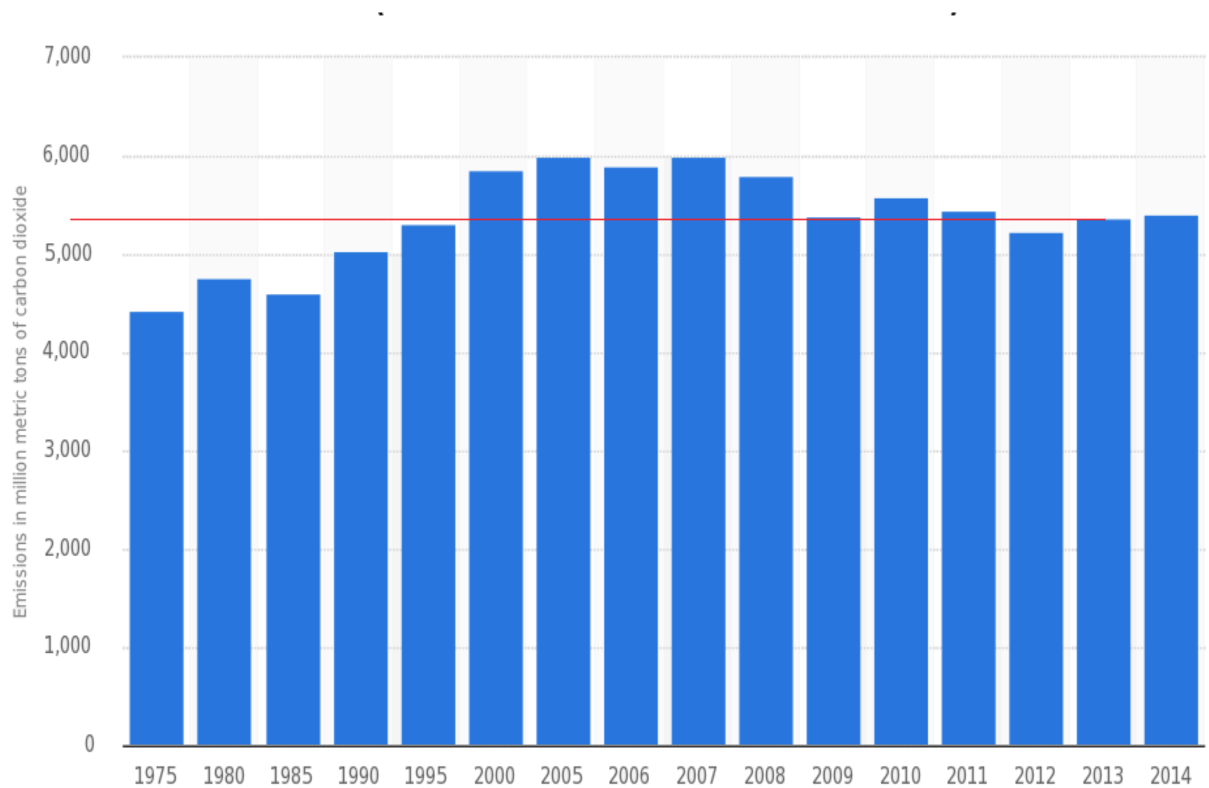


Figure 3: Total U.S Carbon dioxide Emissions from Energy Consumption between 1975 and 2014 (in million metric tons of carbon dioxide)

Image source: http://www.statista.com/statistics/183943/us-carbon-dioxide-emissions-from-1999/

Data Source: U.S. Energy Information Administration (EIA), 2015

From the end-user perspective, the literature shows that the industrial sector is the largest contributor of energy consumption and greenhouse gas emissions in the United States. In industrial sector, manufacturing activities is the leading source of energy-related carbon dioxide emissions in the U.S (M. Schipper, 2006). It dominates the industrial related energy consumption and greenhouse gas emissions.

The United States EPA states that, “the most effective way to reduce carbon dioxide (CO2) emissions is to reduce fossil fuel consumption” (EPA, 2015). The power plants are considered the major source of carbon emissions, accounting for approximately one-third of all domestic greenhouse gas emission. To address climate change, on June 2, 2014, EPA proposed the Clean Power Plan (CPP). This requires individual states to develop plans for achieving emission reduction to protect human health and environment, while maintaining an affordable, reliable energy system. The CPP rule allows states to meet state-specific goals through a combination of strategies of energy management including energy efficiency and electricity demand response.

Energy efficiency can help end users reduce energy consumption while allowing the customers receive the same measure of end service. Electricity demand response involves the use of flexible programs that modify the energy consumers’ demand for electricity by allowing the consumers play a role in shifting their demand for electricity during peak hours. It encourages the end users of electricity to transfer or shift their electricity load during periods of high demand to off-peak periods to reduce their consumption cost.

The benefits of energy management have been widely studied. The Advanced Energy Management Alliance (AEMA) which is a union of demand response providers and consumers, indicated that participating in demand response programs can result in a number of advantageous outcomes, including reductions in carbon dioxide emissions. Navigant Consulting Inc. (2014) also demonstrated that the implementation of demand response can reduce carbon dioxide emissions appreciably.

In addition, energy management can also help to balance the electricity supply and demand throughout the electricity grid for a reliable operation of the electricity grid. The challenges of increasing demand in electricity, and the resultant increase in the cost of its generation can be addressed as energy management gives the energy users a control over their energy consumption, and reduces the stress on the electricity grid to generate more electricity.

Various authors have studied energy management (A. Faruqui, 2007; M. Chupka et al., 2008; P. Cappers, 2010; L. Greening, 2010, etc. see details in Section 2.2). However, these existing studies have the following limitations: 1) only energy-related cost is considered in the models, while productivity-related cost is usually ignored; 2) many studies are focused on commercial and residential building sectors, while the state-of-the-art in industrial manufacturing sector is less developed; and 3) many studies are focused on the different manufacturing processes, while the method for the production scheduling and planning for the entire manufacturing system is lacking.

In this research, motivated by the status-quo, to address the aforementioned limitations, we propose a cost-effective energy integrated production scheduling model for manufacturing systems to obtain an optimal production schedule that can minimize the overall cost including the following aspects:

(a) The inventory of products in the buffers

(b) The raw materials utilized

(c) Cost of setup

(d) Electricity billing cost

An analytical model of the decision-making of the production scheduling is established. The decision variable denotes the production scheduling of each machine in the manufacturing system throughout the production horizon. The problem is formulated as a Mixed Integer Non-linear Program (MINLP). General Algebraic Modeling System (GAMS) is used to solve the problem to obtain the optimal solution.

The rest chapters of this thesis are organized as follows: Chapter 2 comprises of the literature and background research, Chapter 3 demonstrates the proposed model, highlighting the results of a numerical case study. Finally, the conclusion and projection into future work are discussed in Chapter 4.

2. LITERATURE REVIEW

As proposed by the title of this thesis, “Cost-effective Energy Integrated Production Scheduling in Sustainable Manufacturing”, the theory of this research has been built on ideas from scientific studies which are based on some of the most important problems in production that are but not limited to cost in manufacturing, energy management, and production scheduling. The literature focusing on cost analysis in manufacturing, energy management in manufacturing, and production scheduling in manufacturing will be reviewed in this chapter.

2.1. Cost Analysis in Manufacturing

Generally, an important production problem appears to be the minimization of the total manufacturing cost. Cost is a vital and well recognized aspect of production process. Traditionally, the researchers have focused more on the productivity-related cost analysis in manufacturing including material cost, maintenance cost, quality cost, setup cost, etc. For example, E. Aghezzaf et al. (2007) proposed an integrated analytical model for production and maintenance planning with the primary objective of minimizing the overall cost of maintenance and production over a finite production horizon. A. Dolgui et al. (2014) established a constructive heuristic algorithm and an integer linear programming model to minimize the number of operation stations and setup cost of a transfer line, requiring multiple setups as a result of its design to produce several types of parts. R. Zhang et al. (2014) developed an optimization approach to minimize the unit cost of manufacturing in a uniform parallel machine production system, primarily focusing on the relationship between operation-based variables and manufacturing cost. B. Sakar et al. (2015) extended the model of I. Moon and S. Choi (1994) which focused on applying a distribution-free technique to develop an iterative procedure to find optimal reorder levels by establishing two algorithmic expressions to minimize defective production and manufacturing setup cost. C. Lenoir and H. Carino (1989) developed a linear programming model to determine an optimal purchasing policy of wood raw material in a cabinet manufacturing firm that will minimize raw material cost. It was declared that 32% of wood raw material cost under the market condition could be salvaged with this model. Z. Wu et al. (2007) proposed a nonlinear model to minimize the cost associated with monitoring a multi-stage manufacturing system by considering the cost of poor quality and manpower deployment. K. Kim et al. (2006) established a mathematical model to maximize the profit of a manufacturing company by determining the optimal number of new purchases and returned products to be remanufactured in order to reduce total remanufacturing cost. M. Fitouhi and M. Nourelfath (2012) proposed a model to minimize the holding cost, cost of maintenance, backorder, and production in a single machine production system with lot size production in a finite production planning horizon. Studies carried out by E. Selvarajah and R. Zhang (2014) focused on problems a manufacturer encounters with supply chain scheduling. This research was geared towards minimizing holding cost and delivery cost. Y. Zong and J. Mao (2015) proposed a model for manufacturing cost and quality loss with primary focus on the design of tolerance. The reported results of this model displayed a reduction of 0.927% in total cost and a significant reduction of 31.285% in quality loss.

Recently, with increasing pressure of environmental protection by the government, energy cost in manufacturing is also being considered. Manufacturing companies are facing increasing pressure to reduce their carbon footprint as a result of climate change concern. This increase in pressure is expected to be enlarged in future due to growing cost in energy ascribable to carbon emission taxes and regulations, as well as rising energy demands (K. Fang et al., 2011). The remarkably growing cost of energy in manufacturing has resulted in the increasing emphasis on energy management practices (L. Li et al., 2013). S. Anderberg et al. (2010) declared that their proposed approach incorporating energy cost amongst other costs in manufacturing cost can be employed to give some understanding of the relative size of various machining cost components which includes both fixed and variable cost. Some research on energy cost includes the following:

Studies of S. Anderberg et al. (2010) exhibited the modelling of cost models monitoring energy consumption and tool wear. This work focused on the impact of energy efficiency on energy cost, setup cost, machining cost and carbon dioxide emission cost. However, electricity demand was not considered and the case study was limited to a single machine. H. Yoon et al. (2013), proposed cost models to control the consumption of energy and the cost of manufacturing incurred in the micro-drilling process for printed circuit board manufacturing. Nevertheless, the continuous change in electricity cost was not included in the model. F. Shrouf et al (2013) developed a mathematical model to minimize overall cost of energy consumption during production process by adopting the method of decision making at different states of the machine. The authors considered the continuous change in electricity price but limited the illustration of the potency of the model to a single machine, which is not a representation of an actual modern production system with complex multiple machines operating in a distinctively dynamic and unpredictable environment. L. Özdamar et al. (1999) established a hierarchical approach to minimize the holding cost of inventory cost and energy cost in a tile manufacturing system by reducing the number of active kilns. The authors considered the production target, but did not consider the varying cost of electricity.

It can be observed that there is a shortfall in the joint consideration of both energy and productivity-related cost in manufacturing cost analysis. Some further research is needed, however, it has not yet attracted enough attention.

2.2. Energy Management in Manufacturing

Manufacturing enterprises are faced with the circumstance of increasing energy price, high carbon dioxide emission and rising electricity demand. In order to control this rising demand and cut down on cost, energy management strategies are adopted.

Energy Management is generally considered as an effective method to achieve the goal of sustainability in manufacturing industries, as well as reduce both economic and environmental impacts resulting from increasing electricity demand today and in the future. Energy management strategies consist of energy efficiency and conservation programs, fuel-switching programs, demand response programs and energy management programs (B. Ramanathan et al., 2008; M. A. Pedrasa et al., 2009; B. Davito et al., 2010; A. Mohsenian-Rad et al., 2010). The energy management programs with major impacts appear to be the demand response and energy efficiency programs (North American Electric Reliability Corporation, 2007; B. Davito et al, 2010; EnerNOC, 2015). For example, utility commissions of various states in the U.S want the utilities in their jurisdiction to proceed with demand response, and energy efficiency programs due to the economic and environmental benefits which these programs provide customers (EnerNOC, 2009).

The International Energy Agency defines energy efficiency as, “a way of managing and restraining the growth in energy consumption”. In more explanatory words, it is using a smaller amount of energy to provide the same quality of service or produce the same quantity of products that will meet demand. Energy efficiency is known to reduce electricity demand and greenhouse gas emission. In addition, studies suggests energy efficiency has multiple benefits beyond the aforesaid which includes its capability to advance economic growth and social development (International Energy Agency, 2014; V. Anbumozhi, 2009). Full participation in energy efficiency practices in the United States is estimated to yield savings of 10 – 30% on electricity bills, and a 20% reduction in energy demand by 2025. The benefits of this reduction is estimated to result in: over one hundred billion dollar savings on energy cost by 2025, an annual savings greater than 900 billion kWh, and a reduction in carbon emission of approximately 500 million metric tons annually (Environmental Protection Agency, 2008).

Demand response can be defined as "a tariff or program established to motivate changes in electric use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized" (U.S. Department of Energy, 2006). The demand response program ensures that the demand of electricity does not exceed its supply, and redistributes consumption from peak periods to off-peak periods as a result, flattening the demand curve (J. Blanc et al, 2014). An example of this effect is shown in Figure 4, which displays a chart of forecasted (blue line) and actual (red line) electricity demand in New England on the hot and humid afternoon of the 24th day of June 2010. The Independent System Operator of New England was left with little operating reserves due to approximately 1,800 megawatts of unplanned outages. The actual electricity load was pushed closer to the forecasted load due to the unpredicted high temperature. The Independent System Operator called on their demand response program in order to restore an adequate level of operating reserves. Utilities across New England were asked to activate their demand response resources to reduce load. The demand response action effect made an attempt to flatten the curve as shown in the grey area of the Figure 4.

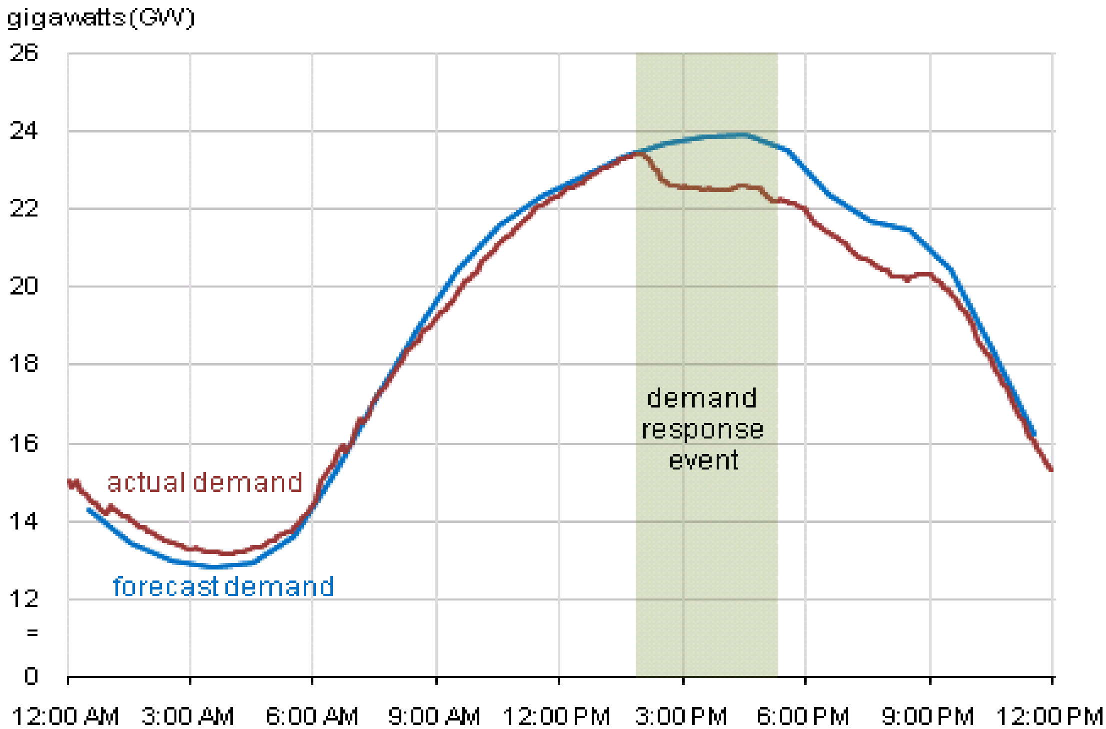


Figure 4: Independent System Operator of New England Electric Load, June 24, 2010
Source: Independent System Operator of New England,
http://www.eia.gov/todayinenergy/detail.cfm?id=130

Demand response can be categorized into price-driven and event-driven (incentive-based), (C. Goldman et al, 2010; M. Moghaddam et al, 2011). The Figure 5 displays the types of demand response programs. Critical-peak period (CPP), Real-Time pricing (RTP) and Time-of-use (TOU), fall under the price-driven category of demand response. In the event-driven, customers are rewarded for reducing their energy consumption. The event-driven demand response programs are triggered by problems of grid reliability or high electricity prices (U.S. Department of Energy, 2006).

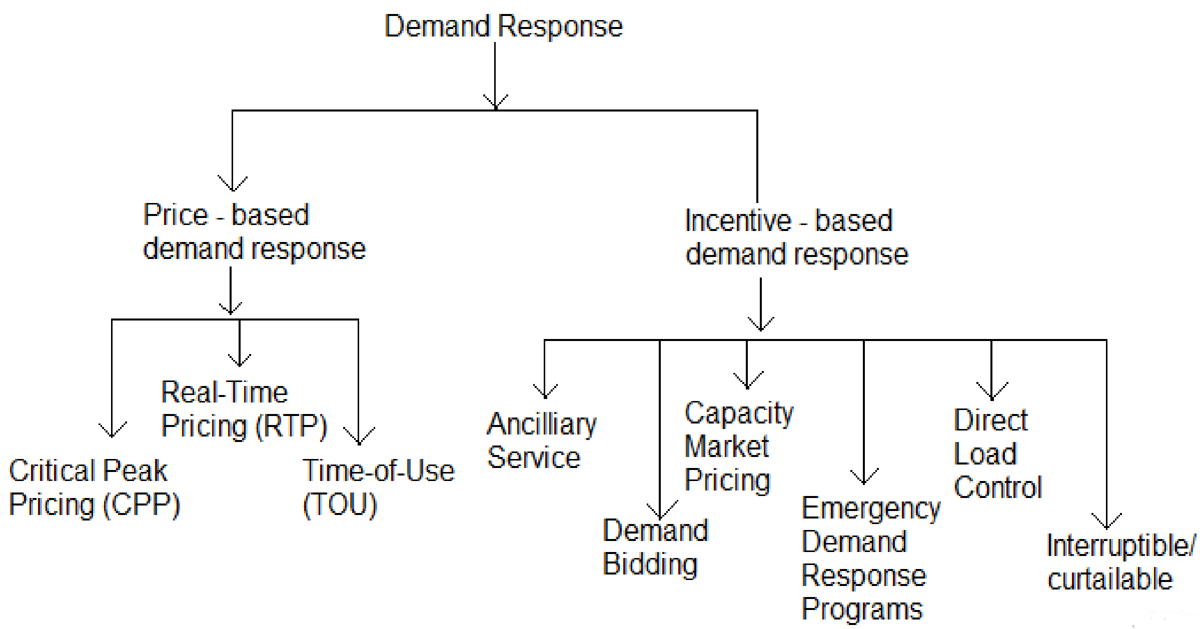


Figure 5: Types of Demand Response Programs

The North American Electric Reliability Corporations' 2007 Long Term Reliability Assessment (LTRA) states that, "demand response is increasingly viewed as an important option to meet the growing requirements in North America, while at the same time addressing greenhouse gas and carbon dioxide legislation". Effective demand response can assist in the reduction of electricity price volatility, mitigate market power, and enhance reliability (J. Norris, 2010). Participating customers of incentive-based and time-based demand response program in the United States had the ability to provide approximately 38,000 megawatts and 2,700 megawatts of potential load reduction respectively in 2008 (P. Cappers et al, 2010; C. Goldman et al, 2010). In 2009, U.S Federal Energy Regulatory Commission estimated a 20% potential change in peak demand by 2019 on the assumption of full participation in the demand response program; with a reduction in peak load as much as 150 gigawatts which is an equivalent of 2,000 peaking power plants of 75 megawatts each (U.S Federal Energy Regulatory Commission, 2009).

Demand response and energy efficiency are deemed similar, though demand response is dispatchable and centered on cost-effective strategies to decrease peak loads; energy efficiency in most cases is non-dispatchable and focused on decreasing total end-use electricity consumption (EnerNOC, 2009; K. Brief et al, 2011). From literature, M. Chupka et al (2008) estimated that by 2030, $697 billion will be required to build 214 gigawatts of new generation capacity in the U.S. In awareness of this information, M. Chupka et al., (2008) estimated that the implementation of demand response programs alongside energy efficiency programs will significantly reduce the need for new generation capacity by 38% or from 214 gigawatts to 133 gigawatts by 2030.

In general, extensive studies on energy management in the commercial and residential sector have been conducted. For example, J. Torriti (2012) assessed the impacts of Time-of-Use tariffs on residential users as it relates to peak load shifting, electricity price savings, and changes in electricity demand. P. Finn et al (2012) demonstrated that the use of demand-side management in charging cycles of an electric car can achieve reduced peak load demand and financial savings. K. Herter (2007) investigated the effects of critical-peak-pricing on residential users with different income levels. V. Daioglou et al (2012) developed a simulation model to describe energy demand for end-use functions and analyze future development of energy use in the residential sector. N. Venkatesan et al (2012) established an analytical model for residential demand response by developing a demand-price elasticity matrix for different types of end-users. N. Motegi et al (2007) introduced strategies and techniques for implementing demand response program in commercial buildings.

Compared to the residential, commercial sector, the industrial sector has consumed more energy over the years in the United States. For example, Figure 6 displays an overview of the trends of energy consumption in the United States from 1970 to 2005. It can be seen that the industrial sector is leading in energy consumption. Beyond the period covered in Figure 6, in 2011, the industrial sector accounted for over 30% of energy consumption in the United States (U.S Environmental Information Administration, 2012). From publications, researchers have shown growing concern about the industrial sector receiving less attention than that of the commercial and residential sectors in terms of demand response and energy efficiency (Y Wang et al, 2013; Z. Sun et al, 2014; M. Fernandez et al, 2014). Research for energy management in the industrial sector has been initialized and is yet to be matured.

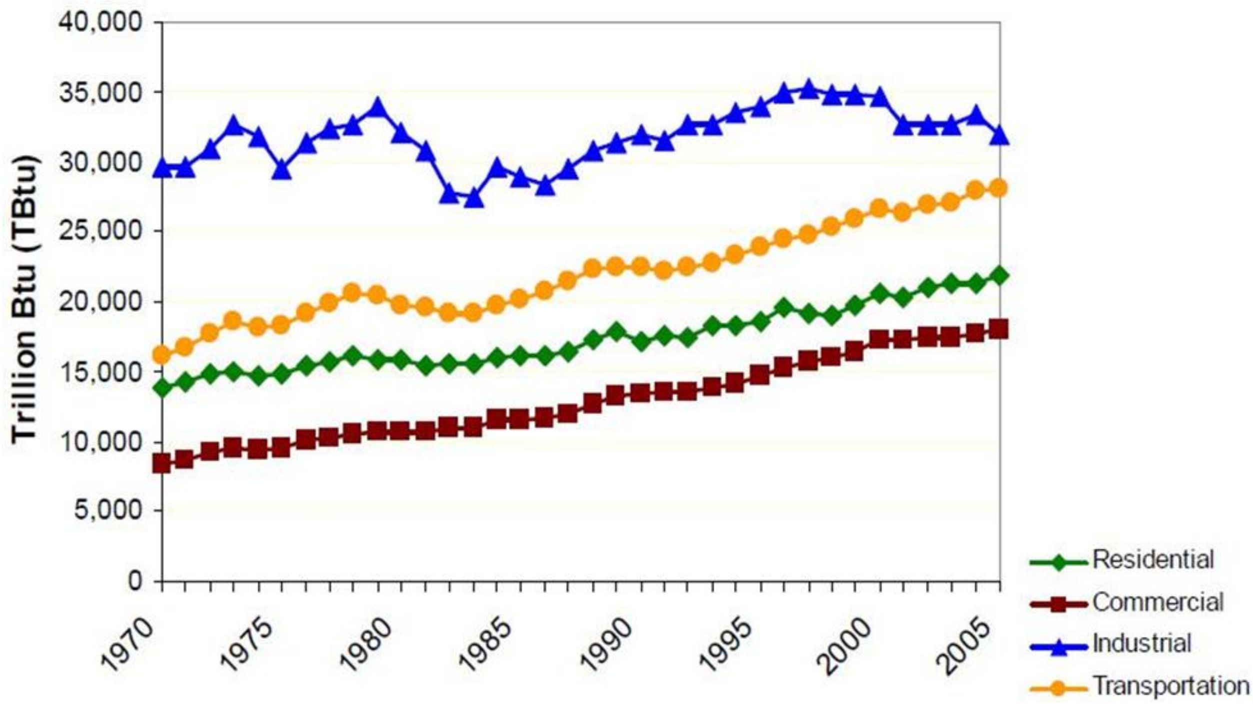


Figure 6: U.S Energy Consumption Trends 1970-2005: Comparison of Residential, Commercial, Industrial and Transportation End Uses
Source: U.S. Environmental Protection Agency 2007
(http://www.epa.gov/sectors/pdf/energy/ch2.pdf)

Furthermore, in industrial sector, manufacturing activities is the largest source of energy-related carbon dioxide emissions in the United States (M. Schipper, 2006). It dominates the industrial related energy consumption and greenhouse gas emissions. The manufacturing area consumes a substantial amount of electrical energy and as a result, has a large number of negative economic impacts associated with it (J. Duflou et al, 2012; M. Hauschild et al, 2005). Figure 7 displays the different energy consumption for both manufacturing and non-manufacturing in 2011 in industrial sector. It can be seen from the chart that manufacturing consumed a large portion of total energy consumption. Estimation in 2006 based on the Manufacturing Energy Consumption Survey

(MECS) carried out by the U.S Energy Information Administration, indicated that the manufacturing sector accounted for 84% of energy-related emissions and 90% of energy consumption in 2002 in the industrial sector. (M. Schipper, 2006). The annual energy outlook of the United States Energy Information Administration recorded 24.5 quadrillion British thermal units (Btu) of energy consumption in the industrial sector, which represented 34% of the total energy consumption in 2013 (U.S Environmental Information Administration, 2015).

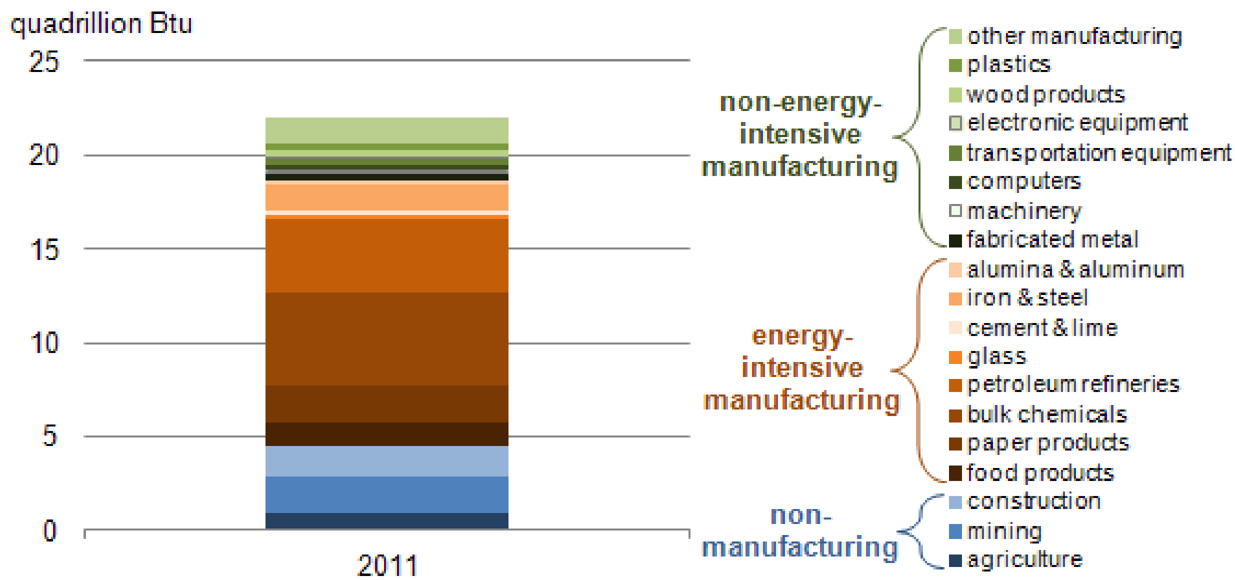


Figure 7: U.S Industrial Consumption of Delivered Energy in 2011
Source: U.S. Energy Information Administration, Annual Energy Outlook 2012.
(http://www.eia.gov/todayinenergy/detail.cfm?id=8110)

Some research focusing on energy management in the manufacturing sector can be found. For example, G. Mouzon and M. Yildirim (2008), proposed a framework to solve multi-objective optimization problems to minimize energy consumption. Z. Sun et al (2011) analyzed the opportunity of saving energy to upgrade energy efficiency for sustainable manufacturing systems with consideration of the multiple power modes that modern machines have. Y. Wang et al (2013) proposed a system approach for Time-of-Use demand response program aiming at minimizing electricity consumption and cost, considering production throughput. Z. Zhou et al (2013) introduced a heuristic method for detecting bottlenecks in real-time which incorporated production throughput and demand response action in a manufacturing system. A. Bego et al. (2014) established a mixed integer nonlinear programming model to minimize the electrical energy cost and penalty cost for multiple machine and buffer manufacturing industries participating in the critical peak pricing program, under the constraint of production target. Z. Luo et al. (1998) developed a mixed integer nonlinear programming model to determine the optimal shedding and restoration schedule to minimize production loss due to load shedding. M. Albadi and E. El-Saadany (2008) outlined the benefits and effects of demand response.

Generally, it can be seen that most existing research in energy management in manufacturing focuses on energy-related cost minimization, while considering less of other productivity-related cost. Therefore, there is a need to consider and relate both energy and productivity-related cost.

2.3. Production Planning/Scheduling

Planning and scheduling are very important aspects of manufacturing activities. Adequate planning and scheduling is known to minimize production cost and enable manufacturing industries achieve their goals within a budget limit. The common goal of planning and scheduling is to derive optimal production decisions.

An adequate amount of research on planning and scheduling in manufacturing has been conducted. For example, K. Kogan (2006) established a mathematical model for a parallel machine manufacturing system which includes renewable resource constrained production scheduling, in order to reduce backorder, inventory and production cost. M. Fitouhi and M. Nourelfath (2012) proposed a model for simultaneously determining the optimal production plans and non-cyclical preventive maintenance actions for a single machine, the results of this research reflected that production planning can minimize overall maintenance and production cost. M. Nourelfath and E. Châtelet (2012) developed a combined maintenance and production planning model with the objective of minimizing maintenance and production cost under the constraint of fulfilling demand. J. Kenné et al. (2012) developed a planning model for a manufacturing/remanufacturing hybrid system to determine an optimal policy that would minimize backlog and holding costs for manufacturing and remanufacturing products. M. Tabucanon and B. Sasiwong (1991) developed a mathematical model with the objective of determining the optimal production planning for an iron and steel factory. The conclusion of this work highlighted a benefit of planning and scheduling to be improved management decisions.

The aforementioned publications and more, focus on productivity-related planning and scheduling in manufacturing. Actually, the implementation of energy management programs also require proper planning and scheduling of production system. The study has shown that manufacturing schedules that have resulted in peak energy reduction can also reduce the cost of energy consumption (K. Fang et al., 2011). This highly correlates with the declaration by N. Weinert et al. (2011) that an integration of energy management into scheduling activities results in an expected reduction of energy consumption. P. Faria et al. (2011) proposed a production cost minimization approach which consists of integrating scheduled demand response with distributed generator units and energy provided by electricity markets. Based on an energy-saving method of jobshop scheduling, D. Grimes et al. (2014) studied the energy cost scheduling that adapts real-time energy price fluctuation, and the results of price forecasting strategies on the end scheduled-cost by building price forecasting models and using it to determine the minimum energy cost for an optimal schedule. F. Shrouf et al. (2013) proposed a mathematical model which integrated the production scheduling of a single machine to minimize the cost of energy consumption. Y. He et al. (2005) carried out a case study of a gear machining workshop to demonstrate the potency of a scheduling integrated analytical model to minimize energy consumption and makespan. C. Le and C. Pang (2013) proposed a combined scheduling and control structure, proven by a mathematical model to minimize the penalty cost of tardiness and energy consumption cost.

It can be seen most existing studies in production planning in manufacturing consider either energy-related cost or productivity-related cost. The ways in which the interests of both sides can be considered is lacking. Some studies have initially illustrated the significance of such scheduling models considering both cost aspects. For example, F. Apostolos et al. (2013) has discussed the importance of planning production including not only consider productivity-related cost but also energy cost. The incorporation of energy consumption during scheduling decision-making along with other productivity related objectives is considered an effective way to avoid wasted energy (G. Mouzon and M. Yildirim, 2008).

In summary, from the literature review in this section as well as Sections 2.1 and 2.2, it can be seen that a great deal of research in cost, energy, and production scheduling has been conducted in manufacturing. However, there is lack of an integrated research that considers the aspects from all the three areas. In this thesis, an overall cost-effective energy-integrated production scheduling model is proposed. The energy cost, i.e., the fluctuating price of electricity at different times, raw material cost, inventory cost, and setup cost are incorporated into the production scheduling system under the constraint of production target.

3. MODEL: COST-EFFECTIVE ENERGY INTEGRATED PRODUCTION SCHEDULING IN SUSTAINABLE MANUFACTURING SYSTEMS

3.1 Introduction

In this chapter, a cost effective energy integrated production scheduling model is proposed. The inventory holding cost, raw material cost, energy cost and setup cost as a result of energy management are considered in the objective function. The objective is to obtain an optimal production schedule that can minimize the summation of the cost items aforementioned.

A mixed-Integer Nonlinear Programming model (MINLP) is formulated to focus on the optimal scheduled production period of the machines in the production system throughout the production horizon that will result in minimized cost.

A numerical case study is used to demonstrate the effect of this method on the cost incurred in a production system. The problem is solved using the LINDO global in the General Algebraic Modeling System (GAMS).

3.2 Mathematical Modeling

In order to analyze the problem of cost incurred in a production system, consider a tandem production line of N machines and $N-1$ buffers of finite capacity positioned between machines as shown in the figure below. The buffers denoted by $B_i\left(i=1,2,...,N-1\right)$ are employed to mitigate production process failure and improve throughput.

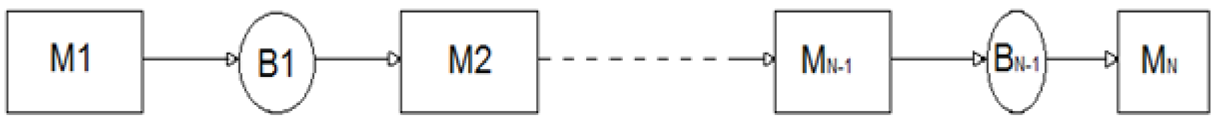


Figure 8: Skeletal Structure of a Tandem Production Line

The production horizon is slotted into a set of intervals with fixed duration L. Let $j, j=1,2,..,J$, be the index of these intervals. Let z_{ij} be the binary decision variable to denote the ON and OFF decisions for machine i at interval j, which can be formulated as

$$z_{ij}=\begin{cases}1, \text{machine } i \text{ is kept on at interval } j\\ 0, \text{machine } i \text{ is turned off at interval } j\end{cases} \tag{1}$$

Let δ_{ij} be the coefficient to denote the percentage of the actual production time of machine i in interval j due to setup resulting from energy management decisions. It can be formulated by (2).

$$\delta_{ij}=\begin{cases}1, \text{ if } z_{i(j-1)}=1 \text{ and } z_{ij}=1 \\ 1-\left(w_i / L\right), \text{ if } z_{i(j-1)}=0 \text{ and } z_{ij}=1\end{cases} \tag{2}$$

where w_i is the setup time of machine i. It is assumed that the duration of setup time is less than the duration of each interval. Let ρ_i be the setup cost per unit setup time of machine i. The setup cost can be formulated by (3)

$$C_{\sup}=\sum_j \sum_i \left[\left(1-\delta_{ij}\right)\cdot L\cdot \rho_i\right] \tag{3}$$

Let b_{ij} be the inventory level of buffer i at the beginning of interval j. Let Q_i be the production rate of machine i. b_{ij} Can be determined as follows

$$b_{ij}=b_{i(j-1)}+Q_i\cdot L\cdot \delta_{i(j-1)}\cdot z_{i(j-1)}-Q_{(i+1)}\cdot L\cdot \delta_{(i+1)(j-1)}\cdot z_{(i+1)(j-1)} \tag{4}$$

with b_{i1} as the notation for initial buffer content.

Figure 9 displays a graphical representation of the buffer level at the beginning of each interval throughout the entire production horizon.

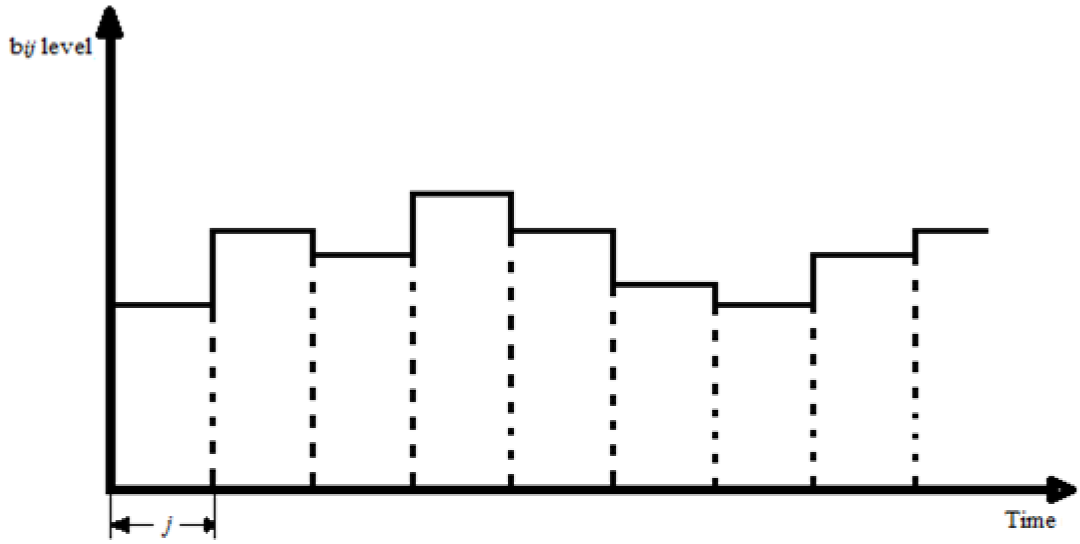


Figure 9: Graphical Representation of Buffer Level at the Beginning of the jth Interval

If we use the buffer level at the beginning of interval *j* to approximately represent the average buffer content at the interval *j*, the average inventory level of buffer i throughout the entire production horizon can be calculated by (5).

$$I_i = \sum_j b_{ij} / J \tag{5}$$

Let c_{B_i} be the holding cost per unit of inventory held in buffer *i*. The total average holding cost of the system throughout the production horizon is obtained as

$$C_H = \sum_{i=1}^{N-1} c_{B_i} I_i \tag{6}$$

For the material cost, let the number of raw materials per parts produced by machine i be r_i and the cost per unit raw material consumed by machine i be c_{R_i}. The total cost of raw material incurred during production horizon can be calculated with the equation given below

$$C_{MA} = \sum_j \sum_i (Q_i \cdot \delta_{ij} \cdot L \cdot r_i \cdot c_{R_i} \cdot z_{ij}) \tag{6}$$

For the electricity consumption cost, two types of charges are considered, i.e., energy consumption charge and power demand charge. The energy consumption charge is subject to the amount of energy consumed in kilowatt-hour (kWh) throughout the billing period. Let ce_j be the charge rate ($/kWh) for the electricity consumption in interval j. Power demand charge is determined by the power demand in kilowatt (kW) during peak period. Let cp be the charge rate ($/kW) for the power demand. The total energy cost of the production system throughout production horizon can be calculated with the formula below

$$C_E = \sum_j \left[ce_j \sum_i \varphi_i \cdot \delta_{ij} \cdot L \cdot z_{ij} \right] + cp \cdot \max_{j \in \mathbf{ONP}} [\sum_i \varphi_i \cdot z_{ij}] \tag{7}$$

where φ_i denotes the rated power of machine i; and $\mathbf{ONP}$ denotes the set of the intervals belong to peak periods.

The objective function can be

$$\min_{z_{ij}}\left(C_{sup}+C_{H}+C_{MA}+C_{E}\right) \tag{8}$$

The constraints to be considered are listed below:

1. The content of buffer i at interval j must be at a level between zero and the buffer capacity.

$$0\le b_{ij}\le B_{i\ \text{capacity}} \tag{9}$$

   where $B_{i\ \text{capacity}}$ denotes the capacity of buffer i

2. The total number of parts produced by machine N in the production horizon must not be less than the production target

$$\sum_{j}\left(Q_{N}\cdot L\cdot\delta_{Nj}\cdot z_{Nj}\right)\ge P_{T} \tag{10}$$

   where P_T denotes the production target

It can be seen that the objective function (8) is a mixed- integer nonlinear program (MINLP) with constraints (9) and (10) that exhibit non-linearity. The MINLP is a problem that can be solved with LINDO in GAMS. LINDO is a powerful, package of solvers that supports most mathematical functions including non-smooth and discontinuous functions. It has the ability to detect the type of given optimization problem and select the appropriate solver to find an optimal solution of the problem (GAMS Development Corporation, 2015). LINDO global is specifically used in solving this problem for a global optimal solution. The LINDO global solver has the ability to convert non-convex and nonlinear problems into several convex and linear sub-problems respectively, after which it applies the technique of branch-and-bound (and the cut for integer optimization problems) for an exhaustive search over the sub-problems for a global optimal solution (GAMS Development Corporation, 2015; Maximal Software Inc., 2013).

For the proposed model, the steps to find an optimal solution are as follows:

1. Find an initial solution to objective function
2. Split objective function into sub-problems
3. Search for a feasible and optimal solution of each sub-problem
4. Eliminate feasible solutions to non-integer sub-problems
5. Terminate search if an optimal solution to a sub-problem is found (solution close enough to initial solution).
6. In the event of no optimal solution to any sub-problem, further partition sub-problems and repeat steps 3 -5.

Figure 10 displays a flow chart for this solution procedure.

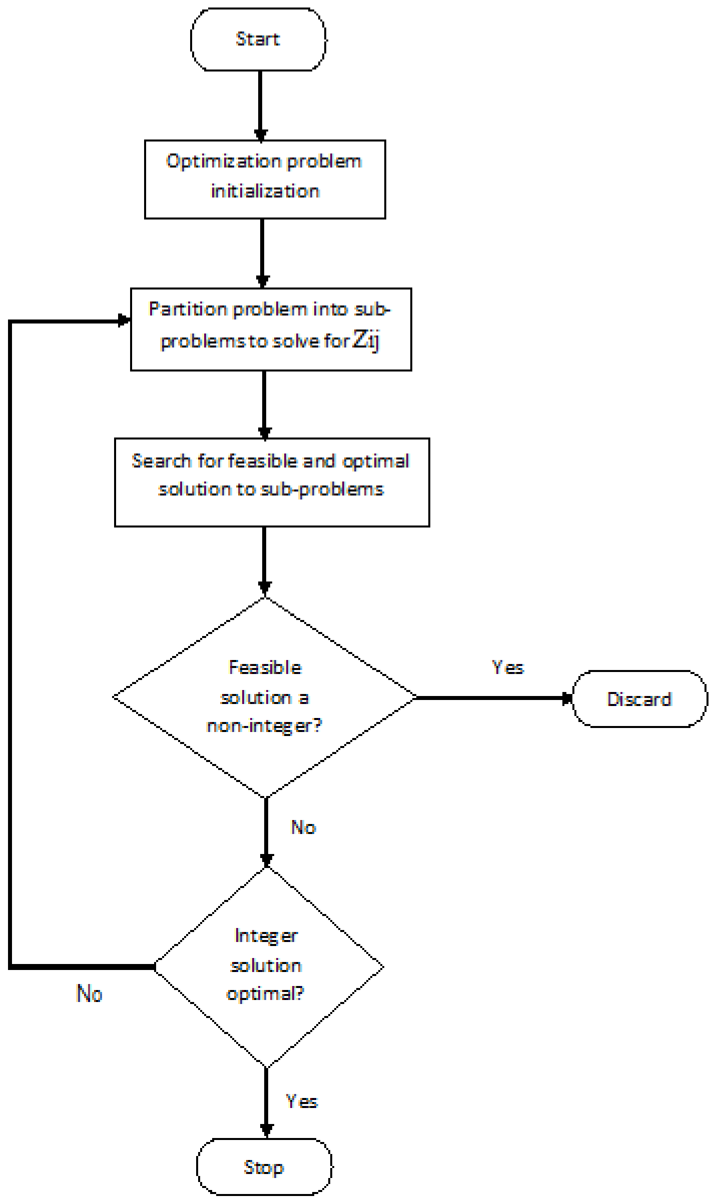


Figure 10: Flow Chart of Solution Procedure

3.3 Numerical Case Study

In order to illustrate the effectiveness of the proposed method, a production system of five machines and four buffers as shown in the figure below is employed. The machine characteristics and parameters include production rate, rated power, setup time, raw materials consumption rate and cost as shown in the Table I and II.

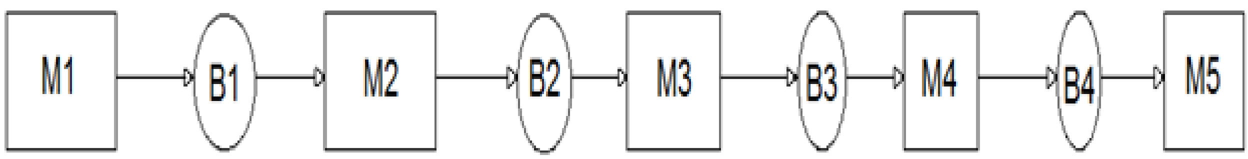


Figure 11: A Serial Production Line of Five Machines and Four Buffers

TABLE I: MACHINE CHARACTERISTICS

Machine, m_i	Production Rate, Q_i, (units/hour)	Rated power, Φ_i, (kW)
1	132	14
2	122	24
3	127	14
4	123	15
5	124	25

TABLE II: SETUP TIME AND RAW MATERIAL CONSUMPTION RATE AND COST OF EACH MACHINE

Machine, m_i	Raw materials per parts produced, r_i, (units)	Cost per unit raw material, C_{Ri}, (dollar)	Setup Time, ω_i, (hours)	Setup cost per unit setup time, ρ_i, (dollar)
1	4	5.50	0.10	3.40
2	5	4.35	0.15	2.40
3	4	6.75	0.12	1.60
4	1	9.25	0.12	2.30
5	3	3.20	0.08	3.20

Table III displays the buffer parameters including the initial content of each buffer, the maximum capacities, and holding cost of buffer inventory. The electricity charge rates are displayed in table IV.

TABLE III: BUFFER PARAMETERS

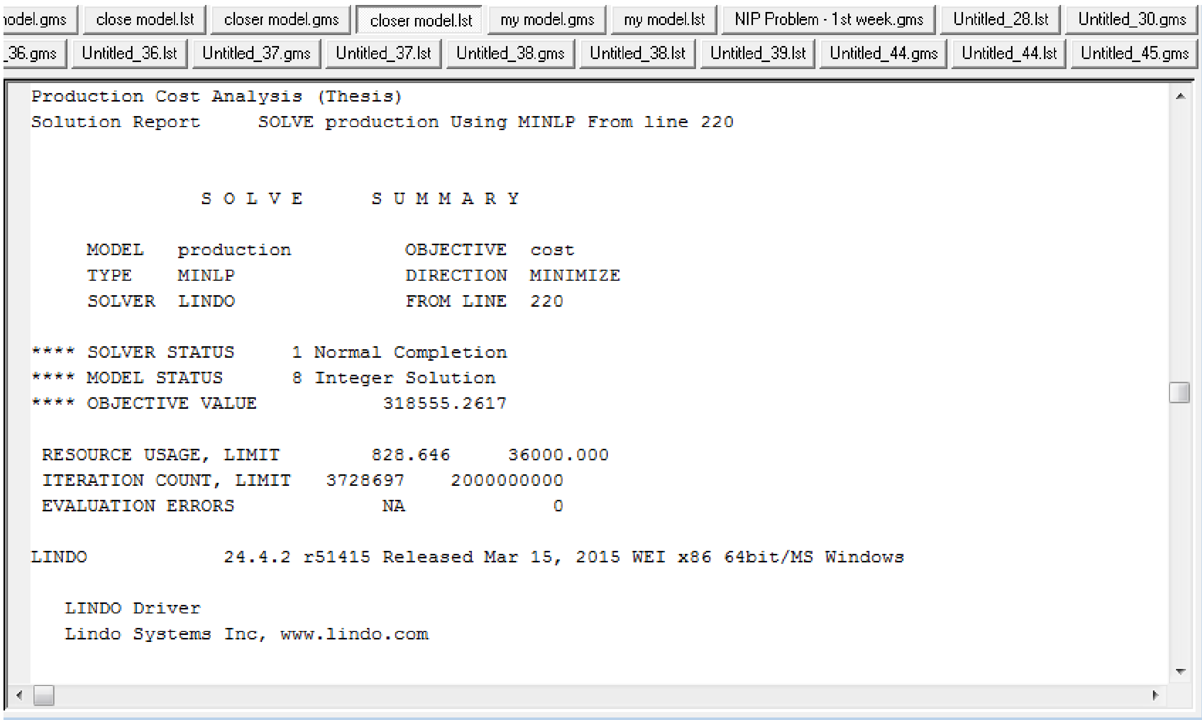
Buffer, b_i	Initial Content, b_{i1}	Maximum capacity, $B_{icapacity}$	Holding Cost, C_{Bi} (unit/dollar)
1	32	142	0.05
2	30	132	0.05
3	40	137	0.05
4	30	133	0.05

TABLE IV: ELECTRICITY RATES AND TIME-OF-USE SCHEDULE

Period Type	Time of Day	Consumption rate (dollar/kWh)	Demand Charge (dollar/kW)
Off-Peak Period	9am - 3pm	0.020	-
Peak Period	3pm - 5pm	0.231	13.340

In this case, the production horizon is set to be one week including five 8-hour working days. The production interval is set to one hour and the production target to be fulfilled at the end of the week is 3820 parts.

LINDO in GAMS is used to solve this case. Figure 12 shows the snapshot of the solver status and the model status of the analytical model, indicating that the problem was solved to completion in 828.646 seconds, and an integer solution was obtained error free. Figure 13 shows the snapshot of the report summary of the case study.

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Production Cost Analysis (Thesis)
Solution Report     SOLVE production Using MINLP From line 220


               S O L V E      S U M M A R Y

     MODEL   production          OBJECTIVE  cost
     TYPE    MINLP               DIRECTION  MINIMIZE
     SOLVER  LINDO               FROM LINE  220

**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      8 Integer Solution
**** OBJECTIVE VALUE           318555.2617

 RESOURCE USAGE, LIMIT        828.646     36000.000
 ITERATION COUNT, LIMIT   3728697     2000000000
 EVALUATION ERRORS             NA              0

LINDO           24.4.2 r51415 Released Mar 15, 2015 WEI x86 64bit/MS Windows

   LINDO Driver
   Lindo Systems Inc, www.lindo.com
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Figure 12: A snapshot of the Proposed Model Solve Summary

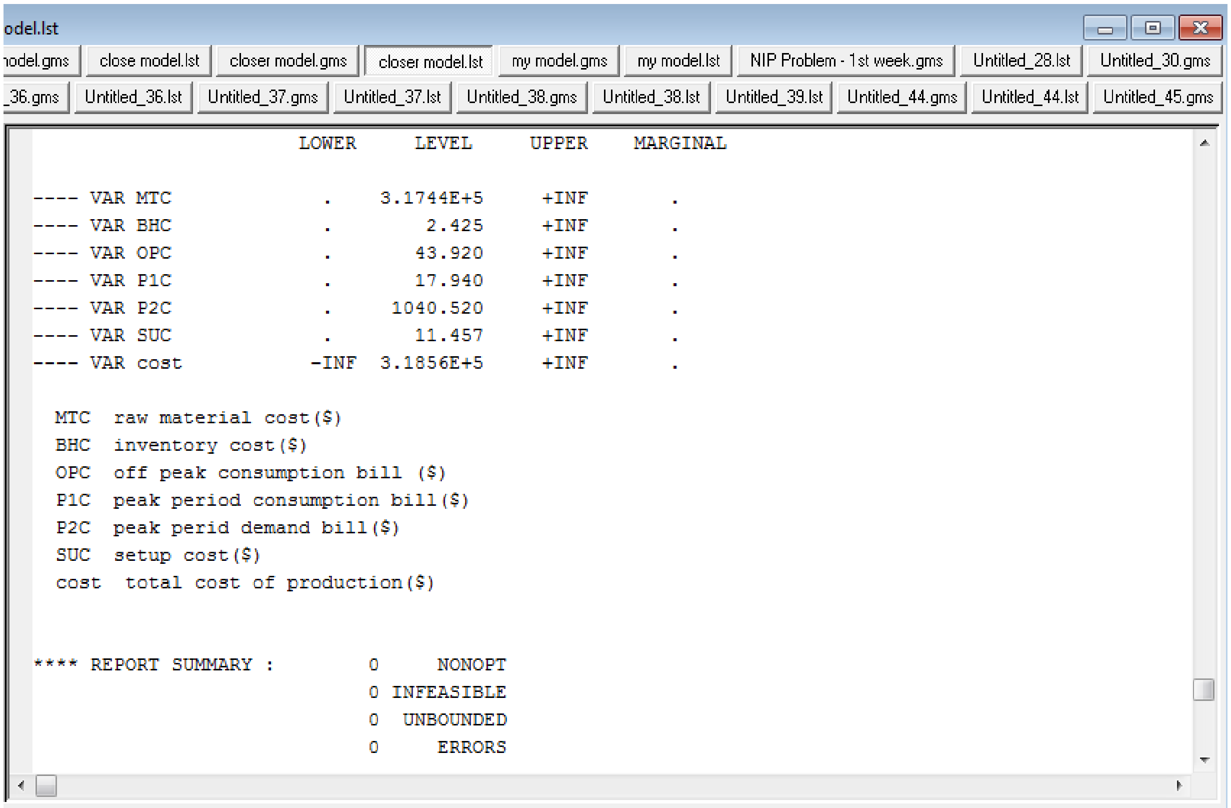

Figure 13: A Snapshot of the Report Summary of the Case Study

Figure 14 below displays the optimal production scheduling of the manufacturing system during the 5-day production horizon with 8-hour shift of each day.

Day	Production Interval	1	2	3	4	5	6	7	8
1	machine 1 status	0	1	1	1	0	1	0	0
	machine 2 status	0	1	1	1	1	1	0	1
	machine 3 status	0	1	1	1	1	1	1	0
	machine 4 status	0	1	1	1	1	1	0	1
	machine 5 status	0	1	1	1	0	1	1	0

Day	Production Interval	1	2	3	4	5	6	7	8
2	machine 1 status	1	1	1	1	1	1	0	0
	machine 2 status	1	1	1	1	1	1	0	1
	machine 3 status	1	1	1	1	1	1	1	0
	machine 4 status	1	1	1	1	1	1	0	1
	machine 5 status	1	1	1	1	1	1	1	0

Day	Production Interval	1	2	3	4	5	6	7	8
3	machine 1 status	1	1	1	1	0	1	0	0
	machine 2 status	1	1	1	1	1	1	0	1
	machine 3 status	1	1	1	1	1	1	1	0
	machine 4 status	1	1	1	1	1	1	0	1
	machine 5 status	1	1	1	1	1	1	1	0

Day	Production Interval	1	2	3	4	5	6	7	8
4	machine 1 status	1	1	0	1	1	1	0	0
	machine 2 status	1	1	1	1	1	1	1	0
	machine 3 status	1	1	1	1	1	1	0	1
	machine 4 status	1	1	1	1	1	1	1	0
	machine 5 status	1	1	1	1	1	1	0	1

Day	Production Interval	1	2	3	4	5	6	7	8
5	machine 1 status	1	0	1	1	0	1	0	0
	machine 2 status	1	1	1	1	1	1	1	0
	machine 3 status	1	1	1	1	1	1	0	1
	machine 4 status	1	1	1	1	1	1	1	0
	machine 5 status	1	1	1	1	1	1	0	1

Figure 14: Obtained Optimal Production Scheduling

TABLE V: COMPARISON OF BASELINE MODEL AND PROPOSED MODEL

Type of Cost	Baseline Model Cost	Proposed Model Cost	Percentage Savings (%)
Raw Material	$ 452,586.00	$ 317,440.00	29.86
Buffer Inventory	$ 9.91	$ 2.43	75.53
Energy	$ 1,495.00	$ 1,102.38	26.26
Setup	$ -	$ 11.45	-
Total cost	$ 454,090.91	$ 318,556.26	29.85

The comparison of the cost between the baseline model (with no energy management action) and the proposed model in this numerical case is shown in Table V. It can be seen approximately 29.85% percent of total cost savings can be achieved. Figure 15 to 18 display graphical patterns and relationships between the cost factors.

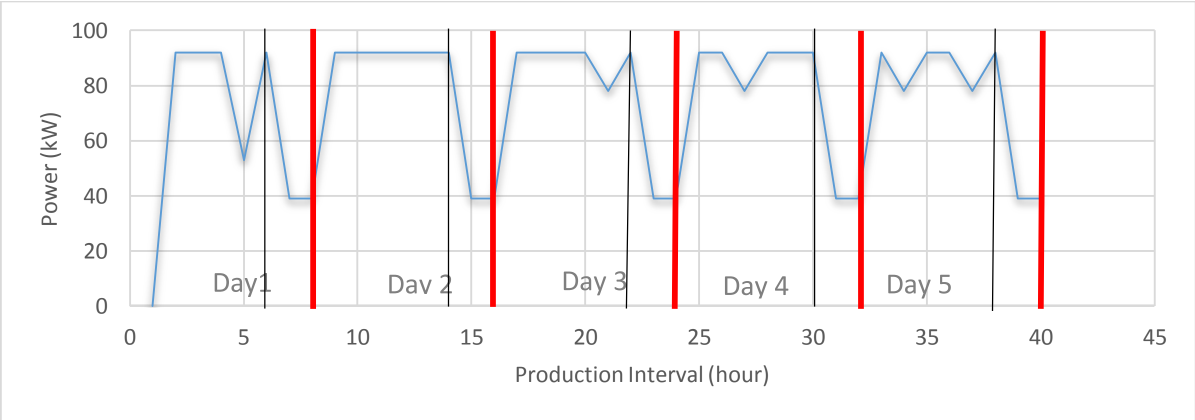

Figure 15: Power Consumption Pattern through Five Production Days

Figure 15 displays the consumption pattern of electricity in the production line. The thick red vertical lines in Figure 15 mark the end of a day and the beginning of another. The black vertical lines in the figure mark the start of peak hours in a day. It can be seen from the pattern that at peak intervals the power demand of the production line, is brought down from about 92 kilowatts to about 40 kilowatts each day, saving about 52 kilowatts of power usage each day on peak hours alone. In addition, power consumption at off-peak hours is minimized as a result of energy control actions. This indicates a reduction in electricity consumption at off-peak hours and a reduction in power demand at peak hours. Furthermore, this is an implication that over 52 kilowatts of power can be salvaged on a daily basis in this production line. 26.26% savings of energy is achieved from the results of the numerical case study.

In Figure 16, the power consumption pattern is represented by multiplying true power values by 10 to show an appreciable display of the relationship between the raw material utilized and power utilized in the course of production.

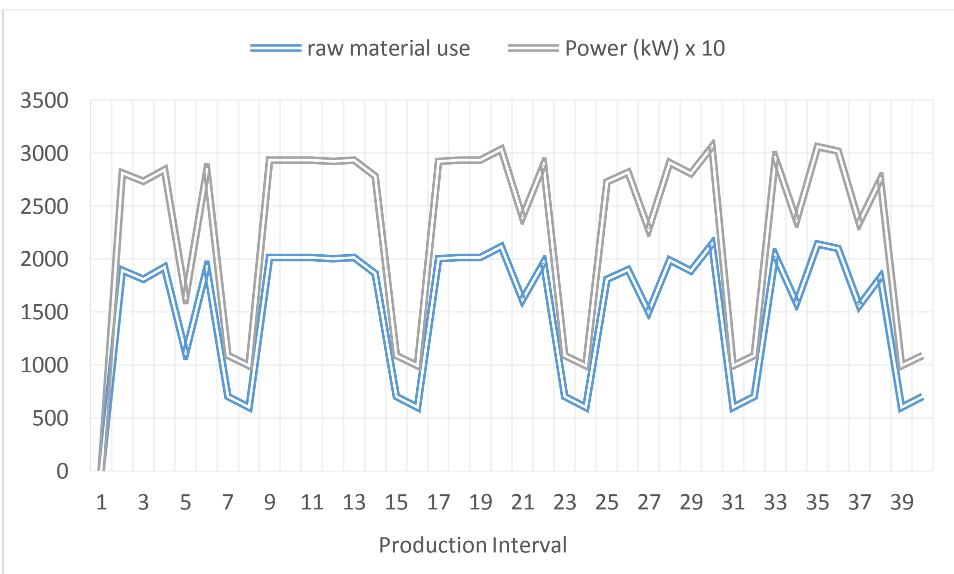

Figure 16: Relationship between Raw Material Parts Use and Power Utilized

It can be seen from the chart above that the raw material consumption pattern is similar to the power consumption pattern. This is an indicator that the raw materials are saved at peak periods. As a result, a substantial amount of cost can be saved on material alone. In this numerical case study 29.86% savings is realized from raw materials.

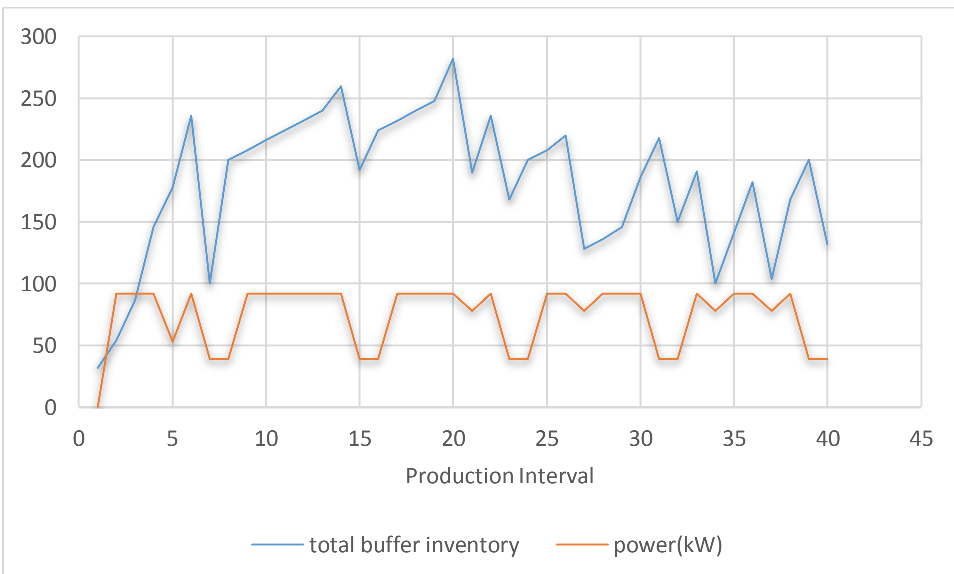

Figure 17: Relationship between Buffer Content and Power Utilized

Once again, from Figure 17, it can be seen from the chart that the buffer content and the energy consumption pattern are similar. At periods when energy management is applied, the buffer content tends to be reduced. This reduction will most likely result in less buffer inventory cost.

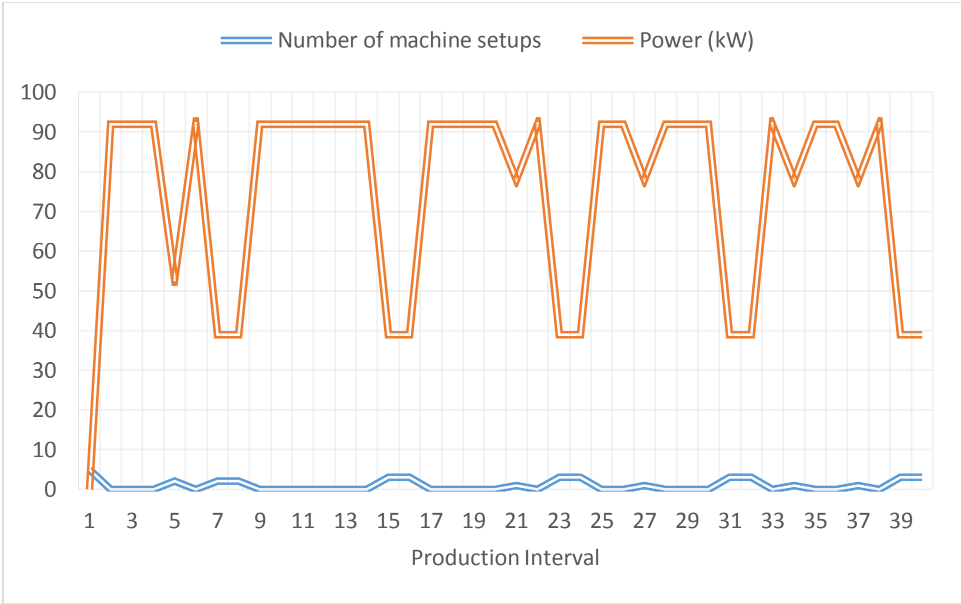

Figure 18: Graphical Relationship between Power Consumption and Machine Setups

In Figure 18, the graphical pattern shows that the number of setups that occur goes up when the power consumption pattern is at its trough. This is an indication of incurred cost of setup is the result of the energy management action. The cost incurred from the case study result is minimal compared to the total savings realized from participating in energy management programs.

3.4 Conclusion

This chapter proposed a cost-effective energy-integrated production scheduling model in a typical manufacturing system with multiple machines and buffers towards sustainability. A mathematical model is established to optimally schedule the production to minimize the total cost which includes: raw material cost, buffer inventory cost, setup cost, and energy cost. A mixed integer nonlinear programming problem is applied to formulate the problem and the General Algebraic Modeling System (GAMS) is used to solve the problem to obtain an optimal solution. The result of the case study show that about 29.85% of total cost savings can be achieved with this model. Raw material is saved by 29.86% and energy is saved by 26.26%.

4. CONCLUSION AND FUTURE WORK

In this thesis, a mathematical model to investigate the effect of energy integrated production scheduling on a production system is developed. The model considers the production target and includes the raw material cost, energy cost, buffer inventory cost and setup cost.

The results of the case study shows that approximately 29.85% of overall cost can be saved from implementing this method. Graphical representation of the various costs indicate that energy management programs (energy efficiency and demand response) cannot only reduce energy consumption and electricity cost, but can also minimize waste by reducing the use of raw materials resulting in the minimization of expenditure on raw materials. In other words, production efficiency can be improved. The minimization of energy consumption from the case study, confirms that carbon dioxide can be reduced by implementing these energy management programs, thereby making an effort to reduce the continuously increasing warmth on planet earth.

This research work represents an initial academic exploration of the effects of scheduled energy management on the related cost factors in manufacturing systems. Further research on more impacts of energy management on manufacturing systems can be carried out.

For future work, focus can be directed towards the impact of these energy management programs on the cost of labor and the maintenance activities that take place during a production process, with consideration of the various operating states of the machine. Considering the labor cost, it may be worthwhile for industries to establish what kind of payment pattern to adopt while participating in the energy management program, the cost-benefits and the risk of adopting a particular payment pattern (hourly or monthly). The maintenance activities on the other hand, may be a good exploration ground. Planned preventive maintenance is known to be designed to improve equipment life and avoid unplanned maintenance, in which case, it can be said that planned preventive maintenance of manufacturing systems will improve sustainability. It is considered important to undertake further studies on the effects and relationship of scheduled preventive maintenance with energy management scheduled programs.

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