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Flow Shop Scheduling for Energy Efficient Manufacturing

Hao Zhang
Purdue University

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Fu Zhao Chair	APPROVED 05/25/2016
John W. Sutherland	APPROVED 05/29/2016
Loring F. Nies	APPROVED 06/01/2016
Andrew (Lu) Liu	APPROVED 05/31/2016

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Approved by Major Professor(s): Fu Zhao

Approved by: Jay P. Gore 6/5/2016

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FLOW SHOP SCHEDULING FOR ENERGY EFFICIENT MANUFACTURING

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Dedicated

to my beloved parents and to my lovely husband

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NOMENCLATURE

Variables

Variable	Description
$P_t(\cdot)$	Real-time electricity rate at time *t*
L_t	Total power demand of residential buildings, commercial buildings, and manufacturing facilities at time *t*
$L_{R,t}$	Power demand of residential buildings at time *t*
$L_{C,t}$	Power demand of commercial buildings at time *t*
$L_{M,t}$	Power demand of factories at time *t*
a, b	Parameters which determine the characteristics of the electricity curve
m	Total number of machines per flow shop
N_0	Production throughput for each flow shop in one factory
N_{it}	Number of products that have been completed on machine *i* by time *t*
p_i	Processing time of machine *i*
q_i	Power demand of machine *i*
x_{it}	Equal to 1 if machine *i* processes a product at time *t*, and 0 otherwise
y_{it}	Equal to 1 if machine *i* starts processing a product at time *t*, and 0 otherwise
f_t	Electricity consumption of a flow shop at time *t*
m_s	Total number of machines per flow shop in factory *s*
$N_{0,s}$	Production throughput for each flow shop in factory *s*
$N_{i,t,s}$	The number of products that have been completed on machine i_s by time *t* in factory *s*
$p_{i,s}$	Process time of machine i_s (to complete process i_s) in factory *s*
$q_{i,s}$	Power demand of machine i_s (to complete process i_s) in factory *s*
$x_{i,t,s}$	Equal to 1 if machine i_s processes a product at time *t* in factory *s*, and 0 otherwise
$y_{i,t,s}$	Equal to 1 if machine i_s starts processing a product at time *t* in factory *s*, and 0 otherwise
T	Total production time
$P_{average}$	The mean electricity price for a previous period
σ	Standard deviation of the electricity price for a previous period
K_{min}, K_{max}	The range of changes in the price for a unit changes in temperature
T_{min}, T_{max}	The range of temperature that customers will accept
$P_{pricesignal}$	Current electricity price signal

T_{set}	Original set temperature
T_{reset}	Reset temperature
$T_{exp.}$	Expected temperature at the average electricity price
T_{set}	Occupies' set temperature
T_{reset}	Occupies' reset temperature
L_h	Average electricity consumption at hour h
T_h	Threshold load at hour h
Δ_h	Difference between threshold T_h and total electricity consumption L_h of all factories at hour h
a_h	Electricity price at hour h
b_h	Electricity price at Level 2 during hour h
c_h	Electricity price at Level 1 during hour h
S	Total number of factories
n_s	Total number of flow shops in factory s
$F_{s,h}$	Hourly electricity consumption of the factory s at hour h
$o_{s,h}$	Non-shiftable loads in factory s at hour h
$f_{s,h}$	Shiftable loads in factory s at hour h
$T_{s,h}$	Factory s's virtual threshold at hour h
$\Delta_{s,h}$	Difference between Factory s's virtual threshold $T_{s,h}$ and its electricity consumption $F_{s,h}$ at hour h
H	Total production time
k	The *kth* iteration
$L_{s,t}$	Electricity consumption of factory s at time t
$L_{v,t}$	Electricity consumption of factory v at time t

Abbreviations

Variable	Description
IBR	Inclining block rate
TOU	Time-of-use
RTP	Real-time pricing
CPP	Critical peak pricing
NP	Non-deterministic Polynomial-time
MOACSA	Multi-objective ant colony system algorithm
MOACO	Multi-objective ant colony
CDS	Campbell, Dudek, and Smith
CNC	Computer (or computerized) numerical control
HVAC	Heating ventilation and air conditioning
FERC	Federal Energy Regulatory Commission

ABSTRACT

Zhang, Hao. Ph.D., Purdue University, August 2016. Flow Shop Scheduling for Energy Efficient Manufacturing. Major Professor: Fu Zhao, School of Mechanical Engineering.

A large number of new peaking power plants with their associated auxiliary equipment are installed to meet the growing peak demand every year. However, 10% utility capacity is used for only 1%~2% of the hours in a year. Thus, to meet the demand and supply balance through increasing the infrastructure investments only on the supply side is not economical. Alternatively, demand-side management might cut the cost of maintaining this balance via offering consumers incentives to manage their consumption in response to the price signals.

Time-varying electricity rate is a demand-side management scheme. Under the time-varying electricity rate, the electricity price is high during the peak demand periods, while it is low during the off-peak times. Thus, consumers might get the cost benefits through shifting power usages from the high price periods to the low price periods, which leading to reduce the peak power of the grid.

The current research works on the price-based demand-side management are primarily focusing on residential and commercial users through optimizing the “shiftable” appliance schedules. A few research works have been done focusing manufacturing facilities. However, residential, commercial and industrial sectors each occupies about one-third of the total electricity consumption. Thus, this thesis investigates the flow shop scheduling problems that reduce electricity costs under time-varying electricity rate.

A time-indexed integer programming is proposed to identify the manufacturing schedules that minimize the electricity cost for a single factory with flow shops under time-of-use (TOU) rate. The result shows that a 6.9% of electricity cost reduction can be reached by shifting power usage from on-peak period to other periods.

However, in the case when a group of factories served by one utility, each factory shifting power usage from on-peak period to off-peak hours independently, which might change the time of peak demand periods. Thus, a TOU pricing combined with inclining block rate (IBR) is proposed to avoid this issue. Two optimization problems are studied to demonstrate this approach. Each factory optimizes manufacturing schedule to minimize its electricity cost: (1) under TOU pricing, and (2) under TOU-IBR pricing. The results show that the electricity cost of each factory is minimized, but the total electricity cost at the 2nd hour is 6.25% beyond the threshold under TOU pricing. It also shows that factories collaborate with each other to minimize the electricity cost, and meanwhile, the power demand at each hour is not larger than the thresholds under TOU-IBR pricing.

In contrast to TOU rate, the electricity price cannot be determined in ahead under real-time price (RTP), since it is dependent on the total energy consumption of the grid. Thus, the interactions between electricity market and the manufacturing schedules bring additional challenges. To address this issue, the time-indexed integer programming is developed to identify the manufacturing schedule that has the minimal electricity cost of a factory under the RTP. This approach is demonstrated using a manufacturing facility with flow shops operating during different time periods in a microgrid which also served residential and commercial buildings. The results show that electricity cost reduction can be achieved by 6.3%, 10.8%, and 24.8% for these three time periods, respectively. The total cost saving of manufacturing facility is 15.1% over this 24-hour period. The results also show that although residential and commercial users are under “business-as-usual” situation, their electricity costs can also be changed due to the power demand changing in the manufacturing facilities.

Furthermore, multi-manufacturing factories served by one utility are investigated. The manufacturing schedules of a group of manufacturing facilities with flow shops subject to the RTP are optimized to minimize their electricity cost. This problem can be formulated as a centralized optimization problem. Alternatively, this optimization problem can be decomposed into several pieces. A heuristic approach is proposed to optimize the sub-optimization problems in parallel. The result shows that both the individual and total electricity cost of factories are minimized and meanwhile the computation time is reduced compared with the centralized algorithm.

CHAPTER 1. INTRODUCTION

1.1 Motivations

According to the International Energy Outlook, world energy consumption will rise by 56% between 2010 and 2040, mainly driven by demand increases in developing countries [1]. About 85% of the total energy consumed comes from coal, oil, and natural gas, which raises concerns regarding greenhouse gas emissions and fossil fuel depletion [2]. Electricity, an inherent portion of energy, flows through power distribution and transmission lines to the end users. However, the electricity is hard to be stored in bulk. Thus, a huge number of infrastructures are installed for peak demand use to meet the electricity demand requirements and avoid risks of a power outage in the grid. Additionally, investments in the grid will be increased due to the cost of peaking power plants and their associated equipment, e.g., power transformers, transmission substation, and distributions, are expensive. However, 10% utility capacity is used for only a few hundred hours per year, which is 1%~2% of the year [3]. Thus, to balance the demand and supply only from the supply side is not economic sense.

Alternatively, demand-side management might improve the system energy-efficiency and reduce the total cost of maintaining demand and supply balance through incentivizing consumers to change their electricity consumptions. The Federal Energy Regulatory Commission (FERC) uses this definition of demand response: "*Changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*" [4]. As FERC suggests, the time-based (price-based) demand-side management is proposed, which incentivize customers to change electricity use in response to price changes [5]. Currently, the most commonly used time-based demand response program consists of TOU pricing, RTP, and critical peak price (CPP) [6]. Under the time-varying electricity rates, the rate is high during the high demand periods, while it is low for the other time periods. Besides, end users are allowed to choose how much electricity to purchase and when to purchase. Thus, consumers have the abilities to shift their electricity usages from high price periods to low price periods under the time-varying electricity rate aiming at reducing the electricity cost. As a result, both the electricity cost of consumers and the peak demand of the grid can be reduced.

Residential, commercial, and industrial sectors each occupies one-third of electricity consumptions in the electricity market. However, most research related to the interactions between the behaviors of consumers and market price has focused on reducing electricity cost of residential or commercial buildings via optimizing the “shiftable” appliance schedules [7]. Much fewer research works have been done to date for manufacturing facilities due to that manufacturing scheduling in factories is much more complicated than scheduling lights, washing machines, etc. in residential and commercial buildings. In a manufacturing facility, the required production throughput capacity needs to be achieved and tasks cannot be interrupted randomly (non-preemptive), which make the scheduling problem challenging [8]. To meet this challenge, a time-indexed integer programming formulation is proposed to formulate the mathematical model of the scheduling problem that finds the minimal electricity cost under the time-varying electricity rate in this research work.

Furthermore, the infrastructure of today’s electrical system is aging which makes difficult to meet yet even greater electricity demand. Moreover, environmental issues, e.g., climate change, ozone depletion, toxicity, acidification, non-renewable energy resource depletion, need to be considered when updating today’s aging power system [9]. Smart grid, a more intelligent, reliable, stable and secure electrical system can integrate the electricity generated by renewable energy sources in the electrical distribution system [10]. This distribution system will be able to meet environmental targets, quickly respond to increasing demands for electricity generation, and electricity distribution to end users in a more efficient way. One of the key features of the smart grid is demand response management. For example, smart meters have been deployed to exchange information on electricity price and electricity demand. As a result, consumers may make more informed decisions on electricity consumption and can reduce their power consumption during on-peak hours and shift their demand to off-peak hours [11].

As electrical distribution systems are moving toward a smart grid structure, these dynamic interactions between the behavior of manufacturing facilities and the market price have to be considered when developing new manufacturing schedules. Accordingly, manufacturing scheduling problem in the smart grid scenario consists of two aspects: (a) optimizing manufacturing schedules based on the time-varying electricity price, and (b) the demand energy changes of manufacturing factories can change the electricity market rate. This brings additional challenges but also raises an opportunity for enterprises to achieve even larger savings on electricity cost. Thus, in addition to optimizing manufacturing schedules under time-varying electricity rate to minimize electricity cost, this research work also investigates on the interactions between the market price and manufacturing schedules.

Thus, this thesis is focusing on optimizing manufacturing schedules for factories under different time-varying electricity rate, i.e., TOU rate and RTP, with the objective to minimize the electricity cost. In addition to minimizing electricity cost for a single factory, the scheduling problems that minimize total cost of collaborative manufacturing facilities are investigated. Each factory optimizes its manufacturing schedules to minimize electricity cost independently, which might lead to shifting peak demand from one period to another. To address this issue, a hybrid TOU combined with IBR pricing is proposed in this thesis. Additionally, a distributed algorithm is explored to improve the computational efficiency. The research objective, goal, and organization of this thesis are listed in the following section.

1.2 Research Objective, Goal, and Organization of the Thesis

This research work is focusing on flow shop scheduling problems that minimize the electricity cost under time-varying electricity rates. Flow shop has lower flexibility than other type of processes, and the direct labor content is very low. The overarching goal will be broken down into major research objectives:

- Flow shop optimization problem that minimizes electricity cost for one manufacturing facility with flow shops under the TOU rate.
- Flow shop optimization problem that minimizes electricity cost for multiple manufacturing facilities with flow shops under the TOU rate.
- Flow shop optimization problem that minimizes electricity cost for one manufacturing facility with flow shops under the RTP.
- Flow shop optimization problem that minimizes electricity cost for multiple manufacturing facilities with flow shops under the RTP.

Chapter 1 introduces the motivation, research objective, research goal and the organization of this thesis. In Chapter 2, the literature on shop floor scheduling with different criteria such as makespan (total production time), energy consumption, and electricity cost are reviewed. Additionally, multi-agent coordination related research works are examined. Chapter 3 focuses on the manufacturing scheduling problem that minimizes the electricity cost for a single manufacturing facility with flow shops under TOU rate. Besides, scheduling of multiple factories under TOU rate and TOU-IBR pricing is also investigated. Chapter 4 optimizes the manufacturing schedules of one factory with flow shops under RTP with the objective to minimize electricity cost. Additionally, the scheduling problem that minimizes the electricity cost for multiple factories under RTP is investigated.

CHAPTER 2. LITERATURE REVIEW

2.1 Shop Floor Scheduling to Minimize Makespan

Over the past few decades, the manufacturing scheduling with the objective of minimizing makespan (total completion time) attracted many researchers [12]. Johnson was a pioneer in research on minimizing the makespan for *two*- and *three*- machine flow shop problems and proposed a “rough” algorithm to solve this scheduling problem [13]. From then on, research groups started to work on the flow shop scheduling problem that minimizes the makespan. This problem is in general challenging, and in most cases, is NP-hard (non-deterministic polynomial-time hard) [14]. Considering the NP-hardness, Ignall and Shrage adopted a branch-and-bound technique to minimize the makespan of a flow shop with *ten* jobs and *three* machines. However, for larger-sized problems, this type of algorithm is not well suited anymore [15]. Following works were focusing on tackled NP problems, heuristics such as genetic algorithms, simulated annealing, ant colony, and tabu search were proposed to solve them [16] [17] [18]. For example, Osman and Potts used simulated annealing to obtain an approximate solution for flow shop scheduling problem with the objective of makespan minimization [19]. Similar work has been done by Van Laarhoven et al.. They further developed the simulated annealing algorithm through creating an approximation algorithm based on simulated annealing for the scheduling problem to find the minimum makespan in the job shop. The result showed a better chance of reaching the global optimum compared with the original simulated annealing algorithm [20]. Even better performance for the flow shop scheduling problem was achieved by adopting a tabu search approach for a manufacturing system with up to 20 machines [21]. Recently, an ant colony optimization approach was demonstrated to be preferable when identifying optimal flow shop scheduling with the goal of minimizing makespan. Considering *m*-machine with objectives of minimizing makespan and total flow time, Yagmahan and Yenisey presented a multi-objective ant colony system algorithm (MOACSA) and tested it against existing heuristics [22]. The results showed that MOACSA was more efficient. For a further study, the ant colony optimization and fast tabu are combined to improve the solution quality to the scheduling problem that minimizes the makespan in job shops [23].

However, to identify the optimal manufacturing schedule that minimizes makespan for a flow shop is computationally demanding. The computation time is dependent on the total number of jobs and machines per flow shop; for example, a flow shop with n jobs and m machines will have $(n!)^m$ possible scheduling sequences. Thus, the computation time will increase dramatically with the problem size. To address this issue, a genetic algorithm was developed based on a CDS (Campbell, Dudek, and Smith) heuristic, which is an extension to Johnson's algorithm; this method was shown to shorten computation time for an m-machine flow shop problem when compared with some existing heuristics [24]. In the above work, the computation time is considered, while the solution quality is not. Considering both computation time and solution quality, an ant colony optimization approach was applied in the flow shop scheduling problem. This approach gives a higher quality solution in a short time compared with other state-of-the-art algorithms [25]. The researchers are not only focusing on the solution quality and computation time of the job shop scheduling problem that minimizes the makespan.

More production constraints or objectives have been taken into consideration to make the scheduling problem more realistic. Fang et al. solved a scheduling problem that minimized makespan of a flow shop with peak power consumption constraints using a primary assignment and positional formulation, and combined this basic formulation with non-delay valid inequalities to study solution quality and computation time [26]. It should be noted that the buffer is infinite in these works. However, in the real manufacturing systems, the buffer size is finite due to the limited production room. A flow shop scheduling problem with limited buffers is considered by Wang et al. [27]. They proposed a hybrid genetic algorithm to find the optimal schedule that minimizes the makespan. Nevertheless, they compared the solution quality with other heuristics regardless of considering the computation time. Considering both the computation time and solution quality, Liu et al. studied a similar flow shop scheduling problem, and proposed an effective hybrid algorithm based on the particle swarm optimization [28]. In the term of time-varying electricity rate consideration, the time associated manufacturing process might be subject to a different electricity cost. Thus, under the time-varying electricity cost, manufacturing facilities might reduce their cost through manufacturing scheduling [29].

2.2 Shop Floor Scheduling to Minimize Energy Consumption

Traditionally, manufacturing scheduling has been focused on minimizing the makespan to reduce the product cost. However, efforts have begun to be initiated relative to developing energy-conscious scheduling strategies [30] [31] [32] [33] [34]. The inclusion of energy considerations into manufacturing scheduling is gaining increased interests, mainly due to concerns about increasing electricity price and environmental considerations.

At the machine level, Mouzon et al. investigated the scheduling of a computer or computerized numerical control (CNC) machine in a machine shop for a supplier of small aircraft parts [35]. It was shown that leaving the non-bottleneck machines idle could lead to energy savings. Shrouf et al. proposed a mathematical model to minimize energy consumption costs for a single machine through optimizing the production scheduling and a near-optimal solution is identified by using the genetic algorithm [36]. In addition, Mouzon and Yildirim studied the same manufacturing environment and proposed a metaheuristic framework to minimize both the energy consumption and the total tardiness on a single machine [37].

There are several recent studies focusing on scheduling at the shop floor level for improving energy efficiency in addition to working at the machine level. For example, Wang et al. proposed an optimal scheduling procedure by selecting appropriate product sequence and batch policies for an automotive paint shop in order to reduce energy consumption and repaints and improve paint quality [38]. He et al. developed a heuristic algorithm for solving the problem of minimizing both energy consumption and makespan in a job shop with constant speed machines [39]. It should be noted that machine speed can also serve as a decision variable, since speed modifications can change machine cycle time, peak load, energy consumption, which in turn affect the utility bill. Fang et al. explored the case when machine speed is allowed to change [31].

In addition, these scheduling problems implemented heuristics to find a near-optimal solution but not a global optimum solution. In this research work, a time-indexed integer programming approach is developed to formulate the mathematical model for flow shop under time-varying electricity rate with the objective of minimizing electricity cost, and meanwhile maintaining the production throughput. Some previous works have been done by my colleagues. For instance, Fang et al. solved a flow shop scheduling problem with peak power consumption constraints, and various machine speeds by an integer programming approach and tested this approach with instances arising from the manufacturing of cast iron plates [31].

2.3 Shop Floor Scheduling to Minimize Electricity Cost under Time -Varying Rate

In addition to minimizing the makespan, and energy consumption, cost saving opportunity exists when the manufacturing facility is subject to time-varying electricity rates. Some relevant research work has been done for residential and commercial buildings through optimizing the appliance schedules under the time-varying electricity rate. For example, Cai et al. applied a multi-agent control approach to schedule the indoor space temperature setpoint for cost minimization of multi-zone building/building clusters under TOU rate structures with demand charges [40]. However, there were a few previous studies investigated optimal manufacturing schedules under the time-varying electricity rate. Nilsson and Söderström studied the impact of different electricity tariffs on industrial production planning and the potential of reducing electricity cost by shifting electricity usage from a high-rate period to a low-rate period [28]. The electricity rate of the above work is a two-rate tariff, i.e., high rate, and low rate. A more complicated electricity tariff is considered, Ashok optimized the demand load schedule for different types of industries (i.e., flour mills, or a mini steel factory) to minimize the electricity cost under a three-rate tariff, meanwhile satisfying production, process flow, and storage constraints. As a result, both the electricity bills and peak demands can be reduced significantly [41] [42].

There are three different forms of time-varying electricity tariffs: TOU pricing, CPP, and RTP [43]. For TOU tariff, the electricity price schedule can be given to consumers in advance, but it may vary by the day, season, and weather to reflect changes in the wholesale electricity market [44]. Under CPP tariff, electricity price on peak days is different from the price on nonpeak days [45]. For RTP, electricity price varies continuously throughout the day and relies on the amount of demand and supply [46].

2.3.1 Shop Floor Scheduling to Minimize Electricity Cost under TOU Rate

The TOU rate provides a huge opportunity to reduce costs for electricity-intensive consumers by shifting electricity usage from on-peak hours to off-peak or mid-peak hours. Under TOU tariffs, the electricity cost is based on consumed electricity over time, and takes into account that each period has a corresponding price per unit of electricity consumed. This presents an interesting challenge in terms of minimizing the total electricity cost in a scheduling problem. For example, Wan and Qi considered a single machine scheduling problem in which each time period has an associated cost [47]. The objective of their paper was minimizing cost while considering traditional scheduling performance measures; they showed that such problems are NP-hard. However, this work is about a single machine scheduling problem. A more complicated manufacturing system model was investigated by Moon et al.. They proposed a hybrid genetic algorithm aiming at minimizing makespan and electricity cost for job shops having unrelated parallel machines under a predetermined hourly electricity rate [29]. For a further research work, computation time and solution quality are considered. Luo et al. presented a new ant colony optimization meta-heuristic (MOACO) to optimize both makespan and cost in a hybrid flow shop under TOU rate. The experimental result showed that MOACO has a better performance of solution quality compared with other evolutionary algorithms [48]. In these research works, the buffer size is infinite. In view of multiple machines and limited buffers, Wang and Li presented the per product electricity cost model with the objective of minimizing electricity consumption and peak demand under TOU rate [3].

Under TOU rate, electricity price is fixed, and the demand side decision making cannot change the market electricity rate. Different from TOU pricing, RTP can better reflect changes in the market's supply and demand balance. Under RTP, the market electricity price and the schedules of machines are coupled. This introduces additional challenges, but also presents an opportunity for enterprises to achieve even larger electricity cost savings.

2.3.2 Shop Floor Scheduling to Minimize Electricity Cost under RTP

Under RTP, the electricity rate is updated every certain period. On the one hand side, manufacturing facilities will dynamically update their optimal schedules that have the minimal electricity cost based on the real-time price signal. On the other hand side, the demand changing of factories might effect on the electricity market price. Thus, under RTP, the dynamic interactions between electricity market and demand side are taken into the considerations, and which can definitely bring additional challenges to identify the manufacturing schedule that minimizes total electricity cost. Most existing research is focusing on residential or commercial buildings. For instance, Mohsenian-Rad et al. investigated how to reduce electricity costs for residents by using price prediction in real-time pricing environments [49]. Utility companies provide the price information for one or two hours in ahead, which will be used for price prediction. Thus, this work has a high requirement for the utility companies. In another work, Mohsenian-Rad et al. tackled this problem by deploying of devices that allow the residents interact with the power grid and local area networks automatically. A distributed algorithm was developed for these devices to identify the optimal energy consumption schedules that minimized both the total electricity cost and the peak to average ratio for residential subscribers [50]. Compared with above works for residential and commercial buildings, much less research has been done for manufacturing facilities. Moon and Park studied on the interactions between the manufacturing facilities and utilities, and optimized productions schedules and distributed energy sources schedules with the objective of minimizing electricity cost [51]. However, in the real market, residential buildings and commercial buildings might exist in addition to manufacturing factories. Additionally, collaborations among multi-factories to minimize electricity cost are not examined in their works.

2.4 Multi-agent Coordination for Energy Consumption Scheduling

Under the predetermined time-varying electricity rate, if all the factories shift their electricity usages from higher price periods to lower price periods aiming at reducing electricity cost, the demand power during the original off-peak period might be increased and become a new peak demand period [52]. As a result, the peak period of the grid moves due to factories shifting their electricity usages, and meanwhile the demand and supply balance of the grid might be disturbed. One commonly used method to deal with this issue is that the utility companies supply all the required demand power. However, to balance the demand and supply, only through the supply side management might be too expensive. An alternative way is to control the aggregate load of a group of consumers instead of individual consumers through demand side program [53].

The current multi-agent demand response related research mainly focuses on energy consumption scheduling, especially for residential and commercial buildings. For example, Li et al. researched on heating ventilation and air conditioning (HVAC) systems and proposed a model that simulates the energy behaviors of HVAC systems in commercial buildings, which can be used to predict the energy consumption of HVAC system. The interactions among multi-agent system are also included [54]. In the term of electricity price consideration, Veit et al. proposed a virtual price signal by a coordinator to guide consumers shifting electricity usages from high price periods to low price periods, and developed a multi-agent coordination algorithm to shape the energy consumption schedules for each agent [52]. It should be noted that the above research work paid close attention to total energy consumption instead of individual energy consumption. However, the situations under manufacturing facilities are more complicated due to the energy consumption schedules are restricted by the manufacturing processes and the production throughput.

Factory optimizes its manufacturing schedule based on the time-varying electricity price to reduce the electricity cost, and the updated manufacturing schedules of the factory can influence electricity market price. In that case, the electricity cost of a factory is dependent on the manufacturing schedules of itself and other factories'. This scheduling problem can be formulated as a centralized problem formulation, in which the computation time is exponential to the size of the manufacturing facility, e.g., the number of machines, flow shops, and manufacturing facilities. In the case when more manufacturing facilities participate in the event, the computation time might be increased dramatically. An alternative method that decomposes this optimization problem into sub-optimization problems is in great needed. For example, Mohsenian-Rad et al., primarily focused on the interactions among users and one utility, proposed distributed demand-side energy management strategies by using game theory [55]. This optimization problem was decomposed into a distributed fashion to reduce the computation time and complexity.

In this thesis, the approach used to identify manufacturing schedules that minimize the electricity cost of manufacturing facilities with flow shops subject to the time-varying electricity rate will be presented. In addition, both the individual electricity cost and total electricity cost will be minimized under TOU rate, and RTP, respectively. In the smart grid scenario, under "cost saving" or "business-as-usual" situations of residential and commercial buildings, and manufacturing facilities will be investigated.

CHAPTER 3. FLOW SHOP SCHEDULING UNDER TOU RATE

Most existing flow shop scheduling problems are focusing on minimizing the makespan to reduce product costs. As the development of the grid, time-varying electricity rate emerges, which has higher electricity price during the high demand periods. Thus, the time-varying electricity rate allows manufacturing facilities to reduce their electricity bills through shifting electricity usages from the high price periods to the other periods. As a result, the overall product cost in the manufacturing factory can be reduced. Two cases will be studied: (1) Flow shop optimization problem that minimizes electricity cost for one manufacturing facility with flow shops under the TOU rate. (2) Flow shop optimization problem that minimizes electricity cost for multiple manufacturing facilities with flow shops under the TOU rate.

3.1 Flow Shop Scheduling For One Factory under TOU Rate

In this section, two optimization problems will be examined for a manufacturing factory with one flow shop under TOU rate through manufacturing schedules: (1) to minimize the makespan, (2) to minimize the electricity cost.

3.1.1 TOU Rate

Under TOU pricing, consumers are charged by the utility companies depending on the time of the day. As shown in Figure 3-1, TOU rate has three periods, i.e., on-peak hours, mid-peak hours, and off-peak hours. The electricity price is high during the peak hours, while it is low at the mid-peak and off-peak hours. Thus, consumers can reduce their electricity bills through shifting electricity usage from the on-peak hours to the mid-peak hours or off-peak hours.

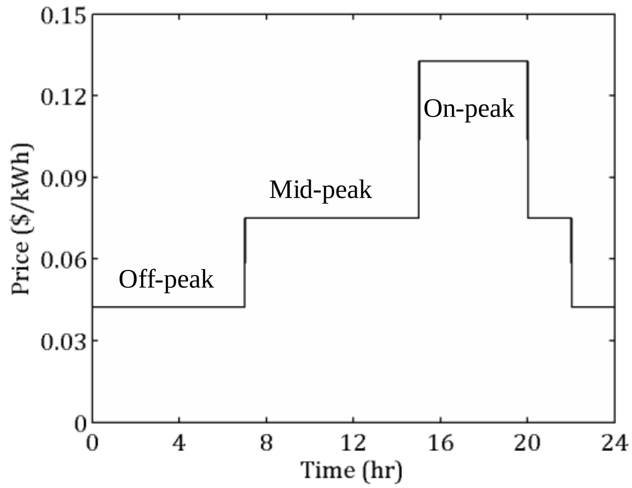

Figure 3-1. Electricity price ($/kWh) over a 24-hour time period.

3.1.2 Optimization Problem Formulation

The flow shop has *m* machines totally. All the products have the same processing order, and each product is processed by machine 1 → machine 2 →,…, → machine *m*. The production quota is N_0. The processing time of a product on machines *i* is p_i, and its associated power demand is q_i.

To simplify the problem, the following assumptions are made: (a) each machine has on-mode and off-mode; (b) each product must be processed continuously; (c) machines run automatically; (d) the machine speed is constant; (e) there is only one machine available for each operation; (f) labor cost is not considered in this research; and (g) the products in the same flow shop are the same.

The decision variables are (a) N_{it} is the total number of products that have been finished on machine *i* by time *t*; (b) when machine *i* is processing a product at time *t*, x_{it} equals to 1, and otherwise x_{it} is 0; and (c) when machine *i* starts processing a new product at time *t*, y_{it} equals to 1, and otherwise y_{it} equals to 0.

The following integer programming model seeks to identify the schedule that has the minimal total electricity cost for this problem with the assumption that both *t* and p_i are integer values:

$$\min \sum_{t=0}^{T} P_t\left(L_t\right) f_t \tag{3.1}$$

where, P_t (•)is the electricity price at time t, and it is subject to TOU rate. L_t is the total electricity consumption at time t. T is total time. f_t is the electricity consumption of one flow shop at time t.

At time t, the electricity consumption f_t of one flow shop can be represented as:

$$f_t = \sum_{i=1}^{m} q_i \, x_{it} \tag{3.2}$$

Subject to:

$$N_{it} = 0, (t = 0, ..., p_i - 1; i = 1, ..., m) \tag{3.3}$$

$$N_{it} = \sum_{k=0}^{t-p_i+1} y_{ik} \; , (t = p_i, ..., T \; , i = 1, ..., m) \tag{3.4}$$

$$N_{it} \geq N_{i+1,t} + x_{i+1,t}, (i = 1, ..., m-1; t = 0, ..., T) \tag{3.5}$$

$$N_{mT} \geq N_0 \tag{3.6}$$

$$N_{it} \in \mathrm{Z}, (i = 1, ..., m; t = 0, ..., T) \tag{3.7}$$

$$x_{it}, y_{it} \in \{0,1\}, \; (i = 1, ..., m; t = 0, ..., T) \tag{3.8}$$

$$x_{it} = \sum_{k=0}^{t} y_{ik}, (t = 1, ..., \; p_i - 1; i = 1, ..., m) \tag{3.9}$$

$$x_{it} = \sum_{k=t-p_i+1}^{t} y_{ik}, (t = p_i, ..., T; i = 1, ..., m) \tag{3.10}$$

$$\sum_{k=t}^{t+p_i\text{-}1} x_{ik} \geq p_i y_{it}, (t = 1, ..., T - p_i + 1; i = 1, ..., m) \tag{3.11}$$

Equation (3.3)-Equation (3.4) determine how many of products that have completed on machine i by time t. Equation (3.5) ensures that the products are produced in the flow shop. Equation (3.6) ensures that the number of products produced by the time T is at least N_0. Equation (3.7)-Equation (3.11) ensure that production process cannot be interrupted.

3.1.3 Case Study

As shown in Table 3-1, the TOU rate for a summer season (June - September) consists of three time periods, i.e., on-peak hours, mid-peak hours, and off-peak hours. The time slots and electricity price at each period are listed in this table.

Table 3-1. TOU electricity rate.

<table>
<tr><th>Period</th><th>Price ($/kWh)</th><th>Weekday:</th><th>Weekend/Holidays:</th></tr>
<tr><td>On-Peak Period</td><td>0.1327</td><td rowspan="3">On-Peak Period:
15:00 through 20:00

Mid-Peak Period:
7:00 through 15:00
20:00 through 22:00

Off-Peak Period:
All Other Hours</td><td rowspan="3">All Hours are off-peak period</td></tr>
<tr><td>Mid-Peak Period</td><td>0.0750</td></tr>
<tr><td>Off-Peak Period</td><td>0.0422</td></tr>
</table>

In this example, the total production throughput per flow shop is 80 over a 16-hour period (6:00-22:00). Each product is required to be produced through eight processes in the order of Process A→ Process B→…→ Process H. The processing time and processing power are listed in Table 3-2.

Table 3-2. Flow shop parameters.

Process	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Processing time (minute/part)	5	2	8	6	5	10	8	6
Processing power (kW)	20	30	15	10	15	30	10	20

Figure 3-2 shows the on and off modes of machines over the time horizon in the case when the makespan is minimized. The processing time per part on machine B is shorter than that on machine A. Thus, machines B works intermittently. Similarly, the processing time per part on machine C is longer than that on machine B. As a result, machine C runs continuously. Machine A and B finish production at the almost same time, which is around 12:40. Machines C, D and E stop at 16:50. Machines F, G, and H finish production at around 20:00.

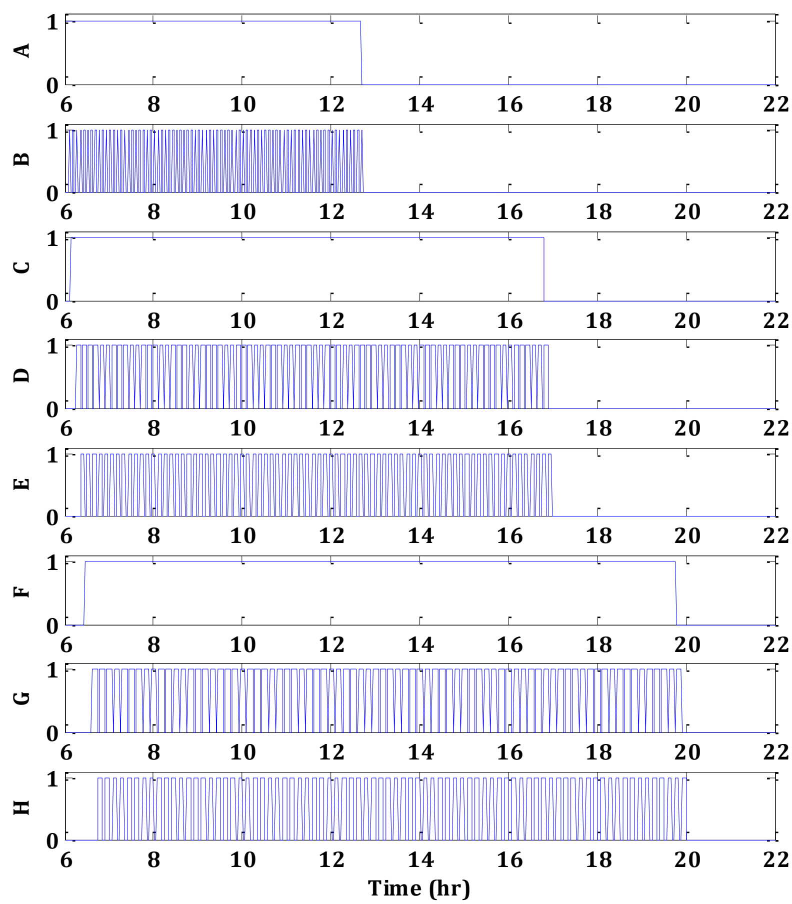

Figure 3-2. Flow shop schedule that minimizes the makespan.

Figure 3-3 shows the real-time power demand of the factory with one flow shop in the case when the makespan is minimized. As shown, all the machines are trying to achieve each target production quota in the shortest possible time. As a result, the production finished at 20:00, and the total production time is 14 hours. The corresponding total electricity cost, in this case, is $103.8.

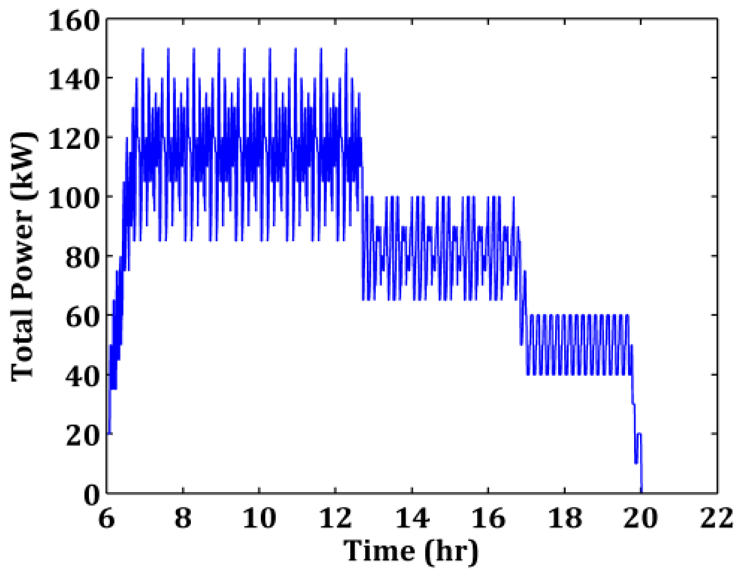

Figure 3-3. Power demand of flow shop in Case 1.

Figure 3-4 shows the on-off status of the machines that minimize the total electricity cost of the manufacturing factory under the TOU rate over 16-hour period. It is noticed that machines are randomly working during the on-peak period, i.e., 15:00-20:00, to avoid the high electricity price, while machines are continuously working during the off-peak period and the mid-peak period, i.e., 6:00-15:00 and 20:00-22:00.

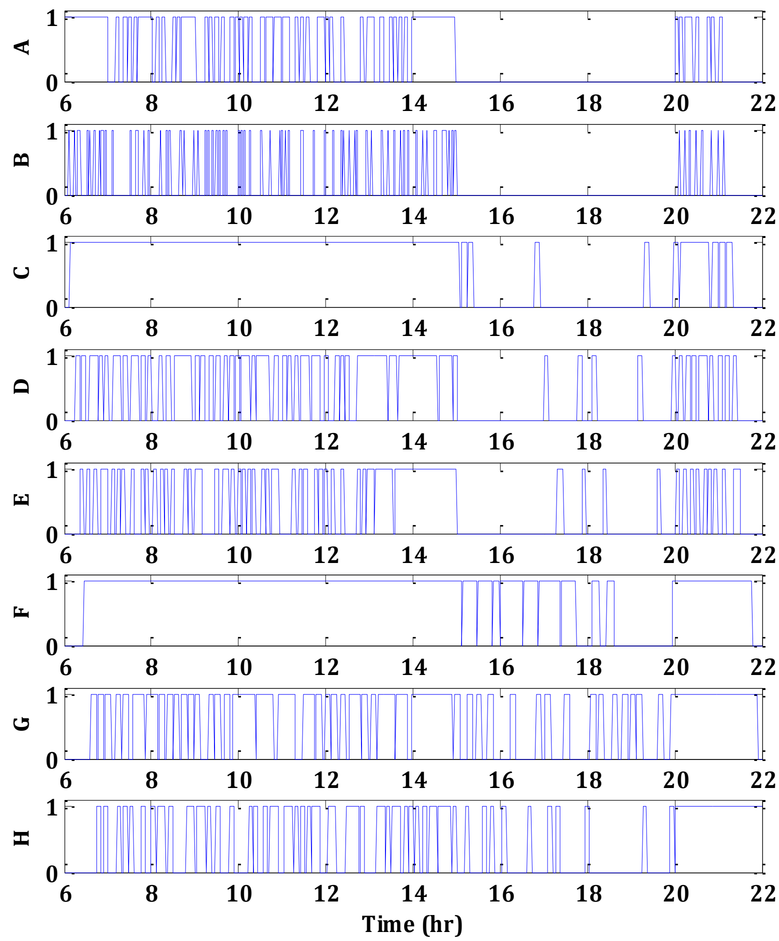

Figure 3-4. Flow shop schedule that minimizes the total electricity cost.

Figure 3-5 shows the real-time power demand of this factory under the TOU rate in the case when minimizing the total electricity cost. As shown, the total power demand during the peak hours (15:00-20:00) is much lower than that during the other periods. The associated total electricity cost is $96.6 in this case, which is 6.9% lower than that in the first case (makespan minimization).

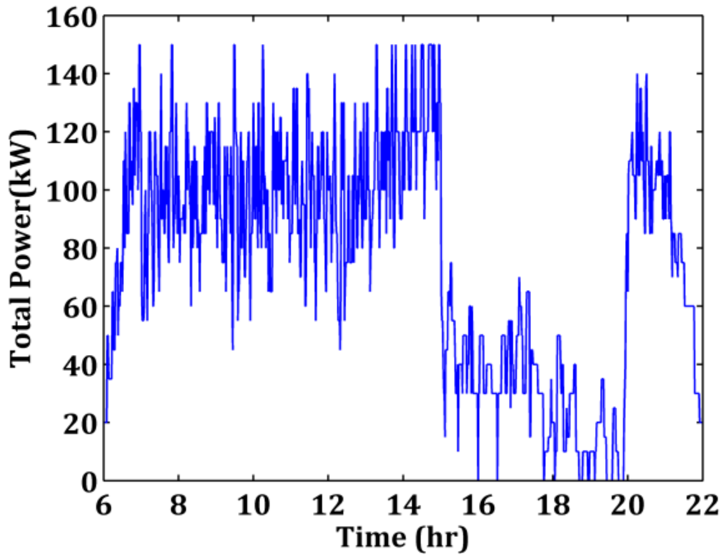

Figure 3-5. Power demand of flow shop in Case 2.

3.1.4 Conclusion

This section has optimized the manufacturing schedules for a factory with one flow shop under TOU rate. Two cases are considered: (1) to minimize the makespan, (2) to minimize the total electricity cost. The integer programming is applied to identify the optimal schedules for this flow shop with one job shop. The optimization problem is solved in Gurobi. A global optimum is obtained, but it is time-consuming. The result shows that a 6.9% of electricity cost reduction can be reached by shifting electricity usage from on-peak period to mid-peak or off-peak periods in Case 2, compared with that in Case 1.

The example shows that cost benefits can be obtained by the factory subject to TOU rate through manufacturing scheduling. However, if all the factories under TOU rate shift electricity usage from the on-peak hours to mid-peak or off-peak periods to reduce electricity costs, which might raise a peak demand during the off-peak period. To solve this issue, a new electricity rate will be proposed and examined in the next following section.

3.2 Flow Shop Scheduling For Multiple Factories under TOU Rate

In this section, the manufacturing schedules of multiple factories with flow shops under TOU electricity rate will be optimized to minimize electricity cost. Two optimization problems will be formulated based on different electricity pricing structures. The first optimization problem is: each factory optimizes the manufacturing schedule to minimize its own electricity cost under TOU pricing. However, the peak period might be shifted from the original time to another period. Due to this reason, a hybrid TOU-IBR pricing is proposed to avoid this issue. Thus, the second optimization problem is that each factory minimizes its own electricity cost under TOU-IBR pricing through manufacturing scheduling.

3.2.1 Model Description

Multiple factories with flow shops are served by one utility grid. Two electricity rates are considered: (1) TOU pricing, and (2) TOU-IBR pricing. One manufacturing facility might have several flow shops. To be simplified, the flow shops in the same manufacturing factories are the same.

3.2.1.1 TOU Rate

TOU rate is dependent on the time of a day and changed hourly. Thus, the TOU rate $P_t(L_t)$ at hour h can be represented as follows:

$$P_h\left(L_h\right)=a_h,\left(h=1,2,...,H\right) \tag{3.12}$$

where, a_h denote the electricity price at hour h. L_t represents the electricity consumption at hour h.

3.2.1.2 TOU-IBR Pricing Structure

In a two-level IBR structure, Level 1 denotes the low-level demand which has a low electricity rate, and Level 2 represents the high-level demand with a high electricity price. Figure 3-6 shows an example of a two-level IBR structure. As is shown, the threshold is

120kWh. Thus, electricity rate is 0.04$/kWh in the case when demand load is less than the threshold while it will be 0.15$/kWh if the threshold is exceeded.

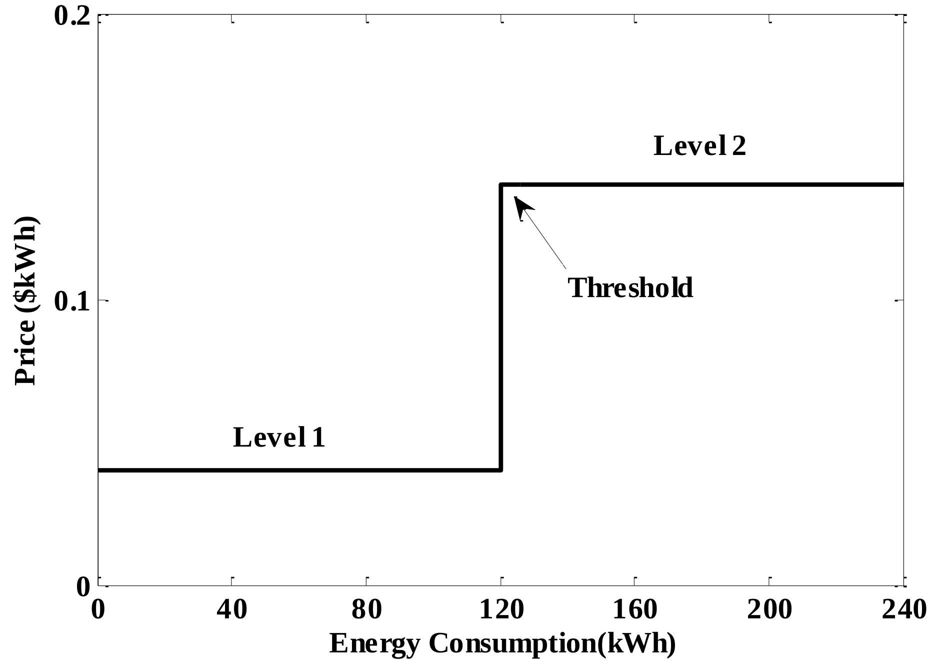

Figure 3-6. A two-level IBR structure.

Electricity price in IBR depends on the total demand of the consumers enrolled in this electricity structure. Thus, electricity rate $P_h(L_h)$ at hour h can be represented as:

$$P_h(L_h) = \begin{cases} c_h, if \ 0 < L_h \le T_h \\ b_h, if \ L_h > T_h \end{cases}, with\ c_h < b_h, (h = 1, 2, ..., H) \tag{3.13}$$

where, L_h is the average electricity consumption at hour h. T_t is the threshold load at hour h. c_h is electricity price at Level 1 during hour h. b_h is the electricity price at Level 2 during hour h. The electricity price at Level 1 (c_h) is lower than the price at Level 2 (b_h).

In this section, TOU rate is combined with a two-level IBR structure by assuming that electricity rate at Level 1 is equal to the TOU rate a_h.

$$c_h = a_h, (h = 1, 2, ..., H) \tag{3.14}$$

According to Equation (3.13) and Equation (3.14), the TOU-IBR pricing $P_h(L_h)$ can be formulated as:

$$P_h\left(L_h\right)=\begin{cases}a_h,\ if\ \ 0<L_h\le T_h\\ b_h,\ if\ \ L_h>T_h\end{cases},with\ a_h<b_h,(h=1,2,...,H) \tag{3.15}$$

where, if the electricity consumption L_h at hour h is less than the threshold T_h, the electricity rate is equal to a_h. The electricity rate is b_h, if the electricity consumption L_h at hour h is larger than the threshold T_h.

3.2.2 Optimization Problem Formulation

In this problem, a set of factories s, b_h is given. It is assumed that each flow shop in factory s (s=1,2,…,S) has several machines and each machine operates one process. The process order for each product in factory s is the same, which is machine 1 → machine 2 →,…, → machine m_s.

For this scheduling problem, it is also assumed that: (a) each the machine has on-mode and off-mode; (b) machines run automatically; (c) manufacturing process cannot be interrupt until it is finished; (d) the speed of machine is constant; (e) each flow shop produces one type of product; (f) the labor cost is not considered in this research; and (g) there is only one machines available for each operation. The electricity consumption of a flow shop in factory s at hour t can be expressed as:

$$f_{s,t}=\sum_{i_s}^{m_s}q_{i,s}\,x_{i,t,s} \tag{3.16}$$

Subject to:

$$N_{i,t,s}=0,(\,t=0,...,\,p_{i,s}-1;i_s=1,...,m_s\,) \tag{3.17}$$

$$N_{i,t,s}=\sum_{k=0}^{t-p_{i,s}}y_{i,k,s}\ ,(t=p_{i,s},...,T\ ,\,i_s=1,...,m_s) \tag{3.18}$$

$$N_{i,t,s}\ge N_{i+1,t,s}+x_{i+1,t,s},(i_s=1,...,m_s-1;t=1,...,T-1) \tag{3.19}$$

$$N_{m,T,s} \geq N_{0,s} \quad (3.20)$$

$$N_{i,t,s} \in Z, (i_s = 1, ..., m_s; t = 0, ..., T) \quad (3.21)$$

$$x_{i,t,s}, y_{i,t,s} \in \{0,1\}, \; (i_s = 1, ..., m_s; t = 0, ..., T) \quad (3.22)$$

$$x_{i,t,s} = \sum_{k=0}^{t} y_{i,k,s}, (t = 1, ..., \; p_{i,s} - 1; i_s = 1, ..., m_s) \quad (3.23)$$

$$x_{i,t,s} = \sum_{k=t-p_{i,s}+1}^{t} y_{i,k,s}, (t = p_{i,s}, ..., T; i_s = 1, ..., m_s) \quad (3.24)$$

$$\sum_{k=t}^{t+p_{i,s}-1} x_{i,k,s} \geq p_{i,s} y_{i,t,s}, (t = 1, ..., T - p_{i,s} + 1; i_s = 1, ..., m_s) \quad (3.25)$$

where, $N_{i,t,s}$ is the total number of products that have been completed processing on machine i_s by time t in factory s. $x_{i,t,s}$ is equal to 1 when machine i_s processing a product at time t in factory s, and 0 otherwise. $y_{i,t,s}$ is equal to 1 when machine i_s starts processing a new product at time t in factory s, and 0 otherwise. $p_{i,s}$ is the process time of machine i_s in factory s. $q_{i,s}$ is the power demand of machine i_s in factory s. $N_{0,s}$ is the production throughput of flow shops in factory s. T denotes the total production time, and it is an integer value.

Equation (3.17)-Equation (3.18) represent the number of products that have been finished on machine i_s by time t in factory s. Equation (3.19) ensures that the products are produced in a flow shop. Equation (3.20) ensures that the number of jobs produced by the time T is at least $N_{0,s}$ in factory s. Equation (3.21)-Equation (3.25) ensure that once a product begins processing on machine i_s in factory s, it cannot be interrupted until it is finished.

3.2.2.1 Multi-Factory under TOU Rate Formulation

All the factories are subject to TOU rate. Each factory optimizes manufacturing schedules based on the time-varying electricity rate to minimize its own electricity cost.

The following objective function seeks to identify the schedule that minimizes electricity cost for manufacturing facility s (s=1,2,…,S) under TOU rate:

$$\min \sum_{h=1}^{H} a_h \cdot F_{s,h} \tag{3.26}$$

where, a_h denotes the hourly electricity rate at hour h. $F_{s,h}$ is the hourly electricity consumption of the factory s at hour h. H is the total time.

The manufacturing factory s has n_s flow shops, and it is assumed that flow shops in the same manufacturing factory are the same. Additionally, the loads in each flow shop are divided into two types: (a) non-shiftable loads, i.e., light systems; (b) shiftable loads, i.e., process machines. The energy consumption $F_{s,h}$ of factory s at hour h can be calculated as:

$$F_{s,h} = n_s \cdot \left(f_{s,h} + o_{s,h} \right), (h = 1,2,...,H, s = 1,2,...,S) \tag{3.27}$$

where, $o_{s,h}$ is the non-shiftable loads in factory s at hour h. $f_{s,h}$ is the shiftable loads in factory s at hour h. n_s is the number of flow shops in factory s.

According to Equation (3.16), the shiftable loads $f_{s,h}$ in factory s at hour h can be expressed as:

$$f_{s,h} = \sum_{i_s=1}^{m_s} \sum_{t=h-1}^{h} q_{i,s}\, x_{i,t,s} \text{ , } (h = 1,2,...,H, s = 1,2,...,S) \tag{3.28}$$

where, m_s is the number of machines per flow shop in factory s. $x_{i,t,s}$ is equal to 1 if machine i_s processes a product at time t in factory s, and 0 otherwise. $q_{i,s}$ is the power demand of machine i_s (to complete process i_s). The Equation (3.28) is subject to Equation (3.17)-Equation (3.25).

3.2.2.2 Multi-Factory under TOU-IBR Formulation

Under the TOU-IBR pricing, each factory s ($s=1,2,…,S$) minimizes its own electricity cost through optimizing the manufacturing schedules. The objective function can be written as:

$$\min \sum_{h=1}^{H} P_h \left(L_h \right) \cdot F_{s,h} \tag{3.29}$$

where, $F_{s,h}$ represents the electricity consumption of factory s at hour h. $P_h(L_h)$ denotes the electricity price under TOU-IBR pricing structure at hour h. L_h represents the total electricity consumption of all the factories at hour h.

The total electricity consumption of all the factories subject to TOU-IBR rate at hour h can be represented as:

$$L_h = \sum_{s=1}^{S} F_{s,h}, (h = 1, 2, ..., H, s = 1, 2, ..., S) \tag{3.30}$$

The optimization problem can be solved in a centralized fashion by GAMS with CPLEX solver. However, the computation time will be increased a lot when increasing the number of machines, flow shops or factories. Thus, a heuristic approach will be proposed to reduce the total computation time by breaking the optimization problem into several sub-optimization problems, which are much easier to be solved. This heuristic method has the following procedures:

Step 1: Use objective function of multiple factories under TOU rate (Equation (3.26)) to identify the optimal results.

Step 2: Calculate the virtual threshold $T_{s,h}^{(k+1)}$ for the factory s at hour h for $(k+1)th$ iteration.

$$\Delta_h^{(k)} = T_h^{(k)} - L_h^{(k)}, (h = 1, 2, ..., H) \tag{3.31}$$

where, Δ_h represents the difference between the threshold T_h and the total electricity consumption L_h of all factories at hour h. k is the kth iteration. $\Delta_h \geq 0$ represents the total electricity consumption of all the factories is lower than the threshold. $\Delta_h < 0$ denotes the total electricity consumption is over the threshold.

As is shown in Figure 3-7, the portion of power which is over the threshold will be allocated. Thus, the following proportion is assumed:

$$\frac{\Delta_{s,h}{}^{(k)}}{\Delta_h{}^{(k)}} = \frac{F_{s,h}{}^{(k)}}{L_h{}^{(k)}}, (h = 1, 2, ..., H, s = 1, 2, ..., S) \tag{3.32}$$

$$\Delta_{s,h}{}^{(k)} = T_{s,h}{}^{(k)} - F_{s,h}{}^{(k)}, (h = 1, 2, ..., H, s = 1, 2, ..., S) \tag{3.33}$$

where, $F_{s,h}$ denotes the electricity consumption of factory *s* at hour *h*. L_h denotes the electricity consumption of all the factories at hour *h*. $T_{s,h}$ denotes factory *s*'s virtual threshold. $\Delta_{s,h}$ denotes the difference between factory *s*'s virtual threshold $T_{s,h}$ and its electricity consumption $F_{s,h}$ at hour *h*. Δ_h denotes the difference between the threshold T_h and total electricity consumption L_h of all the factories at hour *h*.

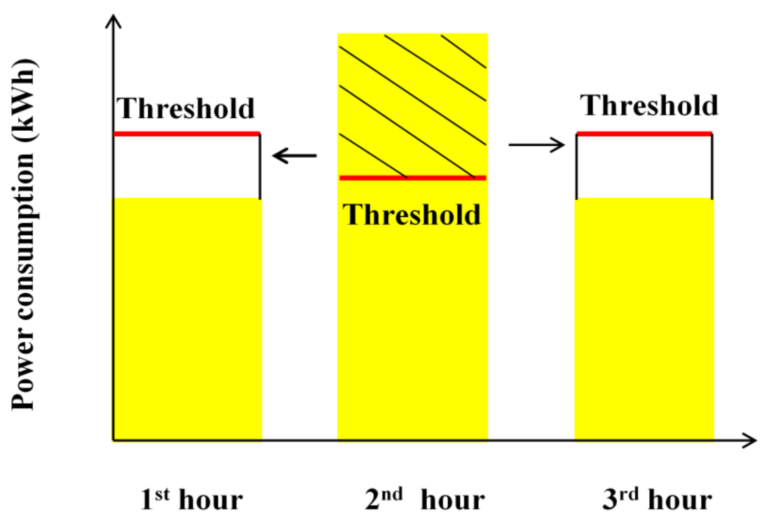

Figure 3-7. Electricity consumption and threshold profiles.

According to Equation (3.30) - Equation (3.33), the virtual threshold of factories *s* at hour *h* for (*k*+1)*th* iteration is formulated as:

$$T_{s,h}{}^{(k+1)} = T_h{}^{(k)} \cdot \frac{F_{s,h}{}^{(k)}}{\sum_{s=1}^{S} F_{s,h}{}^{(k)}}, (h = 1, 2, \ldots, H, s = 1, 2, \ldots, S) \tag{3.34}$$

where, $F_{s,h}$ denotes the electricity consumption of factory *s* at hour *h*. T_h denotes the threshold at hour *h*. $T_{s,h}$ denotes the virtual threshold for factory *s* at hour *h*.

Step 3: Thus, the virtual electricity price $P_{s,h}{}^{(k+1)}(L_{s,h}{}^{(k+1)})$ for factory *s* at hour *h* for (*k*+1)*th* iteration can be represented as:

$$P_{s,h}{}^{(k+1)}\left(L_{s,h}{}^{(k+1)}\right)=\begin{cases}a_h,\ if\ \ 0<L_{s,h}{}^{(k+1)}\le T_{s,h}{}^{(k+1)}\\ b_h,\ if\ \ L_{s,h}{}^{(k+1)}>T_{s,h}{}^{(k+1)}\end{cases} \tag{3.35}$$

$$with\ a_h<b_h,(h=1,2,...,H,s=1,2,...,S)$$

where, $L_{s,h}$ represents the electricity consumption for factory *s* at hour *h*. a_h is the electricity rate at Level 1. b_h is the electricity rate at Level 2. $T_{s,h}$ denotes the virtual threshold for factory *s* at hour *h*. If the electricity consumption of factory *s* at hour *h* is less than the threshold $T_{s,h}$,the electricity rate is a_h; if the electricity consumption of factory *s* at hour *h* is larger than the threshold $T_{s,h}$, the electricity rate is b_h.

Step 4: each factory optimizes its manufacturing schedules based on the virtual electricity price $P_{s,h}{}^{(k+1)}(L_{s,h}{}^{(k+1)})$.

At *kth* iteration, each factory shares the hourly electricity consumption to calculate the virtual electricity price for the (*k*+1)*th* iteration. Repeat the Step 2→ Step 3→ Step 4 until the results of (*k*+1)*th* iteration are closed to that of the *kth* iteration.

The virtual electricity price is used to optimize manufacturing schedules, but it is not the actual electricity price. Thus, manufacturing factories should pay their bills based on the real electricity price instead of the virtual electricity price finally.

3.2.3 Case Study

The total number of factories is 3, and each factory has 10 flow shops. All the flow shops in the same factory are the same. Each flow shop has 3 machines, and each machine is in charge of one process. Two cases will be studied: (1) minimizing electricity cost of multiple factories under TOU rate; (2) minimizing electricity cost of multiple factories under TOU-IBR rate.

Table 3-3 shows the power demand and processing time for three processes in the order of Process A→ Process B→ Process C. The production quota per flow shop is 4, 4, and 5, for Factory 1, Factory 2, and Factory 3, respectively. The total working time has 4 hours with the time interval equal to 10 minutes.

Table 3-3. Flow shop parameters.

Factory	**Process**	**Power demand (kW)**	**Process time (minutes/part)**	**Non-shiftable load per flow shop (kW)**
Factory 1	Process A	10	20	10
	Process B	20	30	
	Process C	10	20	
Factory 2	Process A	20	20	10
	Process B	10	30	
	Process C	10	10	
Factory 3	Process A	10	10	15
	Process B	15	30	
	Process C	15	10	

3.2.3.1 Multi-Factory under TOU Rate Case

In this case, each factory minimizes the electricity cost through optimizing its own manufacturing schedules based on TOU rate. Figure 3-8 shows a 4-hour TOU rate. As is shown, this 4-hour period is divided into 24-time slots, and each time interval has 10 minutes. The peak demand period is at the 3rd hour while the lowest electricity price is at the 2nd hour.

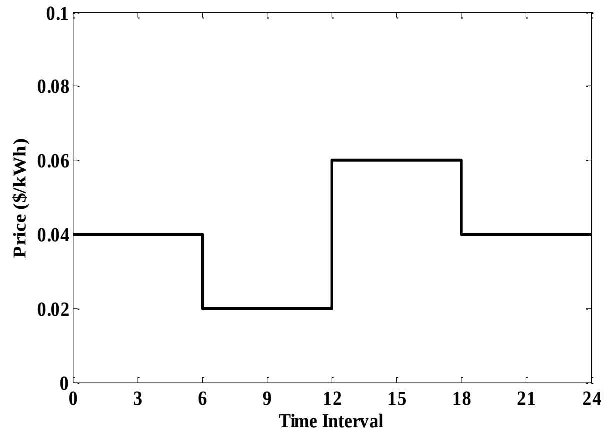

Figure 3-8. TOU rate over 4 hours.

Figure 3-9 shows the optimal manufacturing schedules for three factories. Accordingly, the minimal electricity cost is $36, $31.3, and $42.2 for Factory 1, Factory 2, and Factory 3, respectively. The total electricity cost is $109.5. As shown, machines try to work at the 2nd hour, when the electricity price is the lowest.

Figure 3-9. Gantt charts for multiple machines under TOU pricing.

The total power consumption of all three factories is shown in Figure 3-10. As shown, the highest electricity consumption is at the 2nd hour. However, the electricity price during the 2nd hour is the lowest (See Figure 3-8).

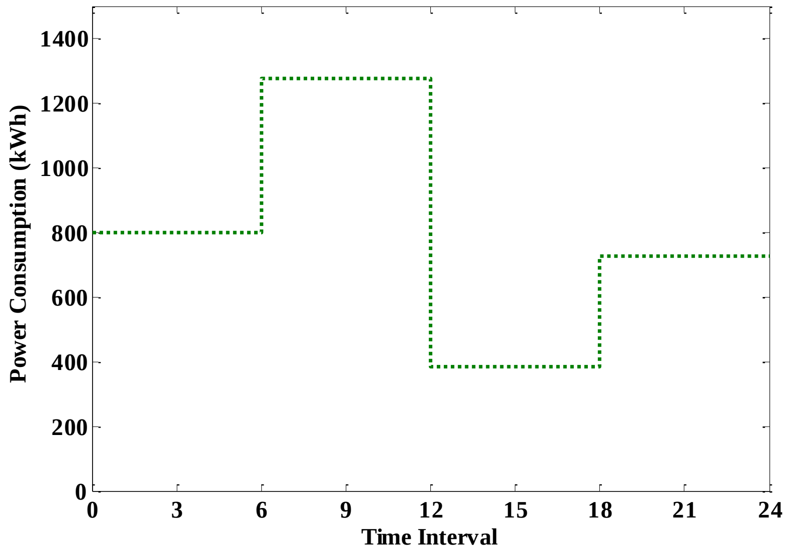

Figure 3-10. Total power consumption of three factories.

As a result, all the factories optimize their manufacturing schedules based on the TOU rate, which leads the peak load shift from the third hour (See 3-8) to the second hour (See Figure 3-10). However, this situation is not desired by the utilities. TOU-IBR pricing is introduced to avoid this shifting.

3.2.3.2 Multi-Factory under TOU-IBR Pricing Case

There are two cases when multiple factories served under TOU-IBR pricing: (1) non-collaborative case, (2) collaborative case. The TOU-IBR pricing is listed in Table 3-4. As is shown, the threshold varies with hours. If the electricity consumption is lower than the threshold, Level 1 price is used. If the electricity consumption exceeds the threshold, the electricity rate is equal to Level 2 price.

Table 3-4. Electricity price during a 4-hour period under TOU-IBR pricing.

	Threshold (kWh)	**Level 1 Price ($/kWh)**	**Level 2 Price ($/kWh)**
1st hour	1200	0.04	0.14
2nd hour	900	0.02	0.12
3rd hour	1800	0.06	0.16
4th hour	1200	0.04	0.14

3.2.3.2.1 Non-Collaborative Case

Figure 3-11 shows the total power consumption of three factories and thresholds over the 4-hour period in the non-collaborative case. As is shown, the optimal power consumption of three factories in the non-collaborative case under TOU-IBR pricing is the same as that under TOU rate (See Figure 3-10 and Figure 3-11). The total electricity cost of three factories in the non-collaborative case is \$147, while the electricity cost of the same manufacturing schedules under TOU rate is \$109.5 due to a penalty is placed for exceeding the threshold at the 2nd hour.

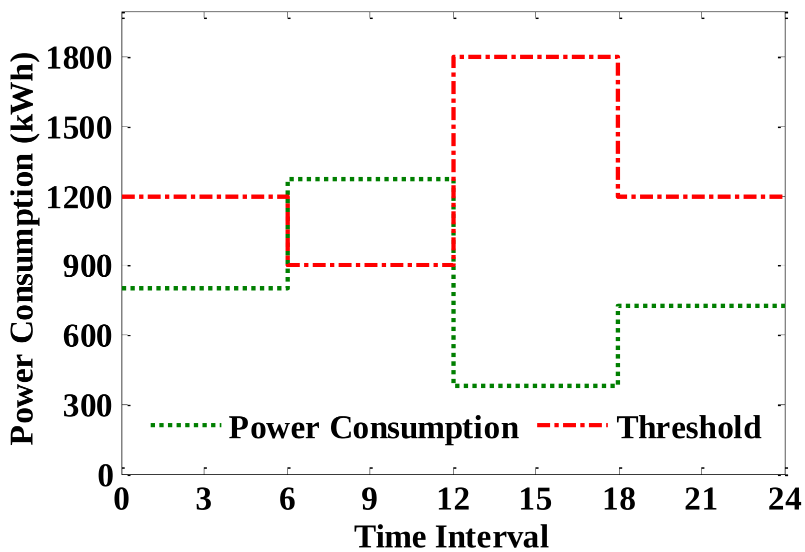

Figure 3-11. Power consumption and threshold in the non-collaborative case.

3.2.3.2.2 Collaborative Case

Figure 3-12 shows the optimal manufacturing schedules that have the minimal electricity cost for each factory. According to Figure 3-12 and Table 3-4, The minimal electricity cost of Factory 1, Factory 2, and Factory 3 is \$38.3, \$34, and \$46.2, respectively. Thus, the total electricity cost of all the three factories is \$118.5.

Figure 3-12. Gantt chart for multi-factory under TOU-IBR pricing.

Figure 3-13 shows the corresponding total power consumption of all three factories over the 4-hour period. It is noticed that the power consumption is lower than the threshold at each hour. The total electricity cost is \$118.5 with a 19.4% reduction in electricity cost compared with that in the non-collaborative case (\$147).

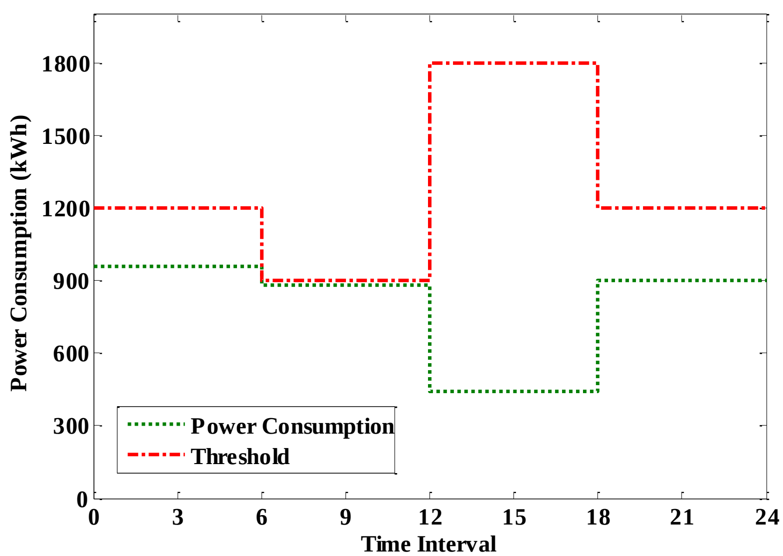

Figure 3-13. Power consumption and threshold profile.

3.2.4 Conclusion

In this section, multiple factories are served by one utility company. Each factory aims at minimizing its own electricity cost under the time-varying electricity rate, and meanwhile maintaining the production quota. Two time-varying electricity schemes are considered: (1) TOU rate, and (2) TOU-IBR pricing. Under TOU rate, each factory minimizes its own electricity cost without sharing any electricity consumption information with others. As a result, the market peak demand hours move from the 3rd hour to the 2nd hour, since the electricity price at the 2nd hour is the lowest. TOU-IBR pricing has been proposed to deal with this issue through introducing a threshold at each hour to limit the total electricity demand of three factories. If the total electricity consumption is beyond the threshold, a high electricity price will be charged. Under the TOU-IBR pricing, the optimal schedules for each factory are dependent on its own electricity consumption and other factories'. Thus, the size of the optimization problem under TOU-IBR pricing is much larger than that under TOU rate. Additionally, the computation time will be increased obviously when the number of machines, flow shops, and factories grows. In light of computation time, the centralized formulation has been decomposed into sub-optimization problems by assigning a virtual electricity price for each factory. The virtual electricity rate is used to guarantee the hourly electricity demand lower than the threshold. Each factory minimizes its own electricity cost under this virtual electricity rate through manufacturing scheduling.

In the real market, the grid serves not only the manufacturing facilities but also other users such as residential and commercial buildings. Thus, the energy consumption management in the residential and commercial buildings should also be considered. In the next chapter, the interactions among different types of users with the objective of minimizing electricity cost under time-varying electricity rate will be discussed.

CHAPTER 4. FLOW SHOP SCHEDULING UNDER RTP

In this chapter, flow shop schedules are optimized based on the real-time electricity price with the objective to minimize the electricity cost. Two sections are studied: Section 4.1 minimizes electricity cost for a single manufacturing facility with flow shops under the RTP through manufacturing scheduling; and Section 4.2 minimizes electricity cost for multi-manufacturing facilities with flow shops under the RTP through manufacturing scheduling.

4.1 Flow Shop Scheduling For One Factory under Real-Time Electricity Rate

This section optimizes the manufacturing schedule of a single factory with flow shops under RTP in a microgrid which also serves residential and commercial buildings. Three cases are considered: (1) "business-as-usual" manufacturing factory, residential buildings, and commercial buildings; (2) "cost saving" manufacturing factory, "business-as-usual" residential and commercial buildings; (3) "business-as-usual" manufacturing factory, "cost saving" residential and commercial buildings. The objective of scheduling problem is to minimize electricity cost under different cases.

4.1.1 Model Description

A microgrid with the manufacturing facility, residential buildings, and commercial buildings operating under the RTP is considered. The modules used to simulate the power demand of residential buildings, and commercial buildings are created in GridLAB-D [56]. GridLAB-D has residential and commercial building modules with devices in details, e.g., lighting system models, HVAC system models, and water heater models. The schedules of water heaters and lighting systems are determined based on the consumers' requirements. The electricity consumption of HVAC system is influenced by weather condition, setting point, and electricity rate [57]. GridLAB-D has the control strategies, which are applied to manage the behavior of HVAC system aiming at reducing the electricity consumption and the electricity cost. However, GridLAB-D does not have the manufacturing factory module. Thus, a manufacturing factory model with several flow shops consisting of machines, lighting systems, and HVAC system is developed in this research. Additionally, an integrated model is developed which combines residential buildings, commercial buildings, and factories, along with HVAC control strategies and electricity market mechanisms. This integrated model is used to simulate the power demand and electricity price in real time.

4.1.1.1 Real-Time Electricity Price Model

The RTP depends on the total power demand of the market, and is updated every certain time. Alternatively, the real-time electricity price can also be represented as a function of power demand. The mathematical model of real-time electricity rate $P_t(L_t)$ is given at time t, and it is formulated as [58] [59]:

$$P_t\left(L_t\right) = \exp(aL_t + b) \tag{4.1}$$

where, a and b are the parameters that determine the characteristics of the electricity curve. L_t is the total demand load from residential buildings, commercial buildings, and manufacturing facilities at time t, which is represented as:

$$L_t = L_{R,t} + L_{C,t} + L_{M,t} \tag{4.2}$$

where, $L_{R,t}$ represents the demand of residential buildings at time t. $L_{C,t}$ represents the power demand of commercial buildings at time t. $L_{M,t}$ denotes the power demand of factories at time t.

Assume that the electricity consumption of one flow shop at time t is f_t. The manufacturing factory has n_s flow shop ($s=1,2,\ldots,S$). Thus, the electricity consumption of this factory at time t is equal to n_s f_t. Based on Equation (4.1) and Equation (4.2), RTP $P_t(L_t)$ is represented as:

$$P_t\left(L_t\right) = \exp(a\left(L_{R,t} + L_{C,t} + n_s \cdot f_t\right) + b) \tag{4.3}$$

where, a and b are the parameters which determine the characteristics of the electricity curve. L_t is the total demand load at time t. $L_{R,t}$ represents the demand of residential building at time t. $L_{C,t}$ represents the power demand of commercial building at time t. $L_{M,t}$ denotes the power demand of factory at time t.

4.1.1.2 Feeder Module

The GridLAB-D feeder module R5-12.47-4 is used, which represents a moderately populated suburban area. The parameter values of the feeder module are listed in Table 4-1.

Table 4-1. The main parameters of feeder module.

Feeder Parameters	**Value**
Total Number of Nodes	1,075
Voltage (kV)	12.47
Load Capacity (kW)	3,700
Total Number of Residential Transformers	150
Total Number of Commercial Transformers	4
Total Number of Industrial Transformers	1

As shown in Figure 4-1, the feeder module consists of transmission lines, transmission substations, power transformers, and other equipment. The residential building modules, commercial building modules, and the factory modules are connected to this feeder module.

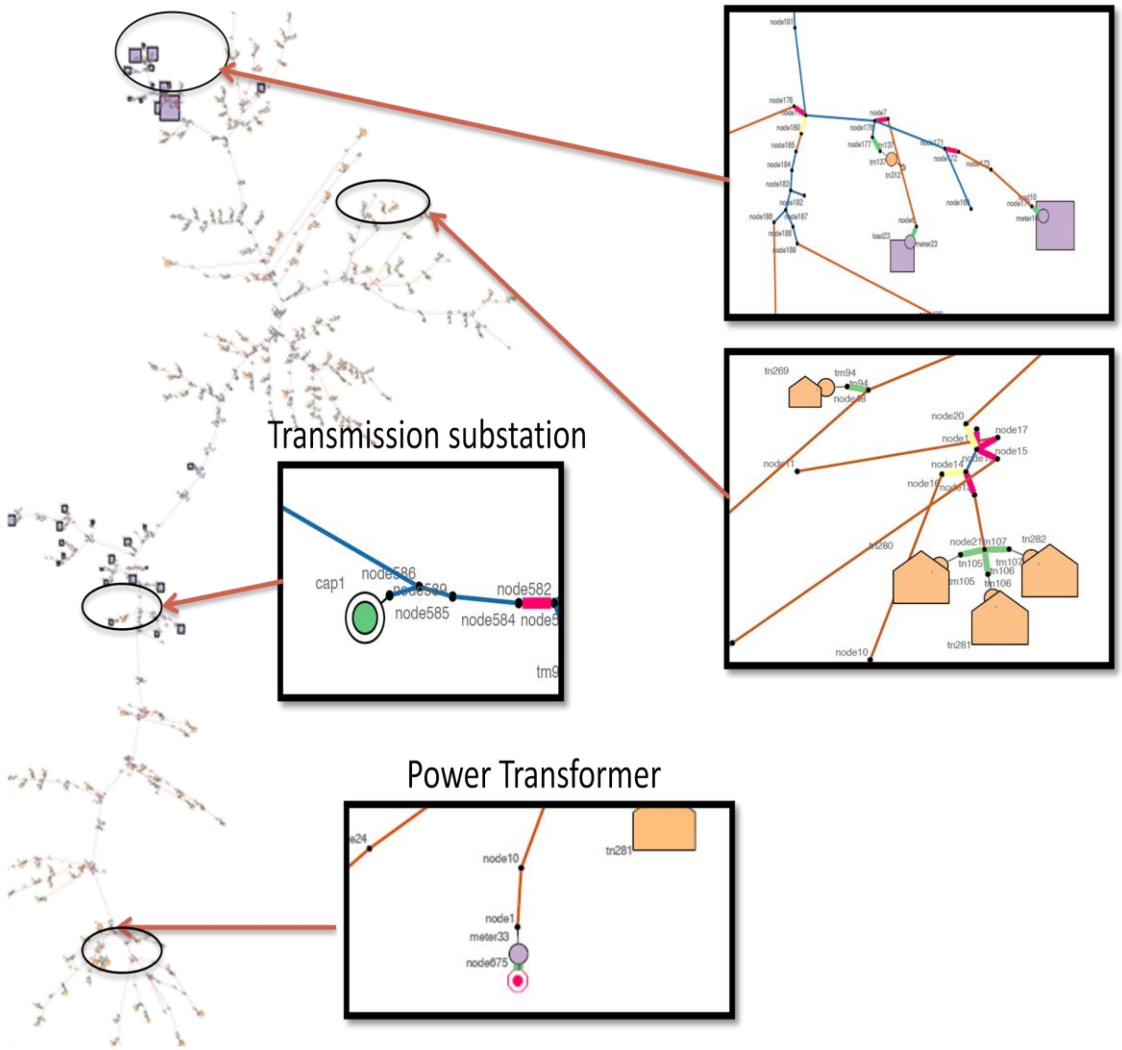

Figure 4-1. Integrated model [60].

4.1.1.3 Residential Building Module

GirdLAB-D has the existing residential building module, and it can be used to describe and identify different residents through setting up the values for each parameter. In addition, the residential building module consists of water heaters, lighting systems, wall outlets and HVAC systems model. Heat gains or losses from water heaters, lights, exterior walls, and air infiltration are also considered. Table 4-2 shows the value of each parameter for a specific house. In a hypothetical region, different residential buildings might have different values for the same parameters.

Table 4-2. Parameters for a specific house.

House Parameters	**Value**
Floor Area (sq. ft.)	2,500
Ceiling Height (ft.)	8
Number of Doors	4
Roof R-value	30
Wall R-value	19
Floor R-value	22
Door R-value	5
Light Capacity (W)	400
Lights Heat Gain Fraction	0.9
Water Heater Capacity (kW)	4.4

4.1.1.4 Commercial Building Module

The commercial building is assumed to have two stories, and there are six zones on each floor. The zone faces to the east will receive more sunlight than other directions. The number of windows, doors, and locations are shown in Figure 4-2. Each zone has lighting systems, plug loads, water heaters, HVAC systems and so forth.

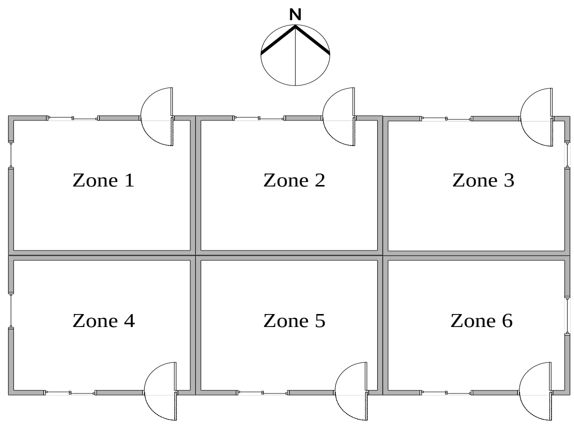

Figure 4-2. Floor plan of a two-story office building (1st floor).

Table 4-3 lists the parameters for a specific zone. It is assumed that the commercial buildings are occupied from 8:00 am (EST) to 5:00 pm (EST) on Monday to Friday, and from 1:00 pm (EST) to 5:00 pm (EST) on Saturday and Sunday.

Table 4-3. Parameters for a specific commercial building.

Commercial Building Parameters	**Value**
Office Floor Area (sq. ft.)	1,000
Office Height (ft.)	11
Light capacity (W)	2,000
Lights Heat Gain Fraction	0.9
Plugs Capacity (W)	1,000
Plugs Fraction	0.9
Plugs Heat Gain Fraction	0.98

4.1.1.5 Operation Strategies

Figure 4-3 shows the operation strategies applied for an HVAC system in the GridLAB-D. If the current market price is lower than $P_{average}$, the device will set parameter T_{limit}=T_{min}, and K=K_{max}; likewise, T_{limt}=T_{max}, K=K_{min}, when the price is larger than $P_{average}$.

$$T_{reset} = T_{set} + (P_{pricesignal} - P_{average})\frac{|T_{limit} - T_{\exp.}|}{K\sigma} \tag{4.4}$$

where, $P_{average}$ is the average of the previous 24-hour price, σ is the standard deviation of the electricity price for the same period, $P_{pricesignal}$ the current electricity price, T_{set} is the original set temperature, T_{reset} is the reset temperature. $T_{exp.}$ is the expected temperature at the average electricity price. K_{min}, K_{max} are the slopes, which are the changes in the price for a unit change in temperature, T_{min}, T_{max} are the range of temperature that customers will accept, K_{min}, K_{max} and T_{min}, T_{max} are comfort-setting parameters. K and T are chosen from K_{min}, K_{max} and T_{min}, T_{max}, depending on where $T_{current}$ presently resides on the lines.

If the price which is provided by price signals is lower than the average price, the HVAC will set parameter T_{limit}=T_{min}, K=K_{max}. Both T_1 and T_2 satisfy the customers' requirements, and temperature T_2 is larger than T_1, then HVAC will choose T_2 as the set point to save energy. If the price is larger than the average price, then HVAC uses K=K_{min} and T_{limt}=T_{max} also for the sake of energy saving because $T_4 > T_3$.

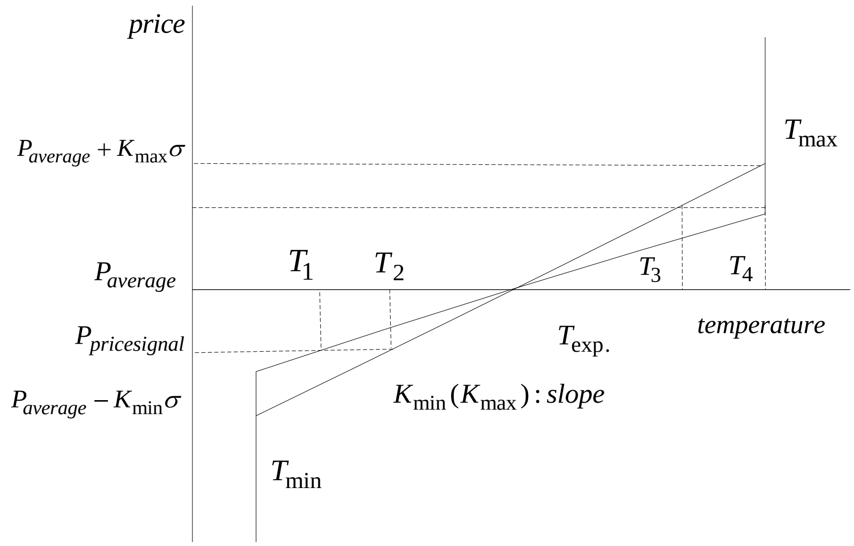

Figure 4-3. Control strategies for the HVAC system.

4.1.2 Optimization Problem Formulation

It is assumed that all the flow shops in the same factory are the same. That means they have the same machines and manufacturing schedules. Each flow shop has a series of process steps, and each process step has one machine. The following integer programming model seeks to find the schedule that has the minimal total electricity cost.

$$\min \sum_{t=1}^{T} P_t\left(L_t\right)\left(n_s \cdot f_t\right) \tag{4.5}$$

where, $P_t(L_t)$ is the real-time electricity price at time t. L_t is the total electricity consumption at time t. n_s is the number of flow shops. f_t is the electricity consumption of the flow shop at time t, and it is formulated by Equation (3.2)-Equation (3.11).

4.1.3 Case Study

As shown in Table 4-4, three cases are examined for comparison purposes. For each case, the manufacturing factory will be operated three shifts: day shift (8:00-16:00), night shift (0:00-8:00), and swing shift (16:00-24:00). In Case 1, manufacturing factory, residential buildings, and commercial buildings run under the “business-as-usual” condition. In Case 2, manufacturing factory is under “cost-saving” mode, while residential and commercial buildings are under "business-as-usual" operations. In Case 3, manufacturing factory operates with "business-as-usual", while the residential and commercial buildings adopt cost-saving control strategies.

Table 4-4. Cases considered with different operation strategies and schedules.

Case	**Manufacturing factory**			**Residential and commercial buildings**
	Typical summer day			Typical summer day
	Day shift (8:00-16:00)	Swing shift (16:00-24:00)	Night shift (0:00-8:00)	
Case 1	Business-as-usual			Business-as-usual
Case 2	Scheduling for minimal electricity cost			Business-as-usual
Case 3	Business-as-usual			Adopting cost saving operation strategies

A microgrid serving one manufacturing factory with ten same flow shop, 200 residential buildings, and six commercial buildings on a summer day is considered. Figure 4-4 shows the temperature on a typical summer day, which can be used to generate the real-time electricity consumption of HVAC systems in the residential and commercial buildings in GridLAB-D.

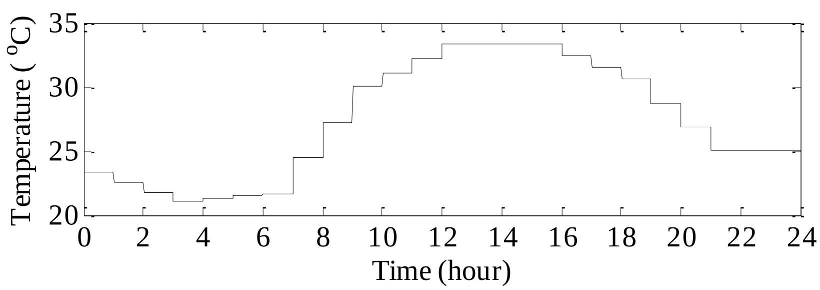

Figure 4-4. Temperature profile of a typical summer day.

The real-time electricity price is determined by:

$$P_t(L_t) = \exp(0.0005L_t\text{-}3.6052) \tag{4.6}$$

where, $P_t(L_t)$ is the real-time electricity price at time t. L_t is the total electricity consumption at time t. The average values for parameters of these residential homes are as shown in Table 4-5. Each residential home has HVAC systems, lighting systems, and water heaters. The parameters of these devices are not listed in this thesis. The electricity consumption of HVAC system is dependent on the temperature of the typical summer day, occupants' comfort range, parameter values of residential houses, the mode of HVAC system, and electricity market price. The schedules of lighting systems and water heaters are determined by consumers. Thus, the total power demand of residential buildings can be predicted in GridLAB-D.

Table 4-5. Average residential building parameters.

Residential house parameters	**Values**
Floor Area (m^2)	209.50
Floor Height (m)	3.35
Ratio of Window Area to Wall Area	0.15
Number of Doors in the House	4
Thermal Resistance of the Walls (W/m^2℃)	0.30
Thermal Resistance of the Floor (W/m^2℃)	0.26
Thermal Resistance of the Doors (W/m^2℃)	1.13
Thermal Resistance of the Windows (W/m^2℃)	2.13
Heating System Type	GAS
Cooling System Type	ELECTRIC

The average parameters of the six commercial buildings are listed in Table 4-6. Each commercial building has its own appliances, i.e., HVAC systems, water heaters, lighting systems. Parameter values of these appliances are not listed in this thesis.

Table 4-6. Average commercial building parameters.

Commercial building parameters	**Values**
Office Floor Area (m^2)	603.87
Office Floor Height (m)	5.33
Windows Facing South (m^2)	3.39
Exterior/Interior Thermal Resistance (K/W)	0.94
Outlets Capacity (W)	1,000
Plugs Heat Gain Fraction	0.98
Outside Air Fraction for Ventilation	0.30

The manufacturing factory has ten same flow shops with three stages in each flow shop. Each stage is in charge of one process. The process order is Process A→ Process B → Process C. Table 4-7 lists the power and time for each manufacturing process. The production quota per flow shop is 40. To be simplified, all the flow shops follow the same product pattern.

Table 4-7. Flow shop parameters.

	Process A	**Process B**	**Process C**
Processing Time (minutes/part)	5	8	6
Power Demand (kW)	80	60	40

4.1.3.1 Case 1

In Case 1, all the manufacturing factory, residential buildings, and commercial buildings operate as “business-as-usual”, which means that they operate without considering electricity costs. The total power demand for the residential and commercial buildings in the 24-hour period is shown in Figure 4-5. It should be noted that the power demand increases between 8:00-16:00, decreases between 16:00-20:00, and is relatively flat with small fluctuations from 0:00-8:00 and 20:00-24:00.

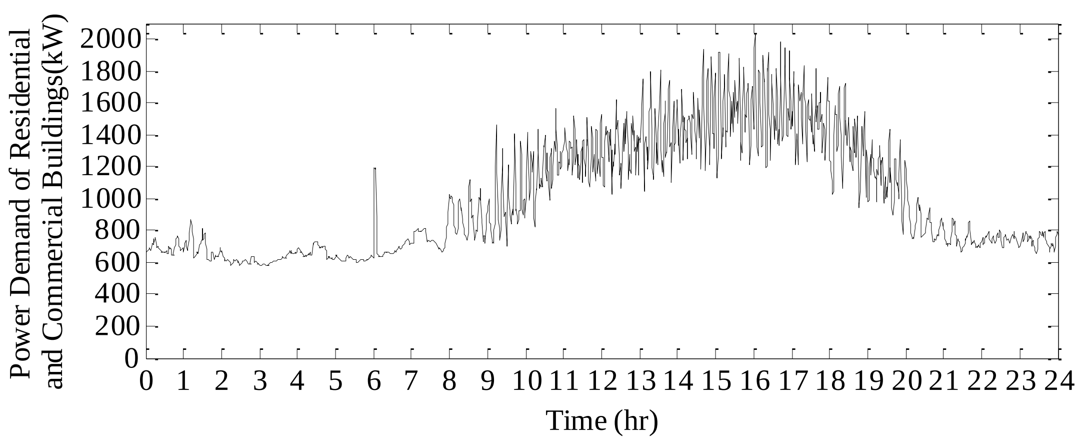

Figure 4-5. Power demand of residential and commercial buildings.

Figure 4-6 shows the schedules for each machine in one flow shop over the 24-hour period. During each shift, both Machine A and Machine B run continuously since processing time per part on Machine B is longer than that on Machine A, so Machine B will never subject to starving. The processing time per part on Machine C is shorter than that on Machine B. As a result, Machine C is subject to starving and only works intermittently. For the day shift, Machine A finishes processing all 40 parts at 11:20 am, Machine B finishes processing at 13:25, and Machine C finishes processing a few minutes later (at 13:31). Similar patterns are observed for both the swing and night shifts. As mentioned previously, there are ten flow shops in this manufacturing factory.

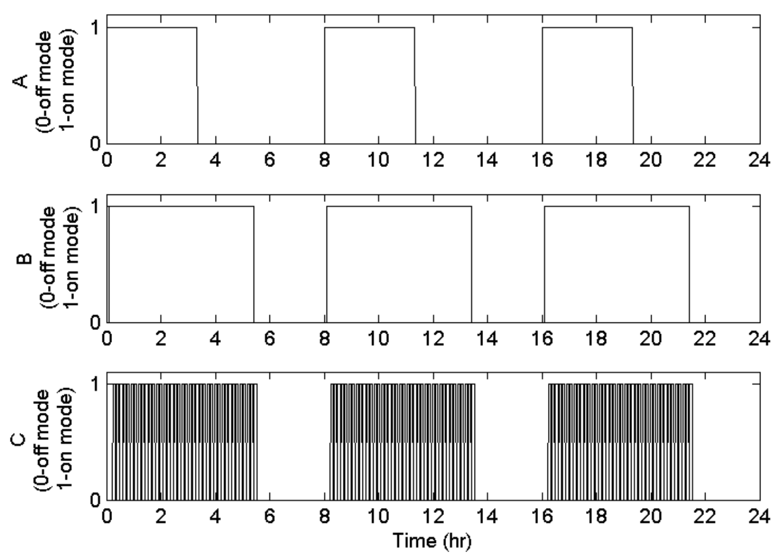

Figure 4-6. Schedule of the “business-as-usual” manufacturing factory.

Figure 4-7 shows the total power demand of the factory in the case of “business-as-usual” over a 24-hour period. Figure 4-8 displays the time-varying electricity price over 24 hours in this case. The electricity price is impacted by the total power demand of the residential buildings, commercial buildings, and manufacturing factory. According to Figure 4-7 and Figure 4-8, the total electricity cost of the manufacturing factory for “business-as-usual” operation is $711 for the day shift (8:00-16:00), $913 for the swing shift (16:00-24:00), and $614 for the night shift (0:00-8:00). The total electricity cost of the manufacturing factory is $2,238 over the 24-hour period. According to Figure 4-5 and Figure 4-8, the total electricity cost of the residential and commercial buildings is $2,002 over the 24-hour period.

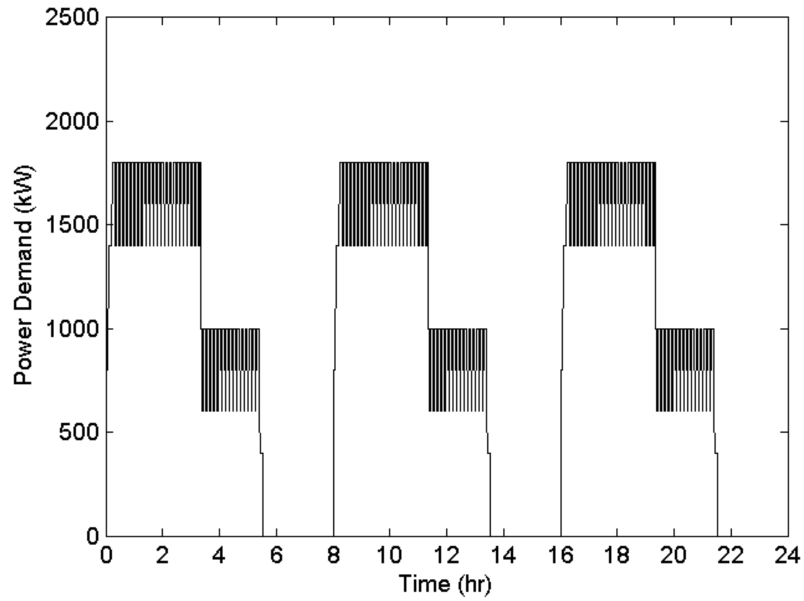

Figure 4-7. Power demand of the “business-as-usual” manufacturing factory.

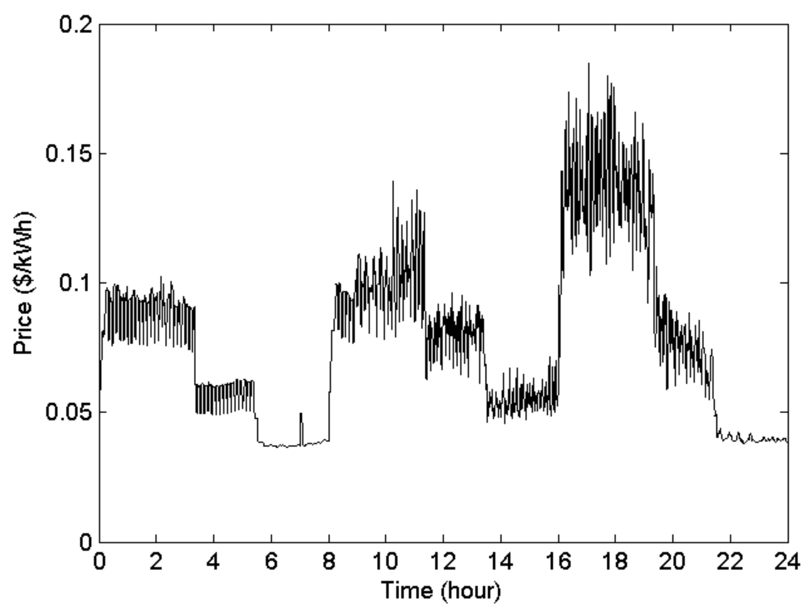

Figure 4-8. Real-time electricity price.

4.1.3.2 Case 2

In Case 2, the flow shop schedules are identified to minimize the electricity cost by shifts (day shift, swing shift, and night shift). Residential and commercial buildings are operated under “business-as-usual” situation for the 24 hours. Thus, the power demand profile of residential and commercial buildings in Case 2 is the same as that in Case 1 (See Figure 4-5). As the power demand of residential and commercial buildings is obtained, the manufacturing schedules of the factory can be optimized by using Equation (4.5). Figure 4-9 shows the optimum schedules that have the minimal electricity cost of the flow shop. It can be seen that all machines work discontinuously. The corresponding total power demand of the manufacturing factory is shown in Figure 4-10.

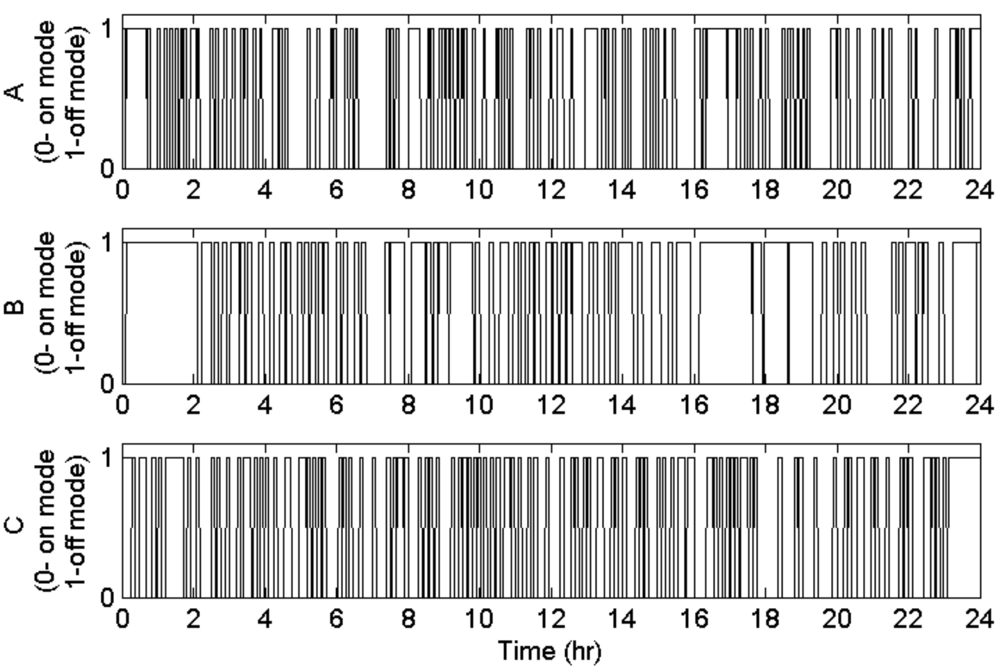

Figure 4-9. “Minimal electricity cost” schedules of the manufacturing factory.

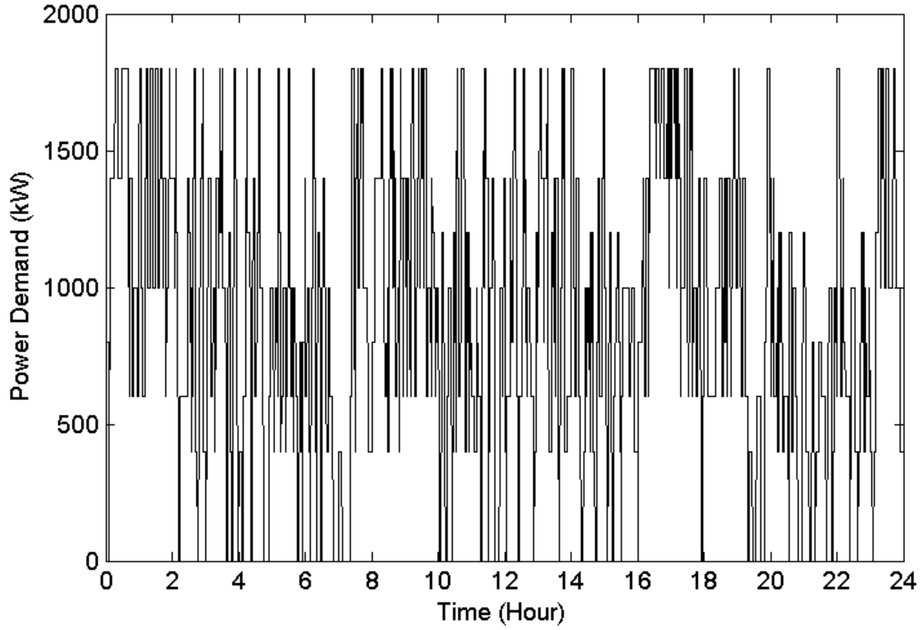

Figure 4-10. Power demand of the “cost saving” manufacturing factory.

Figure 4-11 shows the time-varying electricity price in this case, which is determined by total power demand of the residential buildings, commercial buildings, and manufacturing factory. The total electricity cost of the manufacturing factory for the day shift (8:00-16:00) is $666 in Case 2. A relatively small cost reduction 6.3% is achieved in Case 2 ($666) when comparing with Case 1 ($711). This is because the power demand of residential and commercial buildings increases between 8:00 and 16:00 (Figure 4-5), while the power demand of the factory decreases over the same time (Figure 4-7) in Case 1. The opposite trends in the power demand balance off with each other and lead to reduced electricity cost.

For the swing shift (16:00-24:00), the total electricity cost of manufacturing factory in Case 2 is $686, and a reduction of 24.8% is obtained on electricity cost for swing shift compared with Case 1 ($913). A larger percentage decrease in the cost of electricity is achieved in the swing shift as compared to the day shift. In Case 1, both power demand of manufacturing factory and power demand residential & commercial buildings is at the high level at the beginning and decreases over time (See Figure 4-5 and Figure 4-7). This peak overlap leads to higher electricity price during the first 3 hours. In Case 2, the optimal manufacturing schedule shifts the peak demand of the factory to a later time period and partially eliminate the peak overlap. This leads to a reduced average electricity price and is the main reason for obtaining a larger cost saving for the factory during swing shift.

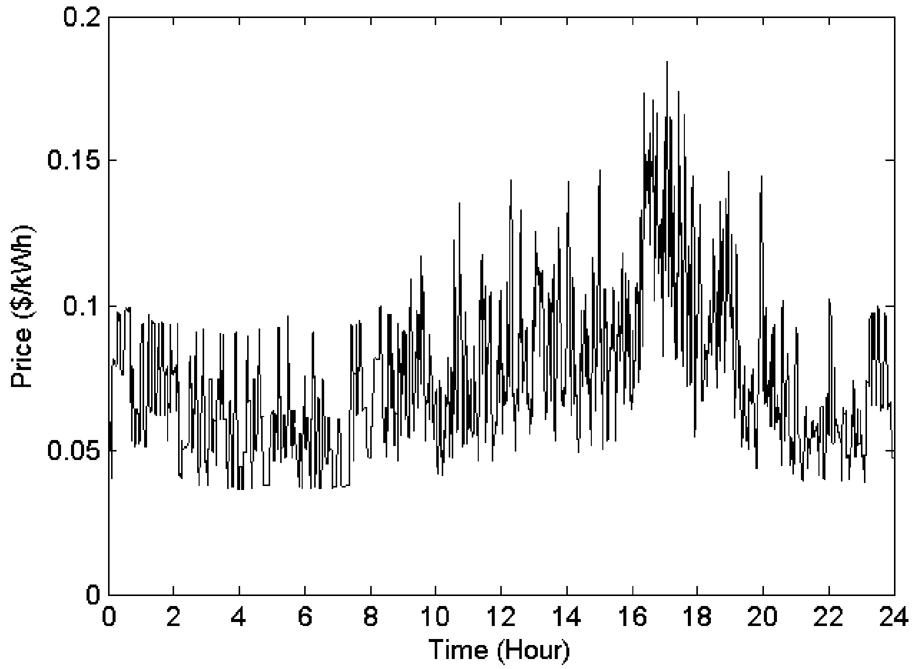

Figure 4-11. Real-time electricity price.

For the night shift (0:00-8:00), the total electricity cost of the manufacturing facility is $548 in Case 2, while that is $614 in Case 1 (a reduction of 10.8% in electricity cost is reached in Case 2 as compared with Case 1). As shown in Figure 4-5, the collective power demand for “business-as-usual” residential and commercial buildings fluctuates within a narrow range during the night shift period. Thus, the power demand of manufacturing facility dominates the market electricity price.

The cost of residential and commercial buildings also changed owing to the power demand changing in the manufacturing facility. According to Figure 4-5 and Figure 4-11, the total electricity cost for the residential and commercial buildings is $1,933 over the 24-hour period with a 3.4% reduction. This suggests that changing manufacturing schedules influence the real-time electricity price, which also benefits the residential and commercial buildings.

4.1.3.3 Case 3

In Case 3, residential and commercial buildings adopt energy cost saving strategies through managing the set point of HVAC systems within the occupiers' comfort range, while the manufacturing factory operates under "business-as-usual" conditions.

The machines schedules in the flow shop and power demand of the manufacturing factory are the same as that in Case 1 (See Figure 4-6 and Figure 4-7). The total power demand of residential and commercial buildings applied with electricity cost reduction strategies are shown in Figure 4-12. The electricity price is determined by the total power of residential buildings, commercial buildings, and manufacturing factory as it shown in Figure 4-13.

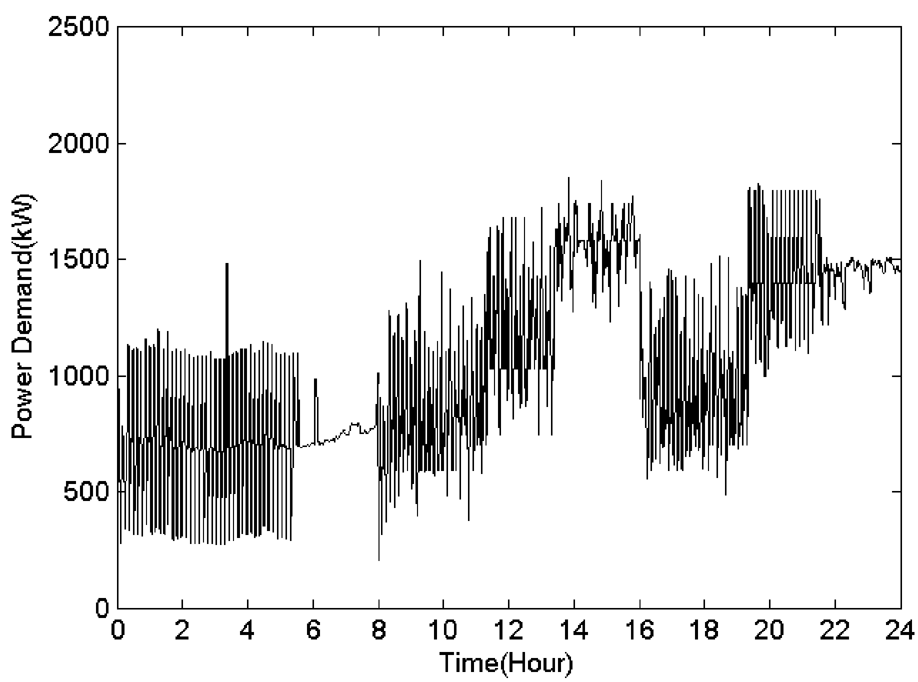

Figure 4-12. Power demand of the "cost saving" residential and commercial buildings.

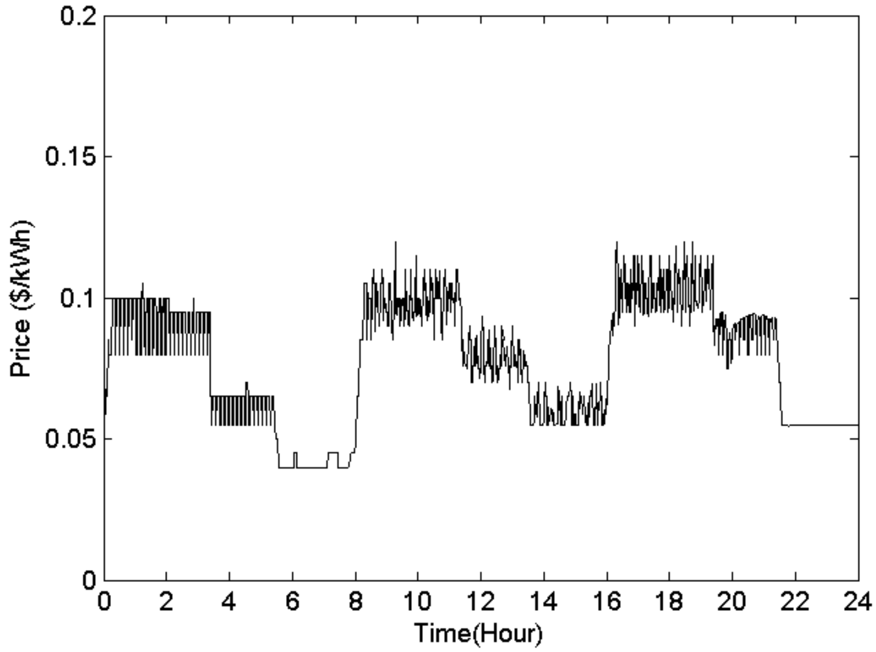

Figure 4-13. Real-time electricity price.

The electricity cost of residential and commercial buildings using cost reduction strategies over the 24-hour period is $1919.7 in Case 3, while the electricity cost for the “business-as-usual” residential and commercial buildings is $2,002 as in Case 1. This corresponds to a 4.1 % reduction of electricity cost for residential and commercial buildings.

The energy cost of manufacturing facility is also changed owing to the power demand changing in residential and commercial buildings. According to Figure 4-7 and Figure 4-13, the total electricity cost for the “business-as-usual” manufacturing schedules is $2,066 over the 24-hour period. It should be noted that changing residential and commercial buildings influences the real-time electricity price, which also benefits manufacturing schedules. Compared with Case 1, electricity cost of manufacturing factory is reduced by 7.6%.

With a manufacturing schedule optimized to reduce electricity cost, the cost for the day shift is reduced by 6.3%, swing shift is reduced by 24.8%, and night shift reduced by 10.8%. That is to say, the total electricity cost of the manufacturing factory over a 24-

hour period is $2,238 in Case 1, while it is $1,900 in Case 2 (a reduction of 15.1%). Thus, the cost savings associated with manufacturing (15.1%) is higher than the savings achievable through controlling the behaviors of HVAC systems in the residential and commercial buildings (4.1%).

4.1.4 Conclusion

In this section, the electricity cost of one manufacturing facility operating ten same flow shops under real-time electricity rate is minimized, and meanwhile, the production quota is maintained. The time-varying electricity rate is determined by the total electricity demand from residential buildings, commercial buildings, and manufacturing factory. The power demand for residential and commercial buildings is generated by using GridLAB-D. The electricity demand for the manufacturing facility with flow shops is assumed to depend on machines schedules. A time-indexed integer programming is developed to identify the manufacturing schedule that minimizes the electricity cost for the factory. To demonstrate this approach, a hypothetical region with residential buildings, commercial buildings, and one manufacturing factory are considered, and three cases are examined. The result shows that the "cost-saving" operated manufacturing factory over the 24-hour period can save 15.1% on electricity cost, while the "cost-saving" operated residential and commercial buildings over the same period can achieve 4.1% reduction in electricity cost. Additionally, the "business-as-usual" residential and commercial buildings obtain economic benefits in the case when manufacturing factory is under "cost-saving" situation. Similarly, "cost-saving" residential and commercial buildings can also benefit the "business-as-usual" manufacturing factory.

Time-indexed integer programming helps find the optimal solution, but requires significant computation efforts. This hypothetical model only has one manufacturing facility. However, in the real market, there might be a group of factories served by the grid. Thus, developing a more efficient algorithm suitable for solving large-size scheduling problem is urgent. Thus, multiple manufacturing facilities under RTP will be investigated. An alternative formulation will be proposed with considering the computation time.

4.2 Flow Shop Scheduling For Multiple Factories under Real-Time Electricity Rate

Scheduling of multiple factories under the RTP will be investigated in this section. Two cases will be discussed. Case 1: non-collaborative case, factory minimizes its own electricity cost without sharing the information with other factories, and Case 2: collaborative case, factories collaborate with each other to minimize the total electricity cost.

4.2.1 Model Description

In this scheduling problem, the manufacturing schedules of multiple factories with flow shops under the RTP will be optimized to minimize the electricity cost. A hypothetical model consisting of residential buildings, commercial buildings, and manufacturing factories are created. The factories are served by one utility company, and enrolled in RTP. It is assumed that the factories are under the "cost saving" conditions through optimizing the manufacturing schedules, while residential buildings and commercial buildings are operated under "business-as-usual" situation without considering the electricity cost.

The real-time power demand of residential and commercial buildings is simulated in GridLAB-D. The parameters in residential and commercial buildings are listed in Table 4-8 and Table 4-9.

Table 4-8. Average residential buildings characteristics.

House Parameters	**Value**
Floor area (m^2)	209.50
Floor height (m)	3.35
Number of doors in the house	4

Table 4-9. Average commercial building characteristics.

Commercial Building Parameters	**Value**
Office floor area (m^2)	603.87
Office floor height (m)	5.33

Each manufacturing facility has n_s flow shops, and there are all the same. Each flow shop has the shiftable load (i.e., machines), and the non-shiftable load (i.e., lighting systems). Thus, the total electricity consumption in factory *s* at time *t* can be written as:

$$L_{s,t} = n_s \cdot \left(f_{s,t} + o_{s,t} \right), (t = 1, 2, ..., T, s = 1, 2, ..., S) \tag{4.7}$$

where, n_s is the total number of flow shops. $o_{s,t}$ is the non-shiftable load of factory *s* at time *t*. $f_{s,t}$ is the shiftable load of the factory *s* at time *t* and it is formulated as Equation (3.16).

4.2.2 Optimization Problem Formulation

4.2.2.1 Non-Collaborative Manufacturing Factories

The factory *v* optimizes the schedules to reduce its electricity cost under the RTP, and the objective function is written as:

$$\min \sum_{t=1}^{T} P_t(L_t) \cdot L_{v,t}, (v = 1, 2, ..., S) \tag{4.8}$$

where, $P_t(\cdot)$ is the RTP (See Equation (4.1)). $L_{v,t}$ is the electricity consumption of factory *v* at time *t*. L_t is the total electricity consumption of all users at time *t*, i.e., residential buildings, commercial buildings, and factories.

The total electricity consumption of all the manufacturing factories $L_{M,t}$ at time t is:

$$L_{M,t} = \sum_{s=1}^{S} L_{s,t} (s = 1, 2, ..., S) \tag{4.9}$$

where, $L_{s,t}$ is the electricity consumption for factory *s* at time *t*.

Thus, based on Equation (4.2) and Equation (4.9), L_t is written as:

$$L_t = L_{R,t} + L_{C,t} + \sum_{s=1}^{S} L_{s,t}, (s = 1, 2, ..., S, t = 1, 2, ..., T) \tag{4.10}$$

where, $L_{R,t}$ is the electricity consumption of residential building at time t. $L_{C,t}$ is the electricity consumption of commercial buildings at time t. $L_{s,t}$ is the electricity consumption for factory s at time t.

The electricity consumption is determined by the total electricity consumption of all users, (i.e., residential buildings, commercial buildings, and factories). However, for the non-collaborative case, there is no information exchange among users. Thus, a factory has to minimize its electricity cost without knowing the power information of others. Because of incomplete information, the factory has to depend on the assumptions. In this section, three assumptions are made:

(a) Each factory v assumes that the electricity price primarily depends on the power demand of residential and commercial buildings. Thus, the Equation (4.10) can be written as:

$$L_t = L_{R,t} + L_{C,t}, (t = 1, 2, ..., T) \tag{4.11}$$

where, $L_{R,t}$ is the electricity consumption of residential building at time t. $L_{C,t}$ is the electricity consumption of commercial buildings at time t. L_t is the total electricity consumption of all users at time t.

(b) Each factory v assumes that it is the only factory served in the grid. Thus, the electricity price is largely dependent on the total power demand of residential buildings, commercial buildings, and its own. The Equation (4.10) can be represented as:

$$L_t = L_{R,t} + L_{C,t} + L_{v,t}, (t = 1, 2, ..., T, v = 1, 2, ..., S) \tag{4.12}$$

where, $L_{R,t}$ is the electricity consumption of residential building at time t. $L_{C,t}$ is the electricity consumption of commercial buildings at time t. $L_{v,t}$ is the electricity consumption of factory v at time t. L_t is the total electricity consumption of all users at time t.

(c) Each factory v assume that all the other factories have the same power demand schedules as its own. Thus, the Equation (4.10) can be written as:

$$L_t = L_{R,t} + L_{C,t} + S \cdot L_{v,t}, (t = 1, 2, ..., T, v = 1, 2, ..., S) \tag{4.13}$$

where, $L_{R,t}$ is the electricity consumption of residential building at time t. $L_{C,t}$ is the electricity consumption of commercial buildings at time t. $L_{v,t}$ is the electricity consumption of factory v at time t. L_t is the total electricity consumption of all users at time t. S is the total number of factories.

4.2.2.2 Collaborative Manufacturing Factories

The manufacturing schedules of all the factories are optimized to minimize their total electricity cost under RTP. The objective function is formulated as:

$$\min \sum_{t=1}^{T} P_t(L_t)\left(\sum_{s=1}^{S} L_{s,t}\right), (t = 1, 2, ..., T, s = 1, 2, ..., S) \tag{4.14}$$

where, $P(\cdot)$ is the RTP (See Equation (4.1)). T is the total time. $L_{s,t}$ is the electricity consumption for factory s at time t. L_t is the total electricity consumption of all users at time t.

According to Equation (4.10), the total electricity consumption at time t is written as:

$$L_t = L_{R,t} + L_{C,t} + \sum_{s=1}^{S} L_{s,t}, (t = 1, 2, ..., T, s = 1, 2, ..., S) \tag{4.15}$$

where, $L_{R,t}$ is the electricity consumption of residential building at time t. $L_{C,t}$ is the electricity consumption of commercial buildings at time t. $L_{s,t}$ is the electricity consumption for factory s at time t.

The optimization problem can be solved by using TOMLAB in Matlab. However, if the number of machines, flow shops, or manufacturing facilities is increased, the computation time will be increased significantly. Thus, an alternative formulation will be proposed to solve this issue. The total electricity consumption of manufacturing facilities can be written as:

$$\sum_{s=1}^{S} L_{s,t} = \sum_{s=1}^{v-1} L_{s,t} + L_{v,t} + \sum_{s=v-1}^{S} L_{s,t}, (t = 1, 2, ..., T) \tag{4.16}$$

where, $L_{s,t}$ is the electricity consumption for factory s at time t. $L_{v,t}$ is the electricity consumption of factory v at time t.

Based on Equation (4.16), the objective function for each factory v, $v \in \{1, 2, ..., S\}$ at time t for *rth* iteration is as:

$$\min \sum_{t=1}^{T} P_t(L_t^{(r)}) \cdot (L_{v,t}^{(r)}) \tag{4.17}$$

$$L_t^{(r)} = L_{R,t} + L_{C,t} + \sum_{s=1}^{v-1} L_{s,t}^{(r-1)} + L_{v,t}^{(r)} + \sum_{s=v+1}^{S} L_{s,t}^{(r-1)} \tag{4.18}$$

where, $L_{R,t}$ is the electricity consumption of residential buildings at time t. $L_{C,t}$ is the electricity consumption of commercial buildings at time t. $L_{s,t}$ is the electricity consumption for factory s at time t. $L_{v,t}$ is the electricity consumption of factory v at time t. L_t is the total electricity consumption of all users at time t. $P(\cdot)$ denotes the real-time electricity rate.

This distributed algorithm breaks the centralized optimization problem into sub-optimization problems. At each iteration, factories share and update the electricity consumption. Based on the electricity consumption of other factories, each factory minimizes its own electricity cost through optimizing the manufacturing schedules. The procedures of the distributed algorithm are as following:

Step 1: Assume that power demands of Factory 1, 2,…, v-1, v+1, …, and S are equal to 0. Each factory v seeks the optimum manufacturing schedule that minimizes the individual electricity cost under RTP. Step 2: At the end of each iteration, each factory v sends the power demand information to all the other factories (Factory 1, 2,…, v-1, v+1, …, and, S).

Step 3: Each factory updates the power demand records of the other factories. Step 4: Each factory *v* optimizes its manufacturing schedule to minimize its electricity cost using Equation (4.17). Step 5: Repeat Steps 2-Step 4, until convergence is achieved.

4.2.3 Case Study

Assuming *a*=0.0005, and *b*=-3.6052 in Equation (4.1), the real-time electricity price can be written as:

$$P_t(L_t) = \exp(0.0005L_t\text{-}3.6052) \tag{4.19}$$

where, L_t is the total electricity consumption of all users at time *t*. $P(\cdot)$ denotes the real-time electricity price.

A hypothetical religion with 200 residential buildings, and 6 commercial buildings, and 3 manufacturing facilities are modeled to demonstrate the proposed approach. GridLAB-D is used to generate the electricity consumption of residential and commercial buildings. The parameter values of residential and commercial buildings are listed in Table 4-8 and Table 4-9. Figure 4-14 shows the real-time power demand of residential and commercial buildings.

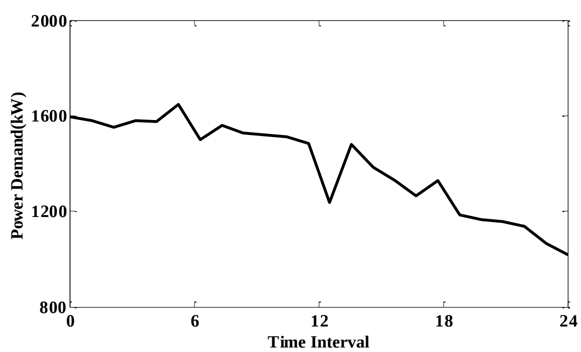

Figure 4-14. Power demand of residential and commercial buildings.

Each factory has 10 same flow shops, and there are 3 processes in each flow shop. The power demand and processing time for each process are shown in Table 4-10. The process order is Process A→ Process B→ Process C. The production quota is 4, 4, and 5 per flow shop in Factory 1, Factory 2, and Factory 3, respectively. The non-shiftable load is 10kW, 10kW, and 15 kW per flow shop for Factory 1, Factory 2, and Factory 3, respectively. The total working time is 4 hours, and the time interval is 10 minutes.

Table 4-10. Flow shop parameters.

Factory	**Power demand (kW)**			**Process time (minutes/part)**		
	Process			Process		
	A	B	C	A	B	C
Factory 1	10	20	10	20	30	20
Factory 2	20	10	10	20	30	10
Factory 3	10	15	15	10	30	10

4.2.3.1 Non-Collaborative Case

In this case, each factory minimizes its own electricity cost under the RTP without the knowledge of other factories' information. Table 4-11 shows the electricity cost under different assumptions based on each factory's scheduling decision. The baseline is manufacturing scheduling aiming at minimizing the makespan without considering the electricity cost reduction. The total electricity cost for 3 non-collaborative factories is $272.4, $266.3, and $265.6 for assumption (a), (b), and (c), respectively. It is noticed that the total electricity cost of the baseline is higher than that of other assumptions. The assumption (a) is a poor one, since factories need to pay more than in the case when assumption (b) or assumption (c) is used.

Table 4-11. Electricity cost ($) comparison.

	Factory 1	**Factory 2**	**Factory 3**	**Total**
Baseline of no optimization (minimum makespan)	98.2	86.2	105.6	290.0
Assumption (a)	92.0	80.3	100.1	272.4
Assumption (b)	89.3	78.4	98.6	266.3
Assumption (c)	89.1	77.7	98.8	265.6

4.2.3.2 Collaborative Case

In this case, all the factories are subject to the RTP, and the manufacturing schedules are optimized to minimize the electricity cost. Figure 4-15 shows the total power demand of all the manufacturing facilities over the 4-hour period that has the minimal total cost.

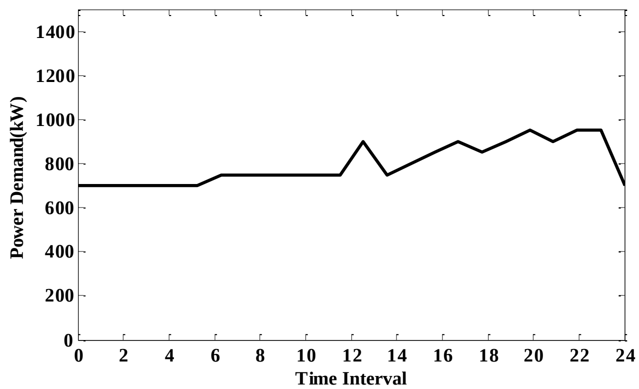

Figure 4-15. Power demand of manufacturing facilities.

The real-time electricity rate is based on the total electricity consumption of all users, i.e., residential buildings, commercial buildings, and factories. Thus, according to Figure 4-14 and Figure 4-15, the real-time electricity price can be obtained (See Figure 4-16). Based on Figure 4-15 and Figure 4-16, the corresponding total electricity cost of three factories over the 4-hour period is $261.1.

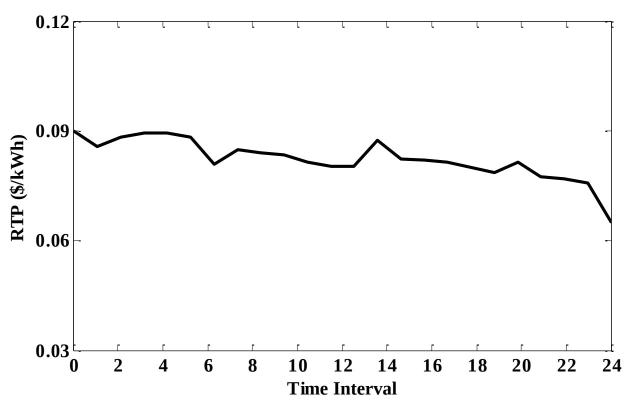

Figure 4-16. Real-time electricity price profiles.

Alternatively, a distributed algorithm (Equation (4.17), and Step 1- Step 5) is proposed to solve the above optimization problem. Figure 4-17 shows the total power demand of three factories over the 4-hour period.

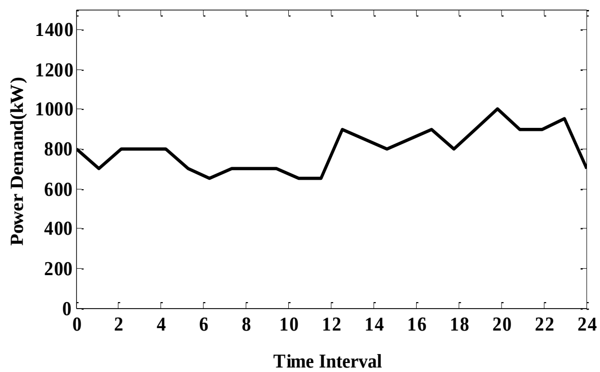

Figure 4-17. Power demand of manufacturing facilities.

Figure 4-18 shows the real-time electricity price, which is obtained based on the power consumption of residential and commercial buildings (See Figure 4-14) and total power consumption of three manufacturing factories Figure 4-17. Accordingly, the total electricity cost is $261.6. The result achieved by using the distributed algorithm is closed to the solution from the centralized algorithm ($261.1), and the computation time is reduced by 90% using the distributed algorithm. Thus, a distributed approach may better mimic an actual situation.

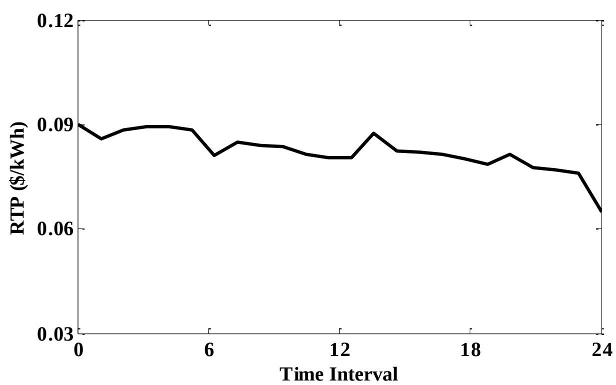

Figure 4-18. Real-time electricity price profiles.

4.2.4 Conclusions

This section studies on manufacturing scheduling of the multiple manufacturing factories aiming at reducing the electricity cost under RTP. Two cases have been explored: (1) non-collaborative case, and (2) collaborative case. The result shows that total electricity cost of all three factories is higher in the non-collaborative case than that in the collaborative case. Additionally, a distributed algorithm is explored to improve the computational efficiency. The results from the distributed algorithm show great agreements with those from the centralized method. The manufacturing scheduling of multiple factories is a complex optimization problem, and introducing RTP makes it even challenge. Efforts are required to advance the problem formulations and algorithms to solve the more realistic scheduling problem.

CHAPTER 5. CONCLUSIONS

5.1 Summary

This research work studies on the scheduling problems that minimize the electricity cost for factories with flow shops under different time-varying electricity rates, i.e., TOU rate and RTP. Additionally, the optimization problems focusing on minimizing the electricity cost for single factory or multiple factories have been investigated. The following flow shop scheduling problems have been covered in this research work:

- To minimize electricity cost for single manufacturing facility under the TOU rate
- To minimize electricity cost for multiple manufacturing facilities under TOU rate
- To minimize electricity cost for single manufacturing facility under the RTP
- To minimize electricity cost for multiple manufacturing facilities under RTP

A time-indexed integer programming formulation is developed to formulate the mathematical model of these scheduling problems. GAMS, Gurobi, and TOMLAB are used to solve them. If multiple factories are shifting electricity usages from on-peak hours to off-peak hours, the original time of peak demand period might be moved. A TOU combined with IBR pricing has been proposed to guarantee the total electricity consumption of the grid at each hour is no more than the threshold.

In the case when multiple factories collaborate with each other to minimize the total electricity cost under the RTP, the optimization problem is formulated as a centralized pattern and distributed formulation. The results showed that the distributed algorithm can achieve a similar result as that of the centralized algorithm while the computation time is reduced by 90%.

5.2 Potential Future Work

The flow shop scheduling problems that minimize the electricity cost have been done; work can be extended in several directions:

- The algorithm is further extended to address other types of shop floor scheduling problems in the future. Additionally, it is assumed each machine has two modes, i.e., on-mode, and off-mode.
- The TOU rate and the equation of RTP are given to the consumers in advance in this thesis. However, in the actual market, consumers shift their electricity consumption based on the real-time electricity price signal, which is updated every certain period, i.e., 15 minutes, 30 minutes, etc.. It is necessary to adjust manufacturing schedules based on the updated electricity rate dynamically, and meanwhile maintain the production throughput. Thus, the dynamic job shop scheduling problem will be studied in the future.
- It is interesting to study on whether or not consumers can achieve more economic benefits from TOU rate than or RTP program.
- The final goal of this research is to optimize the manufacturing schedules for manufacturing factories according to the real-time price signal in the smart grid scenario. The real-time price relies on the total power demand in the grid consists of residential buildings, commercial buildings, and manufacturing facilities. Thus, the collaborations and interactions among different types of users will be studied.

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VITA

VITA

Hao Zhang

School of Mechanical Engineering

Purdue University

Education

Purdue University, West Lafayette, Indiana, U.S.		Aug. 2011-Aug. 2016
Ph.D. in Mechanical Engineering, 2016	GPA 3.76/4.0	
Tsinghua University, Beijing, China		Sep. 2008-Jun. 2011
Master of Science in Mechanical Engineering, 2011	GPA 3.8/4.0	
Beijing Institute of Technology, Beijing, China		Sep. 2004-Jun. 2008
Bachelor of Science in Mechanical Engineering, 2008	GPA 3.8/4.0	

Research Interests

Flow Shop Scheduling, Power Grid Simulation, Life Cycle Assessment, Sustainable Manufacturing.

LIST OF PUBLICATIONS

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[1] Hao Zhang, Fu Zhao, John W. Sutherland, “Manufacturing Scheduling for Reduced Energy Cost in a Smart Grid Scenario”, Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore, April 17-19, 2013.

[2] Hao Zhang, Fu Zhao, Kan Fang, John W. Sutherland, “Energy-Conscious Flow Shop Scheduling under a Time-of-Use Electricity Tariff”, CIRP Annals - Manufacturing Technology, 2014.

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[6] Hao Zhang, John Burr, Fu Zhao, “A Comparative Life Cycle Assessment of Lighting Technologies for Greenhouse Crop Production”, Journal of Cleaner Production, Accepted, 2016.

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