A conceptual approach for managing production in consideration of shifting electrical loads

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ARTICLE INFO

Article history:
Received 27 March 2013
Received in revised form 4 March 2014
Accepted 26 March 2014
Available online 19 April 2014

Keywords:
Smart grid
Load shift
Production operation method
Theory of constraints
Drum–buffer–rope

ABSTRACT

The key concept of the smart grid is demand response for power consumption comprising actions taken by customers to reduce or shift electrical loads temporarily in response to requests from electric service providers. A demand response program offers time-based rates that allow customers to choose whether to adjust their consumption. In the manufacturing sector, production managers are likely to participate in a demand response program if they can schedule their production operations in response to electricity prices at peak times. The drum–buffer–rope (DBR) scheduling system in the theory of constraints (TOC) is a useful production operation method because it helps managers focus on effectively managing capacity based on the critical constraint that limits performance of the system. This paper presents a conceptual approach to managing production in consideration of shifting electrical loads in an effort to deal with the most expensive hours of the day. A DBR-based operation model is developed to determine the running time of production processes depending on power saving vs. throughput loss. Conceptual cases are prepared to demonstrate how a production manager can shift electrical loads in response to electricity prices.

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1. Introduction

The summer season witnesses a tremendous rise in electrical power consumption, and to meet this electric demand, electrical power supply facilities are required to expand. The graph in Fig. 1 shows an example of a very hot summer day [1]. The red line represents customer power consumption throughout the day. The purple line represents what a utility company would have had to generate if interruptible load management programs were not used to reduce customer consumption. You may notice a difference of more than 300 MW at the time of peak consumption. This increased energy demand is usually met by activating additional expensive power plants. The blue line indicates the price of electricity. Electricity prices on peak days can be twice or thrice the price of wholesale electricity on a typical summer day. Hence, reducing electrical power demand in summer by improving the efficient utilization of facilities is critical.

So-called smart grid technology, or the intelligent electricity grid that uses modern IT/communication/control technologies, has attracted increasing attention in recent years and has now become a global trend [2]. It allows real-time monitoring of electric consumption providing end users and utility companies a way to better conserve and plan their use of this limited resource. Smart metering is the fundamental building block of these grids, which are used to provide consumers the information they need to make efficient choices. With the information, utility companies can ensure a higher level of transmission efficiency, thereby saving massive amounts of energy, money, and environmental resources [3].

The key concept of the smart grid is demand response for power consumption comprising actions taken by customers to reduce or shift their electrical load temporarily in response to a request from electric service providers [4]. A demand response program offers time-based rates that allow customers to choose whether to adjust their consumption. In the manufacturing sector, production managers are likely to participate in a demand response program if they can schedule their production operations in response to electricity prices at peak times. Unlike homeowners, however, production managers are concerned that the throughput of their system may be diminished because of suppressing electricity demand during times of peak demand.

However, power management and power-saving efforts in the manufacturing industry are focused on improving efficiency through replacement and improvement of equipment that consumes large amounts of energy considering the heavy burden of investment costs. Recent advances in smart metering, demand response, and communications technologies have significantly increased awareness that will lead production managers to schedule their energy consumption efficiently. They are beginning to
perceive the ability of the smart grid coupled with automated controllers to control the power consumption of each process automatically in the system, triggered by signals sent by utility companies over the power grid.

Production systems rely normally on the just-in-time (JIT) strategy that strives to reduce process inventory and associated carrying costs by producing only what is required in the correct quantity and at the correct time [5]. Actual orders provide a signal for when a product should be manufactured. To meet JIT objectives, therefore, production systems may need to be operated even when energy prices are increased. However, if electricity prices on these peak days are twice or thrice the regular price of wholesale electricity, production managers are likely to reduce or shift electrical loads while JIT schedules are temporarily suspended.

Rather than keeping inventory levels low as in JIT, it might be beneficial to allow affordable stocks to increase and adjust consumption of electricity by using real-time pricing. However, the nature of manufacturing makes it difficult to require customers to reduce their consumption at critical times in response to electricity prices. Reckless power savings cause chaos on the production line and can lead to greater losses. Therefore, it is necessary to consider a production operation method that allows managers to estimate losses and benefits by shifting consumption to less expensive hours.

The drum–buffer–rope (DBR) scheduling system in the theory of constraints (TOC) is a useful production operation method that emphasizes the optimization of performance within a defined set of constraints on existing processes [6]. The fundamental thesis of DBR is that constraints establish the performance limitations for any system, which suggests that managers should focus on effectively managing the capacity of these constraints if they are to improve performance [7]. Hence, DBR can offer a solution for shifting electrical loads to less expensive hours without degrading overall throughput. This paper presents a conceptual approach for managing production by shifting electrical loads in an effort to deal with the most expensive hours of the day. A DBR-based operation model is developed to schedule production processes depending on power savings vs. throughput losses. Conceptual cases are prepared to demonstrate how a production manager can shift electrical loads in response to electricity prices.

The remainder of this paper is organized as follows. Section 2 reviews the current trends in smart grids, and Section 3 introduces a DBR-based operation strategy for shifting electrical loads in response to requests from electric service providers. Section 4 presents a mathematical model and cases of how a production manager can shift electrical loads in response to electricity prices. Section 5 discusses the implications of the cases, and Section 6 ends with the limitations and suggestions for further research.

2. Industry trends

Recent years have witnessed a significant rise in fuel and electricity costs. Electricity prices on these peak days double or triple the price of wholesale electricity relative to a typical summer day. Hence, customers are motivated to adopt a demand response program that allows customers to choose whether to adjust their consumption by time-based rates. It presents an unprecedented opportunity for utilities, third-party energy providers, and customers to create an interactive, reliable, and efficient power network [8]. As a part of this effort, the electric utilities around the globe are heavily investing in the smart grid to support advanced metering infrastructure (AMI), distribution automation (DA), and demand response (DR).

AMI refers to systems that measure, record, and analyze energy usage, and interact with advanced devices such as electric meters, gas meters, heat meters, and water meters, through various communication media either on request (on-demand) or on predefined schedules [9], and it plays an essential role in smart management of consumer power [10]. A smart meter electronically tracks how much electricity a home or small business uses and when it is used. Smart metering generally involves the installation of a smart meter at a residence, which is used to provide regular readings, processing, and feedback of consumption data to the customer [11]. Its intelligence is incorporated to measure the electricity used (or generated), remotely switch the customer off, and remotely control maximum electricity consumption [12].

DA is a method for real-time adjustment to changing loads, generation, and failure conditions in the distribution system, usually without operator intervention. [13]. Real-time data is available to human operators, enabling them to monitor more and more events in their distribution systems and to control automatic equipment remotely. DA allows individual devices to sense the operating conditions of the grid around them and make adjustments to improve overall power flow and optimize performance [14]. Smart building is a grid-connected building application that can control heating, cooling, and lighting with sensors and automatic control technology and is power-adjustable to reduce energy use, depending on the state of the building [15].

DR is designed to enable customers to contribute to energy load reduction during times of peak demand. According to the Federal Energy Regulatory Commission, one of the main goals of the smart grid is to achieve DR by increasing the participation of end users in reducing the peak demand for electricity and the awareness that will lead them to manage their energy consumption efficiently. In this context, DR refers to actions by customers that change their consumption (demand) of electric power in response to price signals and plays a key role in linking the retail and wholesale sectors of electric markets [16].

DR is similar to dynamic demand mechanisms to manage customer consumption of electricity in response to supply conditions, for example, having customers reduce their consumption at critical times or in response to market prices. [17]. DR can be categorized into two groups: incentive-based demand response and time-based rates. The most common demand response program offered is time-based rates, which are offered to residential customers by 55% of publicly owned utilities [18].

The key strategy of demand response is to offer financial incentives for load reduction during times of peak demand [19]. Some utilities have commercial tariff structures that set a customer’s power costs for the month based on top-peak, mid-peak,
and off-peak schedules. This encourages users to flatten their demand for energy, known as energy demand management, which sometimes requires cutting back services temporarily. Utilities may impose load shedding on service areas by agreements with specific high-use industrial consumers to shut down equipment at times of peak demand to better manage their costs of doing business [20].

One study suggested that shifting 5–8% of consumption to off-peak hours and cutting another 4–7% of peak demand could save utilities, businesses, and customers as much as $15 billion a year [21]. However, the New York commission found that planners who rely solely on the supply-side still over-estimate their systems to accommodate a few hours of annual system peak, rather than leveling that peak through conservation and demand response [22].

Customer price-responsiveness varies significantly by market segment among commercial and industrial users. A critical peak-pricing experiment in California in 2004 determined that small residential and commercial customers are price responsive and will produce significant reductions. Participants reduced load by 13% on average, and as much as 27% when price signals were coupled with automated controls such as controllable thermostats [23]. Specially, industrial customers who were also enrolled in the emergency demand response program showed dramatically increased responses during emergency demand response events. The changes in electricity use are designed to be short-term in nature, centered on critical hours during the day or year when demand is high or when reserve margins are low [24].

There is a significant gap between perception of the ability of DR and the reality of current participation. Participants in organized wholesale market DR programs have overestimated their likely performance during declared curtailments events [25]. That is, not all consumers need to respond simultaneously for markets to benefit by lowered overall prices. Only a fraction of all customers, perhaps as few as 5%, is needed to discipline electricity market prices [26]. No approach focuses on the users’ point of view at different levels of the smart grid to achieve demand response [27].

Advances in integrated circuitry, control systems, and communications technologies have significantly increased the functionality of advanced metering and demand response technologies [28]. However, interoperability and standards problems are likely only to worsen as utilities deploy more communications equipment to support their expanding smart grids. The development of network management systems that provide comprehensive, technology-agnostic solutions becomes an emerging and critical technology [29]. Better grid reliability is needed while dealing with an aging infrastructure.

The DR program offers time-based rates that allow customers to choose whether to adjust their consumption of electric power. In the manufacturing sector, production managers are likely to participate in a demand response program if their decision to adjust consumption is driven by the costs and benefits of real-time pricing. This section presents a DBR-based load-shedding strategy that strives to manage the costs of doing business better during times of peak demand.

### 3. DBR-based load-shedding strategy

The DR program offers time-based rates that allow customers to choose whether to adjust their consumption of electric power. In the manufacturing sector, production managers are likely to participate in a demand response program if their decision to adjust consumption is driven by the costs and benefits of real-time pricing. This section presents a DBR-based load-shedding strategy that strives to manage the costs of doing business better during times of peak demand.

#### 3.1. DBR operation

Drum–buffer–rope (DBR) scheduling is an application of the theory of constraints (TOC) in production systems. First introduced by Eli Goldratt [31], DBR is an approach to managing production through a constraint and is named after its three core components. (1) “Drum” is the physical constraint or the weakest link. The rest of the plant follows the beat of this drum. (2) “Buffer” are stocks that protect the drum by ensuring a constant flow of work into the buffer. (3) “Rope” is the work release mechanism or timing.

The goal of the production DBR is to protect the weakest link in the system against process dependencies and variations and to maximize the system’s effectiveness [32]. Fig. 2 shows the production DBR that constitute the building blocks of a production operation that minimizes excess inventory and is resistant to disruptions. Jobs are shipped at the rate of the constraint production. Once a job leaves the buffer and enters the drum (the control point), the rope pulls the next operation into the first process.

The TOC sets only one DBR to manage the entire production line through a constraint. The speed of the entire production is synchronized with that of the drum (production constraint). It means that material in the first process is released at the same rate that the production constraint can consume it.

However, utilities may impose load shedding on service areas by agreements with specific high-use industrial consumers to shut down equipment at times of peak demand [33]. Therefore, production managers need a load-shedding strategy that can make ON/OFF decisions for equipment in terms of throughput losses and energy savings in their systems.
3.2. DBR-based load-shedding strategy

Utilities may impose load shedding on service areas via rolling blackouts or by agreements with specific high-use industrial consumers to shut down equipment at times of peak demand. In order to prepare for load shedding in production systems, we have developed a DBR-based load-shedding strategy that can allow production processes except for the constraint to stop temporarily during times of peak demand. The core of DBR-based load-shedding strategy is to identify additional DBRs, called utility DBRs, which are used to manage load shedding in production systems.

In production DBR, the production constraint is typically the most heavily loaded process (or work center) in the production system. The buffer is a period of time to protect the constraint from problems that occur upstream from its operation. Orders are shipped at the rate of the constraint production. If the constraint is stopped, the throughput is diminished. Therefore, it should be fully utilized even during times of high electrical demand.

In utility DBR, likewise, the utility constraint is the second slowest process located before or after the production constraint. The utility buffers coupled with the utility constraints are located before or after the production constraint. They are additional stocks to be kept for electrical load shedding during high electrical demand. The utility ropes are the work release mechanism or timing. The speed of processes before or after the production constraint is synchronized with that of the utility constraints. Fig. 3 shows the two utility DBRs.

To incorporate the utility DBRs into the load-shedding strategy, we need to decide which part of the processes can be turned off. There are three options: shutting down all processes except the production constraint, shutting down the processes before the constraint, and shutting down the processes after the constraint. The load-shedding strategy is determined by the costs and benefits of real-time pricing during high electrical demand.

3.2.1. Shutting down the processes before the constraint

Utility DBR A in Fig. 3 is a case of shutting down processes that occur before the constraint. When a utility constraint is located before a production constraint, the processes before the production constraint can be shut down during a time of peak demand. The utility constraint is the second slowest process before the production constraint. The speed of the utility constraint is synchronized with that of the leading process and determines amount of stock produced in advance for the utility buffer. The size of the utility buffer is determined by the speed difference between the two constraints.

For example, the speed of the production constraint is 10 stocks/h, and the speed of the utility constraint is 15 stocks/h. If processes are to be shut down for 2 h, the production constraint needs 20 stocks for nonstop operation. Therefore, 20 stocks need to be stored in the utility buffer. The speed of the utility constraint is not synchronized with that of the production constraint until required stocks are stored. During times of peak demand, the processes before the production constraint can be shut down. The other processes should continue to prevent throughput loss. After a 2-hour shutdown, the production constraint is again the drum for the entire production system.

3.2.2. Shutting down processes after the constraint

Utility DBR B in Fig. 3 shows a case of shutting down the processes that occur after the constraint. When a utility constraint is located after a production constraint, the processes after the production constraint can be shut down during times of peak demand. The utility constraint is the second slowest process, and its speed determines whether it can supplement throughput loss when shutting down the processes after the production constraint during times of peak demand. Hence, there are two ropes to control the production operation when considering load shedding. One is the production rope that controls the release of material from the first process, and the other is the utility rope that controls the release of material after the production constraint. The size of the utility buffer is determined by the speed difference between the two constraints.

The DBR-based load-shedding strategy allows production managers to shut down all or some production processes in response to peak electricity prices. In the next section, its mathematical model is presented to demonstrate how a production manager can analyze and propose changes to production schedules.

4. Mathematical model

The mathematical model of the DBR-based load-shedding strategy can help us to set up a new schedule based on a daily production schedule and the degree to which energy cost is saved. The following assumptions have been made in order to prepare this model: a DBR-based load-shedding strategy applies to discrete
parts and batch-manufacturing environments; DBR is the main scheduler to plan the entire production process; additional buffers with larger sizes are affordable and sufficient to hold additional stocks; the power consumption rates of processes are constant; and differential power prices are available in advance.

4.1. Measures of a DBR-based load-shedding strategy

In the utility DBR approach, simultaneously shutting down all machines except the constraint is considered first to model the DBR-based load-shedding strategy. It is clear that shutting down the machines brings some throughput loss and inventory increases. Now, we develop two performance measures: (1) throughput losses and (2) power savings. With these performance measures, our approach provides a guideline for a production manager to consider load shedding in production.

Suppose a production line comprising $n$ machines with production capacities $P_i$, $i = 1\ldots n$, and machine $k$ is the constraint of the production line. As shown in Fig. 4, machines located before machine $k$ belong to production block $A$ (PB$_A$), and machines after machine $k$ to production block $B$ (PB$_B$). Since the throughput of a production block is determined by the slowest machine in the block, the production rates of blocks $A$ and $B$, $PPB_A$ and $PPB_B$, respectively, are $\min(P_1, \ldots, P_{k-1})$ and $\min(P_{k+1}, \ldots, P_n)$. Clearly, $PPB_A$ and $PPB_B$ are greater than or equal to $P_k$.

Now, consider shutting down the entire production line except machine $k$ for $h$ hours from time $t$ to time $t + h$. In the scenario, PB$_A$ needs to produce additional $h \cdot P_k$ stocks before time $t$ so that machine $k$ never stops operating during the shutdown period, while PB$_B$ produces additional $h \cdot P_k$ stocks after time $t + h$ to guarantee the throughput of the whole manufacturing line. To have additional $h \cdot P_k$ stocks, PB$_A$ and PB$_B$ should produce at their full production rate, $PPB_A$ and $PPB_B$, instead of $P_k$ for some period. As shown in Fig. 5, PB$_A$ must produce at rate $PPB_A$ from time $t - (h \cdot P_k/(PPB_A - P_k))$ to time $t$ (red line), and PB$_B$ must produce at rate $PPB_B$ from time $t + h$ to $t + h + (h \cdot P_k/(PPB_B - P_k))$ (green line). Let $t_{\text{start}}$ and $t_{\text{end}}$ be the start and end times of operation for a day, respectively. Then, it is clear that no throughput loss occurs for a day if $t_{\text{start}} \leq t - (h \cdot P_k/(PPB_A - P_k))$ and $t + h + (h \cdot P_k/(PPB_B - P_k)) \leq t_{\text{end}}$.

Since PB$_A$ and PB$_B$ have enough time to produce additional stocks to store in utility buffers $A$ and $B$, no throughput loss occurs, whereas the level of stocks increases temporarily. Fig. 6 presents the temporal increase of stocks in utility buffers $A$ and $B$.

4.1.1. Throughput loss

Some throughput loss is inevitable by shutting down the entire production line except machine $k$ from time $t$ to time $t + h$. The following are the three cases of throughput loss (see Fig. 7).

Case 1. $t_{\text{start}} > t - \frac{h \cdot P_k}{PPB_A - P_k}$ and $t + h + \frac{h \cdot P_k}{PPB_B - P_k} \leq t_{\text{end}}$.

In this case, the throughput loss of the production line is only determined by the PB$_B$. PB$_A$ can only produce additional stocks during $(t_{\text{start}}, t)$ with an extra production rate $(PPB_A - P_k)$. Therefore, expected throughput loss of PB$_A$ is $h \cdot P_k - (t - t_{\text{start}}) \cdot (PPB_A - P_k)$.

Case 2. $t_{\text{start}} \leq t - \frac{h \cdot P_k}{PPB_A - P_k}$ and $t + h + \frac{h \cdot P_k}{PPB_B - P_k} > t_{\text{end}}$.

Different from Case 1, the throughput loss of the production line is only determined by the PB$_B$ in this case. PB$_B$ can only produce additional stocks during $(t + h, t_{\text{end}})$ instead of $(t + h, t + h + (h \cdot P_k/(PPB_B - P_k)))$ with an additional production rate $(PPB_B - P_k)$. Therefore, the expected throughput loss of PB$_B$ is $(t_{\text{end}} - t - h) \cdot (PPB_B - P_k)$.

Case 3. $t_{\text{start}} > t - \frac{h \cdot P_k}{PPB_A - P_k}$ and $t + h + \frac{h \cdot P_k}{PPB_B - P_k} > t_{\text{end}}$.

Since both PB$_A$ and PB$_B$ are not able to produce enough extra stocks for the shutdown period in this case, the throughput loss of the production line is

$$\text{max}(h \cdot P_k - (t - t_{\text{start}}) \cdot (PPB_A - P_k), h \cdot P_k - (t_{\text{end}} - t - h) \cdot (PPB_B - P_k)).$$

By considering these three cases, the throughput loss of the production line can be determined by the following equation. Expected throughput loss of the production line is

$$\text{max}(0, h \cdot P_k - (t - t_{\text{start}}) \cdot (PPB_A - P_k), h \cdot P_k - (t_{\text{end}} - t - h) \cdot (PPB_B - P_k)).$$

(1)

4.1.2. Utility benefit

The utility benefit of the shutdown is the sum of utility costs of all machines except machine $k$ during the shutdown period and calculated by the following equation:

$$\text{Utility benefit} = \sum_{i = k}^{n} \sum_{j = t}^{t + h} u_j \cdot c_i,$$

(2)

where $u_j$ is the per-unit utility cost of time $j$, and $c_i$ is the power consumption of machine $i$.

4.2. Numerical example

Consider a serial production line having eight machines A to H, and the sequence of production processes is A $\rightarrow$ B $\rightarrow$ C $\rightarrow$ D $\rightarrow$ E $\rightarrow$ F $\rightarrow$ G $\rightarrow$ H. The production rates and power consumption of the
eight machines are shown in Table 1. The constraint process is machine D.

Table 2 shows electric rates over time. In this example, the electric rate for each time period is assumed to be the same over machines; however, differential electric rates over machines can be applied according to Table 2.

Now, shutting down the machines except for machine D from 2 pm to 4 pm (from 14:00 to 16:00 in 24-h time) is considered. All machines except machine D during the period stop their operation to save power cost. Also, the operation is supposed to start at 8 am and end at 8 pm, which means $t_{start} = 8$ and $t_{end} = 20$.

The expected throughput loss in this scenario is determined by Eq. (1). With $t = 14$, $h = 2$, $p_k = 10$, $P_{PB,A} = 15$, $P_{PB,B} = 11$, $t_{start} = 8$, and $t_{end} = 20$, the expected throughput loss of the production line becomes $\max(0, -10, 16) = 16$. Power savings during the shutdown are calculated by Eq. (2). The total saving becomes $1160 ((200 + 150 + 300 + 300 + 150 + 200 + 150 \text{ kW}) \times 0.4/\text{kWh} \times 2 \text{ h})$. If a per-unit profit margin of $50$ is applied to the throughput loss, then the total cost of the throughput loss becomes $50 \times 16 = 800$. With this information, a production manager or decision maker might implement the load shedding.

4.3. Load-shedding strategy using the performance measures

More cases are introduced to identify the effects of production rates and shutdown periods on the performance measures. Table 3 shows throughput losses with six different production rate distributions. All the same experimental settings except production rates are used to determine the throughput losses in Table 3. Line efficiency (LE) shows the percentage utilization of the line for a given assembly line balance. It is expressed as the ratio of total station time to the cycle time multiplied by the number of workstations. Perfect utilization is indicated by LE 1. The larger the value of LB, the more the line is utilized. TL stands for throughput loss.

As shown in Table 3, it is clear that minimum throughput loss occurs if production blocks have relatively high production rates compared to the production constraint ($p_k$). With lower LE, therefore, throughput loss is minimized because the processes are unbalanced enough to create the opportunity for power saving in the production line. In such a production condition, load shifting or shutdown might be considered.

The managers of the production lines can practice load shedding because the power saving ($1160$) is greater than the
maximum throughput loss ($800). If the managers want to apply a load-shedding strategy that causes minimum throughput loss, however, it is necessary for them to consider that the production lines are partially shut down. For scenarios 1, 2, and 6, as shown in Table 4 PB_A can be shut down during times of peak demand because PB_B is the major cause of the throughput losses. For scenarios 3 and 4, PB_B can be shut down during times of peak demand because PB_A is the major cause of the throughput loss. For scenario 5, PB_A and PB_B can be simultaneously shut down during times of peak demand.

In addition, the effect of the duration of peak demand on throughput loss is investigated. Consider Fig. 8 which plots the throughput loss of PB_A, PB_B, and machine k during different durations of peak demand. This case is prepared with scenario 5 in Table 3 and follows the assumptions that the throughput loss is less than the power saving, and the throughput loss is minimized. Since there is no throughput loss during the first a 2-h duration, the recommended strategy would be to shut down PB_A and PB_B together. Since the production rate of PB_B (15) is higher than that of PB_A (14), the throughput loss by PB_A is greater than PB_B for up to 4 h. In order to minimize the throughput loss, the recommended strategy would be to shut down PB_B up to 4 h. However, if shutdown duration is longer than 5 h (from noon to 5 pm), the throughput loss of PB_B is going to greater due to the shortened operation time. The recommended strategy would be to shut down PB_A.

5. Discussion

To evaluate a DBR-based load-shedding strategy, a numerical study was conducted for a production line using the load curve of the peak day of a power system grid. In the numerical study, six different scenarios were analyzed and investigated for recommending a load-shedding strategy as shown below.

- **Strategy 1:** If there is no throughput loss during times of peak demand, shut down PB_A and PB_B together.
- **Strategy 2:** If the throughput loss is less than the power saving, and throughput loss does not matter, shut down PB_A and PB_B together.
- **Strategy 3:** If the throughput loss is less than the power saving, and throughput loss is minimized, shut down PB_B if the throughput loss of PB_A is less than that of PB_B.
Table 4
Comparison of throughput losses.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TL_{PB_A}</th>
<th>TL_{PB_B}</th>
<th>TL_{Onload}</th>
<th>Throughput loss by turning off</th>
<th>Load-shedding strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>16</td>
<td>16</td>
<td>0</td>
<td>$800 $800 PB_A</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>16</td>
<td>16</td>
<td>$100 $800 $800 PB_A</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>0</td>
<td>14</td>
<td>$700 0 $700 PB_B</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>8</td>
<td>14</td>
<td>$700 $400 $700 PB_B</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 $200 $200 PB_A+PB_B</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0 PB_A</td>
</tr>
</tbody>
</table>

- **Strategy 4**: If the throughput loss is less than the power saving, and throughput loss is minimized, shut down PB_A if throughput loss of PB_B is less than that of PB_A.
- **Strategy 5**: Even though throughput loss is greater than power saving, to minimize throughput loss, shut down PB_A if throughput loss of PB_B is less than that of PB_A.
- **Strategy 6**: Even though throughput loss is greater than power saving, to minimize throughput loss, shut down PB_B if throughput loss of PB_A is less than that of PB_B.

Strategies 5 and 6 can be applied where utilities may legally impose load shedding on service areas via rolling blackouts or by agreements with specific high-use industrial consumers to shut down equipment at times of peak demand.

### 6. Conclusion

The grid is now a basic term when it comes to providing electricity to end users, such as homeowners, schools, factories, hospitals, retailers, and office buildings. The key concept of the smart grid is demand response in power consumption comprising actions taken by consumers to reduce or shift their electrical loads temporarily in response to a request from an electric service provider. Real-time measurement of power and real-time power prices are key technology elements to make production systems responsive to the smart grid. Electricity prices varying at different times of the day can encourage production managers to think more about how and when they use electricity. However, the nature of manufacturing makes it difficult to connect with the smart grid. Reckless power savings cause chaos on the production line and can lead to greater losses. Therefore, a production-scheduling technique needs to be developed for a factory seeking a way to shift its electrical load.

Once considered simply a production-scheduling technique, DBR has broad applications in diverse organizational settings. Grouping utility DBRs with production processes can allow electric load shifting in response to financial incentives during periods of high demand for electricity. Properly sized utility buffers can increase stocks in production lines but are necessary to maintain production as planned during times of peak demand.

Findings from the numerical study demonstrated that a DBR-based load-shedding strategy can be successfully applied to a production system as a way of shifting its electrical load, and it provides a simple way to create production schedules. However, this conceptual approach to how a production manager can analyze and propose delays in production schedules must consider many scenarios because current production systems are more flexible and complex, various products are produced in systems that have different profit margins, and demand response is more dynamic when it is applied in the industry to name a few.

The future research direction is to develop a mixed binary integer programming model for handling DBR-based load-shedding strategies to address the production situations mentioned above. Linear programming can be used as a technique for optimizing a linear objective function subject to a set of linear constraints.

### Acknowledgements

This paper was completed with Ajou university research fellowship of 2009.

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