Energy Management in Manufacturing Systems

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ABSTRACT

Conventionally, improving production efficiency, flexibility and responsiveness has been the primary research focus of production management, while energy consumption has received relatively little attention. Energy consumption plays a more and more important role in manufacturing environment. This is mainly driven by energy cost and environmental concerns. When the energy system becomes complicated and coupled with ongoing production, it is very difficult to hunt the “hidden treasure” which affects the overall benefit of a manufacturing system. This paper provides a systematic method for energy management in a production system. We start from dynamic production transient analysis and provide quantitative analysis for energy saving opportunity in a system. Furthermore, energy saving is integrated into production system which includes downtime and throughput to provide integrated energy management framework for a production system. A case study is conducted to demonstrate its potential on energy savings in a multi-stage manufacturing system.

INTRODUCTION

When most people think of energy management, they think of monitoring building utility systems and environmental variables. Both are typically associated with institutional or commercial facilities such as banks, office complexes, hospitals or educational institutions such as school systems or college campuses. Less obvious and less visible, but equally important, is the role energy management plays in the manufacturing sector.

The primary relationship between manufacturing and energy management is that every manufacturing plant is a facility, and manufacturing facilities have all of the same energy consumption issues that other types of facilities have, plus the additional challenge of production operations.

In modern manufacturing, real-time control of production operation to improve system responsiveness, increase system efficiency and reduce downtime is becoming more and more critical [1, 2]. For example, General Motors (GM) reaps significant savings from deploying decision support systems based on real-time control methodology [1-3]. Similar trends are observed in other automotive companies and manufacturing industries in general. Substantial research effort has been devoted to production control and analysis [3-6]. Much of the work related to plant floor analysis addresses the issues of maintenance, downtime reduction, material handling, throughput bottleneck mitigation, etc., in production operations [7-11].

Most previous research has sought to maintain the desired productivity and quality while neglecting energy considerations. The motor vehicle industry alone in the U.S. spends about \$3.6 billion on energy annually [12]. With rising energy costs, increased global competitiveness, environmental concerns, and more government regulations, manufacturers are realizing that energy management plays a critical role in modern manufacturing operation. Energy-efficient solutions often include "additional" benefits, which will reduce the negative impact of environmental variables and unpredictability associated with variable energy prices in today's marketplace. In short, energy efficiency investment is sound business strategy in today's manufacturing environment [12].

However, with this new awareness, there is a lack of scientific understanding of the complex issues of improving energy efficiency while maintaining traditional production goals. There exist unique opportunities and challenges, such as:

1) Monitoring and control of energy systems can have a significant impact on operations and costs;
2) In low-margin industries, the ability to manage total production costs including those associated with energy can make the difference between profit and loss;
3) Inability of manufacturing systems to obtain access to energy consumption systems and data leads to lost opportunities to coordinate all aspects of manufacturing;
4) Uncontrolled and often unmonitored energy consumption systems introduce costs related to the manufacturing facility or the manufacturing process; and
5) Inability to track and analyze energy and manufacturing data as integrated and interdependent variables masks problems in the overall operation.

Although the issue is very important, it is almost entirely neglected. The current literature provides few studies, of which a 2008 review of energy efficiency improvement and cost saving opportunities for the vehicle assembly industry [12] is probably the most comprehensive. The report discussed energy efficiency opportunities available for assembly plants and provided specific primary energy savings for each energy efficiency measure based on case studies, listed costs and typical payback periods.

In [13], an "energy treasure hunts" method was presented. General Electric Company (GE) performed energy "treasure hunts" through a lean manufacturing process developed by Toyota, to help reduce energy costs and carbon footprint. By design, "energy treasure hunts" started on a Sunday afternoon, when an operation was "sleeping." The team kicked off by splitting participants—a cross-functional group of GE employees—into teams and training them to identify opportunities in the facility where energy and resources were needlessly in use—lights left on, equipment operating, pumps or motors running—and to quantify those opportunities for follow up during the rest of the event. On Monday morning, the team interviewed facility employees about the opportunities identified for energy saving, a critical step to secure operator buy-in to the proposed changes. Throughout the day, they continued to quantify their projects, obtaining cost and savings information from process experts, and ideas for operational change from the employees who ran the operation. By Tuesday afternoon, each team had a list of at least 10 quantified ideas for energy savings—and most notably, these projects on average had a simple payback of less than two years.

It can be observed that the "energy treasure hunt" is about *Kaizen*—continuous improvement applied to energy use. The process is still a trial-and-error approach and depends heavily on expert knowledge and experience. There is no systematic and quantifiable tool available for energy-saving decision-making. When the energy system becomes complicated and coupled with ongoing production, the "energy treasure hunt" method is difficult to apply and justify.

Therefore, it is imperative and desirable to integrate manufacturing monitoring and control with energy management. This paper provides a systematic method for energy management in a production system. The rest of this paper is organized as follows. In Sec. 2, we provide manufacturing system assumption and background. We present in Sec. 3 the relationship between energy opportunity and system performance. Section 4 provides simulation studies of energy opportunities. Section 5 summarizes our conclusions and future research.

NOMENCLATURE

Energy treasure hunt, continuous improvement, energy management, multi-stage manufacturing systems, opportunity window

2. ASSUMPTIONS AND BACKGROUND

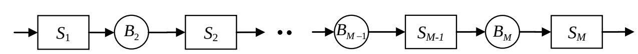

Figure 1: A serial production line with M stations and $M-1$ buffers

We adopt continuous flow models [14-16] in this paper to analyze the impact of energy opportunity on the production process, because the production dynamics can be conveniently described by integral or differential equations. For a serial production line with M stations and $M-1$ buffers as the one shown in Figure 1, we make the following assumptions.

(i) $B_2, B_3, \dots, B_M$ have finite capacity. For simplicity, we also use $B_2, B_3, \dots, B_M$ to denote their maximum capacity.

(ii) Each station has a rated speed (or flow rate) $\frac{1}{T_m}, m = 1, 2, \dots, M$, where T_m is cycle time of station m. An operational station runs at its rated speed when it is neither starved nor blocked. The station can be viewed as operating at a duty cycle less than one when it is starved or blocked.

(iii) The first station S_1 is never starved and the last station S_M is never blocked.

(iv) The energy consumption in an individual machine, equipment item and component can be measured and monitored.

(v) The shutdown of any station S_i has direct impact related to the energy consumption caused by the shutdown, i.e., the consumption of electricity, gas, fuel, and compressed air while applicable, are reduced to certain levels caused by the shutdown. However, non-process energy consumption, such as facility-supported HVAC and lighting, is not impacted.

(vi) Energy consumption data are considered as additional parameters in the context of production line parameters such as downtime and cycle time of machines.

The following notations are used in this paper:

$s_m(t), m = 1, 2, \ldots M$ denotes the actual processing speed of station S_m at time instance t.

$\int_0^T s_m(t')dt', m = 1, 2, \ldots M$ denotes the production volume of station S_m during $[0, T)$.

$M^* = \arg\min_{m=1,\ldots M}\{\frac{1}{T_m}\}$ denotes the slowest machine in the line.

$b_m(t), m = 1,2, \ldots M$ denote the buffer level of buffer B_m at time instance t, $B_2, B_3, \ldots, B_M$ to denote their maximum capacity.

$\vec{e}_i = (m_i, t_i, d_i), i = 1, \ldots, n$ denotes a downtime event that station m_i is down at time t_i for d_i time unit.

$E = \{\vec{e}_1, \vec{e}_2, \ldots, \vec{e}_n\}$ denotes a sequence of downtime events of the line.

3. ANALYSIS OF DOWNTIME EVENTS AND ENERGY OPPORTUNITIES

The production system is a complex dynamic system, with complex interactions among individual internal operations. It is noticed that not every disturbance at one location will permanently affect system-level performance. We introduce the concept of opportunity window. The opportunity window $W_m(t)$ is defined as the longest possible downtime of station m that does not result in permanent production loss at the end-of-line station, and satisfies the following definition [17-19]:

Definition 1 *The opportunity window $W_m(T_d)$ for station m at time T_d is*

$$W_m(T_d) = \sup\{d \geq 0 : s.t. \exists T^*(d), \int_0^T s_M(t)dt = \int_0^T \tilde{s}_M(t; \vec{e})dt, \forall T \geq T^*(d)\}$$

where $\int_0^T s_M(t)dt$ and $\int_0^T \tilde{s}_M(t, \vec{e})dt$ are the production counts of the end-of-line station M at time T, with and without inserted downtime event $\vec{e} = (m, T_d, d)$ respectively. $T^*(d)$ signifies the potential dependency of T^* on d.

This opportunity window can be utilized for energy savings without impacting the normal production. For example, machines can be forced to energy saving mode or shut down mode with duration of $W_m(T_d)$ at time T_d. We define this opportunity as energy opportunity window (EOW).

We denote a disturbance or downtime event $\vec{e}$ as a 3-tuple (m, t, d), which signifies that station *m* is down at time *t* for a duration of d. $T^*(d)$ signifies the potential dependencies of T^* on d. The definition of opportunity window requires the production count to recover as if the downtime event had never occurred and only a downtime event that has lasted longer than the opportunity window contributes to permanent production count loss at the end-of-line station.

For the serial production line shown in Fig. 1, if all stations operate perfectly without downtime, the opportunity window of any station m at time t in the serial production line is described in [18, 19] as

$$W_m(t) = \begin{cases} T_{M^*} \sum_{k=m+1}^{M^*} b_k(t), & m < M^* \\ 0, & m = M^* \\ T_{M^*} \sum_{k=M^*+1}^{m} (B_k - b_k(t)), & m > M^* \end{cases} \quad (1)$$

The opportunity window is essentially the time it takes for the buffers between the downtime station and the slowest station to become empty ($m < M^*$) or full ($m > M^*$), or, in other words, for the slowest station to become starved ($m < M^*$) or blocked ($m < M^*$).

Given the fact that production line does not operate perfectly synchronized and effects of random downtimes, the opportunity window can be systematically utilized to reduce overall production line energy consumption and improve energy efficiency.

If there is a single failure event $\vec{e}$, we can express the permanent production time loss using the following equation [18, 19]:

$$L(\vec{e}) = \begin{cases} d - W_m(t), & d > W_m(t) \\ 0, & d \leq W_m(t) \end{cases} \quad (2)$$

The results obtained from the analysis of a single failure event, however, are not directly applicable to a sequence of concurrent downtime events. The combined production time loss is no longer the simple accumulation of the production time loss calculated in *isolation* for each individual downtime event.

Let $E = \{\vec{e}_1, \vec{e}_2, \ldots, \vec{e}_n\}$ be a sequence of downtime events, where $\vec{e}_i = (m_i, t_i, d_i), i = 1, \ldots, n$. For convenience, we use vector $\vec{b}(E) = [b_2(E), \ldots, b_M(E)]^T$ to denote the buffer levels at time t_i of the production line subject to a sequence of downtime events E. Without loss of generality, we assume $t_1 \leq t_2 \leq \cdots \leq t_n$. Given a realization of the production process for the time period $[0, T)$ during which a sequence of downtime events E has occurred, we want to decide the proper contribution of each failure event to the total production time loss.

In the case of a single downtime event, any stoppage of the slowest station M^* contributes to the permanent production time loss of the whole line. It turns out this is still valid in the case of multiple downtime events. Note that the stoppage includes not only the downtime of M^* due to failure, but also the temporary stoppage due to blockage or starvation.

Proposition 1 *Given a realization of the production process subject to a sequence of downtime events* $E = \{\vec{e}_1, \ldots, \vec{e}_n\}$ *and suppose* $\max_{i=1,\ldots,n}\{t_i + d_i\} < T$, *if the slowest station* M^* *stops for D time units during* $[0, T)$, *then for any station* m *in the line, there exists* $T^* > T$, *such that*

$$\int_0^{T'} s_m(t')dt' - \int_0^{T'} s_m(t'; E)dt' = \frac{D}{T_{M^*}}, \ \forall\, T' > T^* \qquad (3)$$

Where $\int_0^{T'} s_m(t'; E)dt'$ and $\int_0^{T'} s_m(t')dt'$ are the production volume with and without a sequence of downtime events E, respectively.

Proof:

When $m = M^*$, since the slowest station M^* operates either at its rated speed $1/T_{M^*}$ or zero, we have $\forall T' \geq T$

$$\int_0^{T'} s_m(t')dt' = T'/T_{M^*}$$

$$\int_0^{T'} s_m(t'; E)dt' = (T' - D)/T_{M^*}$$

Taking the difference, yields

$$\int_0^{T'} s_m(t')dt' - \int_0^{T'} s_m(t'; E)dt' = \frac{D}{T_{M^*}}$$

When $m < M^*$, consider the line segment between station m and M^* as shown in Figure 2, applying the principle of conservation of flow, yields

$$\int_0^{T'} s_m(t')dt' - \int_0^{T'} s_{M^*}(t')dt' = \sum_{k=m+1}^{M^*}(b_k(T') - b_k(0))$$

without downtime E, and

$$\int_0^{T'} s_m(t'; E)dt' - \int_0^{T'} s_{M^*}(t'; E)dt' = \sum_{k=m+1}^{M^*}(b_k(T'; E) - b_k(0; E))$$ with downtime E.

It is obvious that the initial buffer levels are the same: $b_k(0) = b_k(0; E), k = 1, \ldots, M$. Let T^* denote time instance such that

$$T^* - T > \sum_{k=m+1}^{M^*} B_k / (\min\left\{\frac{1}{T_1}, \ldots, \frac{1}{T_{M^*-1}}\right\} - \frac{1}{T_{M^*}}),$$ which represents the time needed for the buffers between m and M^* become full after downtime events finish. Therefore,

$$\sum_{k=m+1}^{M^*} b_k(T') = \sum_{k=m+1}^{M^*} b_k(T'; E) = \sum_{k=m+1}^{M^*} B_k, \ \forall\, T' > T^*.$$

And consequently,

$$\int_0^{T'} s_m(t')dt' - \int_0^{T'} s_m(t'; E)dt' = \int_0^{T'} s_{M^*}(t')dt' - \int_0^{T'} s_{M^*}(t'; E)dt' = \frac{D}{T_{M^*}} \quad \forall\, T' > T^*$$

Similarly, one can also prove the case when $m > M^*$. ■

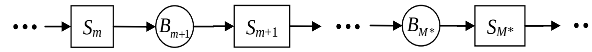

Figure 2: The line segment between the station m and the slowest station M^*

Consider an arbitrary downtime event $\vec{e} = (m, t, d) \in E$ and assume $m < M^*$. Applying the principle of conservation of flow to this line segment from t to $t + d$ during which station m is down, yields

$$\int_t^{t+d} s_m(t'; E)dt' - \int_t^{t+d} s_{M^*}(t'; E)dt' = \sum_{k=m_i+1}^{M^*}(b_k(t + d;\, E) - b_k(t;\, E)) \qquad (4)$$

Since $s_m(t; E) = 0, \forall\, t \in [t, t + d)$, we have

$$\int_t^{t+d} s_{M^*}(t'; E)dt' = \sum_{k=m_i+1}^{M^*}(b_k(t;\, E) - b_k(t + d;\, E)) \qquad (5)$$

We want to find the exact time when the buffers between station m and M^* just become empty (i.e. $\sum_{k=m+1}^{M^*} b_k(t + d;\, E) = 0$) and station M^* just becomes starved if station m remains down. In other words, we want to find the smallest d such that

$$\int_t^{t+d} s_{M^*}(t'; E)dt' = \sum_{k=m+1}^{M^*} b_k(t; E) \qquad (6)$$

Similarly, if $m > M^*$, following the same procedure by applying the principle of conservation of flow to the line segment between station M^* and m, except letting $\sum_{k=m+1}^{M^*} b_k(t + d;\, E) = \sum_{k=M^*+1}^{m} B_k$, we want to find the smallest d such that

$$\int_t^{t+d} s_{M^*}(t'; E)dt' = \sum_{k=M^*+1}^{m}(B_k - b_k(t; E)) \qquad (7)$$

If the downtime duration of station m exceeds this threshold, the slowest station would be blocked. Since every second of the downtime at the slowest station M^* counts toward the total production time loss, by the use of (1), we can combine (6) and (7) into a single equation.

$$T_{M^*}\int_t^{t+d} s_{M^*}(t'; E)dt' = W_{m_i}(t), \ \ m \in \{1, \ldots, M\} \qquad (8)$$

Given a realization of the production process, the trajectory $s_{M^*}(t; E)$ of the slowest station in particular, one can always find the smallest possible downtime duration d_i^* for the i^{th} failure event $\vec{e}_i = (m_i, t_i, d_i)$ such that (8) is satisfied, i.e.,

$$d_i^* = \inf\{d \geq 0: s.t.\, T_{M^*}\int_t^{t+d} s_{M^*}(t'; E)dt' = W_{m_i}(t)\} \qquad (9)$$

d_i^* is the time it takes, starting from t_i, for the buffers between station m_i and M^* to just become empty (if $m_i > M^*$) or full (if $m_i < M^*$) if station m_i remains down and all other downtime events unchanged. If the actual downtime duration d_i is less than this threshold d_i^*, there is no permanent production time loss. On the other hand, if d_i exceeds d_i^*, the permanent production time loss due to $\vec{e}_i$ becomes nonnegative and is linearly proportional to $d_i - d_i^*$.

One may notice that (9) is perfectly applicable to the case of a single downtime event. For example, if we assume E contains only one failure event $\vec{e} = (m, t, d)$, then d^* will be exactly $W_m(t)$. When E contains more than one failure events, the processing rate $s_{M^*}(t; E)$ of the slowest station M^* is no longer constant during the time period $[t_i, t_i + d_i^*)$ and the impact of other concurrent downtime events is manifested in the realization of $s_{M^*}(t;E)$.

4. APPLICATION TO ENERGY OPPORTUNITIES AND SIMULATION RESULTS

Simulation studies are conducted on a model of a section in an automotive power train plant as shown in Fig. 3. The line under consideration consists of fifteen work stations and three big buffers, each has capacity of 100 parts. All work stations are serially linked by conveyors. The line segment under consideration is interconnected with other sections of the power train plant. For real time production control and energy management purpose, an 8 hour shift is adopted as the length of simulation studies.

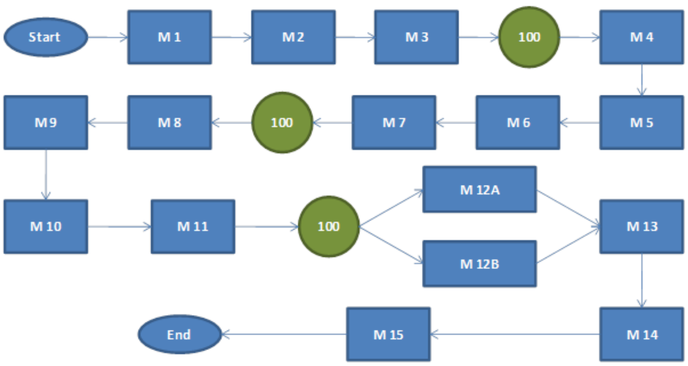

Figure 3: The line segment of consideration in a power train plant

The actual downtime events recorded during a three-month period are used to generate downtime at the work stations during simulation. The cycle times are also collected using the actual data collected from the shop floor. Table 1 shows a typical example of the real data.

Table 1: Typical parameters collected. All numbers are scaled for confidentiality

Machine Name	Average CT (sec)	MTBF (min)	MTTR (min)
M1	29.35	23.7	21.82
M2	24.43	105.02	34.07
M3	29.27	197.87	68.37
Buffer 1	-	-	-
M4	28.94	90.67	46.65
M5	28.11	106.88	34.25
M6	28.99	104.18	41.80
M7	28.61	114.3	39.62
Buffer 2	-	-	-
M8	28.4	79.49	34.48
M9	29.98	50.63	34.35
M10	28.37	2395	58.12
M11	26.78	44.56	16.28
Buffer 3	-	-	-
M12A	57.8	22.61	18.28
M12B	58.5	13.62	15.85
M13	30	66.15	27.42
M14	27.25	50.55	20.12
M15	30.81	16.27	12.62

First, we start from the studies of zero downtime scenarios. The purpose is to analyze the energy saving potential in the case of no random disturbance and approximately synchronized operation. At any time point, the EOW can be calculated based on (1). Fig. 4 demonstrates that the more stations take the EOW, the more energy saving potential can be achieved.

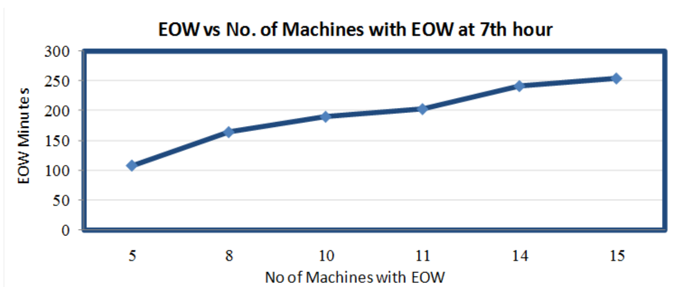

Figure 4: EOW vs. number of machines utilizing EOW at the 7th hour

Figure 5 compares the EOW for accumulated time effects. It is obvious that buffer contents accumulated as time increasing although no downtime event happens. Therefore, EOWs increase with increasing buffer contents. It can be observed that for a well-designed production system, even in the case of approximately synchronized operation, energy opportunities still exist (up to 250 minutes in an 8 hour shift).

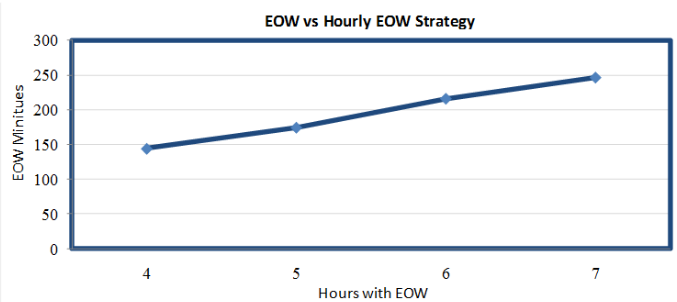

Figure 5: EOW vs. Time

Second, we study the scenarios when production in face of random downtime disturbance. It is found that the EOW significantly increased (up to 900 minutes in an 8 hour shift) without impacting production throughput. This phenomenon can be explained by the analysis in Section 3. As long as the inserted EOW does not impact the current bottleneck and within the time period derived from (9), EOW does not contribute to extra production loss. Fig. 6 demonstrates the comparison of various EOW strategies and EOW over total downtime ratios. It can be concluded that EOW strategies play an important role on total energy savings – a good strategy has high energy saving potential (EOW can reach up to 700% of total downtime on the line) without significantly impacting production.

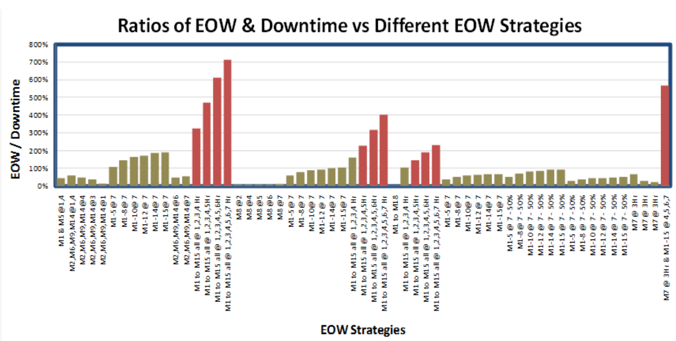

Figure 6: EOW strategies vs. EOW/Downtime

5. CONCLUSION AND FUTURE WORK

The paper investigates the energy saving opportunities in a manufacturing system. Through the analysis of production system random failure properties, the energy opportunity window is quantified and utilized to improve the energy efficiency.

Our case study indicates that the EOW has high potential for energy savings without impacting normal production. During EOW of each station, intelligent control actions will be performed to adjust power state to reduce energy consumption, considering the fact that more and more modern machines have multiple power states. More importantly, the time and location of the machines or equipments for achieving energy saving potential is not straightforward results from the current study and is the next step and goal for this research.

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