Simulation-based Production Scheduling with Optimization of Electricity Consumption and Cost in Smart Manufacturing Systems

Zeyi Sun, Dong Wei, Lingyun Wang, and Lin Li

Abstract— **Due to the increasing awareness of environmental protection, the industrial sector is facing mounting pressure to reduce its energy consumption and carbon footprints. The application of energy management system for industrial plants is of high interests by industrial practitioners in their pursuit of high performance smart manufacturing systems. Many system integrators and solution providers have developed their own packages for energy management system for industrial plants. In this paper, we conduct a brief survey on the existing commercial packages of industrial energy management systems by different vendors. A future development direction regarding the functionality of decision-making of industrial energy management system is discussed and a method focusing on the decision-making of energy-integrated production scheduling is proposed. The performance metrics of energy consumption and cost as well as production throughput are modeled for operational performance optimization. A numerical case study of a real auto part manufacturing plant is presented to illustrate the benefits brought by the proposed method.**

I. INTRODUCTION

The energy demand in the U.S. is expected to keep increasing for the next several decades. A 29% increase, from 3,826 billion kilowatts (kWh) in 2012 up to 4,954 billion kWh in 2040, is estimated by Energy Information Administration [1]. The industrial sector is a main contributor to this increasing trend. Approximately, one-quarter of the energy is consumed by the industrial sector in the U.S. [1].

Traditionally, industrial practitioners have focused more on the productivity and quality analysis [2-4] to improve their operation profit, while largely neglecting the issue of energy consumption. Recently, with the increasing awareness of environmental protection from the society, many countries have enacted legislation to curb energy consumption and greenhouse gas (GHG) emissions. Similar legislation is being considered in various states in the U.S. as well as by the U.S. congress. For example, the U.S. government has set up a target to reduce GHG emissions to 17% below 2005 level by 2020 [5]. Due to the aforementioned legislative pressure as well as moral responsibility concern and cost reduction for competitiveness goal, more and more industrial practitioners are eager to shift their current operation strategy to a sustainable one that jointly considers economic, environmental, and social metrics [6].

Industrial energy management system is an indispensable component in the smart manufacturing systems that can help industrial plant achieve the transition towards sustainability. It is of high interests by many industrial practitioners. The general functionality of energy management system includes energy related measure definition, energy related data communication, visualization, and decision-making to improve energy efficiency. The energy related measure definition means the establishment of the Key Performance Indexes (KPI) to evaluate the performance of the industrial plant from machine level to enterprise level. Energy related data communication and visualization aim to set up the data exchange channels by specific hardware and software infrastructure to make both online information and historical data visible to the plant staffs at different levels. The decision-making focuses on the adjustment and optimization towards certain objectives based on either online or historical information. The ultimate objective of the use of energy management system in industrial plant is to help industrial plant reduce energy consumption of their daily production operation without comprising their production throughput.

Many industrial solution & service providers and system integrators have also recognized the potential market demand for the commercial package of industrial energy management systems. Different products that can be integrated into existing enterprise control system for industrial plant have been developed. Generally, the enterprise control system for industrial plant consists of several different levels defined by ISA-95 model [7] as shown in Fig. 1. The existing commercial portfolios on different levels of enterprise control system are reviewed and summarized in Table I.

It is observed that recently, some products that integrate energy concerns into the different levels of enterprise control system have been developed. For example, Rockwell analyzed a plant-wide integration framework that aggregates and analyzes different data collected for specific quantifiable sustainability measures [8]. The module EnergyMetrix in FactoryTalk can provide users with the access to the critical energy information from different locations [9]. Mitsubishi Electric proposed a factory automation energy solution that integrates both business level and shop floor systems through a united interface to achieve high productivity and energy savings [10]. The eco-f@ctory platform has been developed and combined with the e-f@ctory platform to form a new e&eco-f@ctory platform which integrates the energy information and production information [10]. Ampla of Schneider enables operation and energy managers to identify and track overconsumption of energy usage based on production context [11]. It also enables plant management team to improve the system performance continuously by analyzing the cause of energy overconsumption [12]. GE Proficy - accelerator defined production context with energy usage [13]. It helps production planning with consideration of energy consumption possible by defining energy as a type of raw material in the bill of material (BOM) [13].

However, the packages mentioned above, to a large extent, are information platforms which collect and organize data in a preliminary way. It mainly focuses on the measurement, monitoring, visualization, and KPI

Z. Sun and L. Li are with the Department of Mechanical & Industrial Engineering, University of Illinois at Chicago, Chicago, IL 60607, USA.

D. Wei and L. Wang are with Corporate Technology, Siemens Corporation, Princeton, NJ 08540, USA

D. Wei is the corresponding author. Email: dong.w@siemens.com, Phone: 609-734-3525

evaluation of the energy-related measures. Advanced decision-making method which helps plant managers take right actions on both production and energy management has been less considered. It greatly impedes the achievement of the ultimate purpose of the use of industrial energy management system. Few products with this advanced decision-making method are available.

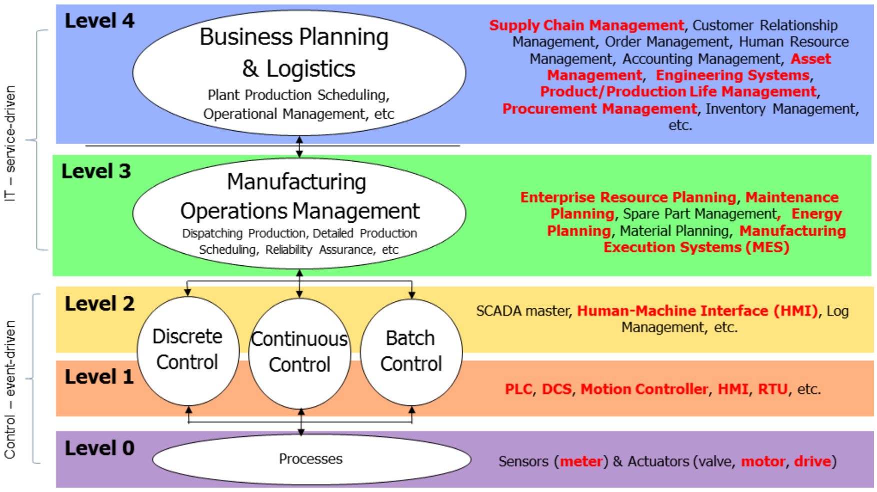

Figure 1: Different levels in enterprise control system in ISA-95 Model

TABLE I. SUMMARY OF ENERGY MANAGEMENT PRODUCS

	ABB	GE	Invensys	Rockwell	Mitsubishi	Yaskawa	Schneider
Solution	Industrial[IT] 800xA Technology	Accelerator Manufacturing Energy Management Solution	Energy Efficiency Control System (EECS)	GreenPrint	e&eco-F@ctory	Total System Solution	EnergySTEP
Architecture	IndustrialIT 800xA Technology	Digital Energy Multilin/ EnteGreat	Energy Efficiency Control System	GreenPrint	Factory Automation	Total System Solution	PlantStruxture
Technology	Industrial[IT] 800xA Technology	Digital Energy Multilin/EnteGreat	Wonderware/ArchestrA System Platform	Production Center Technology	Factory Automation	Classic PLC Control SPEED7	PlantStruxture
Product							
Level 3	cpmPlus Energy Manager	Proficy (Accelerator Manufacturing Energy Management Solution)	Wonderware MES	FactoryTalk (EnergyMetrix)	e&eco-F@ctory	N/A	StruxureWare Plant Operation Ampla (Energy)
Level 2	Power EMS	EnerVista ViewPoint; EnerVista ViewNode (HMI, OPC Server, client)	Corporate Energy Management, HMI	FactoryTalk (VantagePoint, historian)	HMI-GOT SCADA MC Work	HMI Series, SPEED7 Studio	SCADA
Level 1	800xA Controller	Motor Protection	EECS Edge Computer	Energy Efficiency Module (AB PLC)	Programmable Controller "Universal Model QnU"	PLC ControllerRobotics automation systems (MotionWorks IEC)	PLC
Level 0	MCCs, Drives and Motors, even Power Generators	Meters & Infra., Protection & Control, Drives & Motors	N/A	MCCs, Drives and Motors	Industrial Robot, Processing Machine, AC Servo, Inverter Drive	AC Inverter Drive, Servo Drive, Robot	iPMCC, Meters, Drives & Motors, Protection

Two recent technologies developed by Siemens are examples. The first one is the patent regarding production rescheduling utilizing machine slack time and buffer capacity redesign to reduce the production energy cost [14]. It can shift the production from the periods with high energy price to the ones with low price and thus, the production energy cost can be reduced while the energy consumption still keeps the same. The second one is an energy efficient switching off controller considering different operational modes in manufacturing systems [15-16]. However, it needs the information from the production schedule regarding production breaks for each sub-system to generate the optimal switch-off sequence.

Motivated by the status quo, to further strengthen the functionality of existing energy management system from the perspective of decision-making to realize smart manufacturing systems, we propose a simulation-based methodology focusing on energy integrated production scheduling for industrial plants in this paper. The objectives of this method are to 1) explore the potential benefits and feasibility of implementing advanced decision-making functionality in industrial energy management systems; and 2) advance the state-of-the-art of production schedule tools that are currently used in plants by jointly considering the metrics of both environmental and economic performances.

Traditionally, customer demand satisfaction is considered the first objective of the production schedule. It is usually generated through the objective such as minimum tardiness or minimum overall production span [17-18]. The timely delivery to customer is thought to be the only metric to evaluate the effectiveness of production schedule. The energy related metrics such as energy consumption and energy cost are usually not included.

The proposed decision-making method regarding energy-integrated smart production scheduling in this paper can overcome the above drawbacks. It is able to reduce either energy consumption cost or energy consumption while maintaining the production throughput compared with the method in [14]. It can also provide the production schedule that is needed by the method in [15-16] with a more environmentally efficient way. The rest of this paper is organized as follows. Section 2 introduces the simulation-based energy-integrated production scheduling for industrial plant. Section 3 presents a case study based on a real auto part manufacturing plant to illustrate the effectiveness of the proposed method. Section 4 concludes the paper and proposes some future work.

II. PROPOSED METHODS

The proposed simulation-based energy-integrated smart scheduling method is developed on the platform of Tecnomatix Plant Simulation, a simulation software package for manufacturing plants developed by Siemens [19]. The manufacturing system modeled in this research can be generally described as shown in Fig. 2 where the rectangles denote the manufacturing stations (denoted by $S_1,\ldots S_N$) and the circles denote the buffers (denoted by $B_1,\ldots B_{N-1}$). The production schedule generated is on a 15-minute basis.

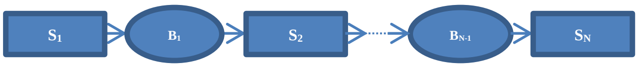

Figure 2: A typical manufacturing system with *N* stations and *N*-1 buffers

Users can determine the preferred objective - either minimum energy consumption or minimum energy cost. For example, in a winter day, it is highly possible that the electricity consumption rate is flat and no power demand charge is assessed in electricity tariff, and therefore the objective of electricity consumption minimization is an appropriate choice. In contrast, in a summer day, it is possible that the electricity rate is variable and demand charge is also included in the tariff, and thus the objective of minimum electricity cost is a good choice.

The overview of this simulation-based optimal scheduling method is shown in Fig. 3. The baseline simulation model of the plant is first established using Tecnomatix Plant Simulation. The related parameters of all the manufacturing stations and buffers, e.g., production rate, energy consumption profile, buffer capacity, and labor factor are incorporated into this model. The material flow logics are also defined. With this baseline simulation model, both energy consumption-related and productivity-related measures can be obtained.

Figure 3: Simulation-based smart manufacturing scheduling

After that, a two-step procedure will be further implemented based on the baseline model as shown in Fig. 3 to help manufacturers identify an optimal energy-integrated production schedule. In step 1, we use a buffer-based dynamic control scheme to generate a good production schedule for the manufacturing system on a 15-minute basis. The basic idea of this step is to control the production of the stations based on the adjacent buffer levels. The essential logic is to temporarily stop production when upstream buffer is close to empty or downstream buffer is close to full, while keeping production when upstream buffer is close to full or downstream buffer is close empty.

To avoid the potential contradicted actions received by the station (e.g., both upstream and downstream buffers are close to empty), we make the following rules for the buffer selection depending on the location of the stations. For the ending station or the stations with the downstream buffer that relates to some delivery activities, e.g., shipment for out-sourced processing (denoted as type I station), the adjacent upstream buffer level as well as the required delivery condition (e.g., final throughput, delivery for some out-sourced processes) are jointly used for decision-making. For the rest stations (denoted as type II station), the adjacent downstream buffers are used for decision-making. Specifically, a set of threshold values of buffer level ratio (i.e., the ratio of the buffer level to the buffer capacity) is defined to determine the control actions for the stations. The range of the threshold values is set to be between 0.5 and one when they are used by the buffer to control the upstream station since we try to reduce the production when the downstream buffer is close to full. The range of the threshold values is set to be between zero and 0.5 when they are used by the buffer to control the downstream stations since we try to reduce the production when the upstream buffer is close to empty. For type I station, the production will not be stopped unless the delivery condition is satisfied and the upstream buffer level is lower than the threshold value. For type II station, the production will be stopped if the downstream buffer level is higher than the threshold value.

Genetic algorithm (GA) offered by Tecnomatix Plant Simulation is used to find these optimal threshold values and corresponding good schedule on a 15-minute basis. Based on different objectives, either electricity consumption minimization (energy-oriented) or electricity cost minimization (cost-oriented), the fitness functions defined by GA in Tecnomatix Plant Simulation can be formulated by (1) and (2).

$$\text{Fitness(E-O/S1)} = \text{Total Consumption} + \text{Penalty(TP)} \tag{1}$$

$$\text{Fitness(C-O/S1)} = \text{Total Cost} + \text{Penalty(TP)} \tag{2}$$

where notations E-O denotes energy-oriented; C-O denotes cost-oriented; S1 denotes the step 1 of the model. Penalty (TP) denotes the potential penalty that will be incurred if throughput constraint is violated by the candidate solution of the threshold value. The total consumption can be generated by the simulation model based on the input power profiles of the machines. The total cost can also be calculated based on the generated consumption data and the given electricity billing rates by simulation model. After running GA in Tecnomatix Plant Simulation, the optimal threshold values and corresponding good schedule can be obtained.

In step 2, the good schedule obtained by step 1 will be used as the initial solution for the further optimization using GA to obtain the final production schedule. Considering the buffer level variation after the implementation of this algorithm, we also consider two different polices regarding buffer utilization. The first one is an extreme situation, the buffer can vary from zero to its capacity and no preferred range is imposed (denoted as extreme policy). The second one is a more conservative configuration based on empirical data of the plant (denoted as empirical policy), e.g., the range of safety stock, which is narrower to the range of first one. It requires the buffer level at the end of scheduling horizon be maintained in the empirical range. The fitness functions used in GA in step 2 considering two different buffer policies combined with two different objectives can be formulated as (3)-(6).

Fitness(E-O/EX/S2)=Total consumption+Penalty(TP) + Penalty(EX) (3)

Fitness(E-O/EM/S2)=Total consumption+Penalty(TP) +Penalty(EM) (4)

Fitness(C-O/EX/S2)= Total cost + Penalty (TP) + Penalty (EX) (5)

Fitness(C-O/EM/S2)= Total cost + Penalty (TP) + Penalty (EM) (6)

where EX denotes extreme buffer policy; EM denotes empirical buffer policy; and S2 denotes the step 2 of the algorithm. Penalty (EX) and Penalty (EM) denote the potential penalty that will be incurred if the constraint of the buffer level at the end of planning horizon is violated by the candidate solution considering extreme policy and empirical policy, respectively. After running GA in Tecnomatix Plant Simulation, the optimal final schedule can be obtained.

III. CASE STUDY

To illustrate the proposed decision-making method, a case study of a real auto part manufacturing plant is implemented. An 8-hour shift is examined. The entire layout of the manufacturing system is shown in Fig. 4. The manufacturing system includes both machining and assembly processes. The machining process includes three different stages, i.e., RM, SM, and HM. In addition, a heat treatment process between SM and HM is sub-contracted. RM is used to fulfill the initial surface cutting on the castings. SM is then used to further fulfill the surface cutting and hole drilling. HM is used to fulfill the final finishing after heat treatment. Three parallel machining stations, i.e., Station A, Station B, and Station C are deployed to conduct RM process (they will also be denoted as RMA, RMB, and RMC in the rest parts of this paper). Two parallel machining stations, i.e., Station D and Station E are deployed to conduct SM process (denoted as SMD and SME). Two parallel machining stations, i.e., Station F and Station G are deployed to conduct HM process (denoted as HMF and HMG). One assembly station, i.e., Station H is deployed to conduct assembly process (denoted as ASS). Each machining station consists of several different computer numerical controlled (CNC) machines with different functionalities like turning, grinding, and milling. In addition, other auxiliary machines such as demagnetization machine, washing machine, and balance machine may also be included in certain stations. The assembly station includes several workplaces where the operators can fulfill the assembly tasks using the parts after machining and other part materials.

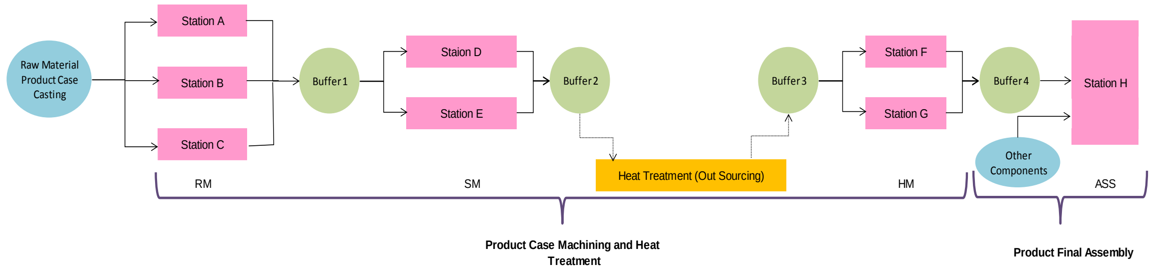

Figure 4: The layout of an auto part manufacturing system

The productivity related data and power consumption profile for each machine are provided. For confidentiality, we can only provide part of the data as shown in Table II and Table III. Table II illustrates the parameters of each buffer. The initial contents are obtained based on the average values of the plant. Table III shows the production capacity of each process and the required production target in an 8-hour shift. It is observed that RM is the slowest process in the system. Assembly and SM are two fastest processes in the system. In addition, the information regarding electricity-billing cost is assumed as shown in Table IV.

TABLE II. THE CAPACITY AND INITIAL CONTENT OF BUFFER

	Raw Material	Buffer 1	Buffer 2	Buffer 3	Buffer 4
Initial contents (units)	500	100	500	400	800
Capacity (units)	900	900	1000	1000	800

TABLE III. THE SHIFT CAPACITY AND DELIVERY

	RM	SM	HT (Out-sourced)	HM	ASS
Capacity (units/shift)	450	500	450	480	520
Required delivery (units)			450		450

TABLE IV. ELECTRICITY RATE

	Electricity consumption rate ($/kWh)	Power Demand Rate ($/kWh)
Off peak period (8:00AM-12:00PM)	0.2	15
Peak period (12:00PM-4:00PM)	0.35	

The baseline simulation model for the above system is first established by Tecnomatix Plant Simulation as shown in Fig. 5. All the related parameters are defined in the model. The results of the simulation using routine operational strategy (keep the production of the entire system throughout the 8-hour shift) match the actual performance regarding productivity and energy consumptions provided by the plant. The detail information of the performance of the baseline model regarding each station is illustrated in Table V.

TABLE V. ENERGY & PRODUCTION PERFORMANCE OF BASELINE MODEL

Station	Total Electricity (kWh)	Operational Electricity (kWh)	Working Electricity (kWh)	Production (parts)	Total Electricity per Part (kWh/Part)
RMA	1533	154.8	1378.2	153	10.02
RMB	1827.9	234	1593.9	154	11.87
RMC	1561.3	168.8	1392.5	156	10.01
SMD	1067.7	185.9	881.8	248	4.31
SME	792	131.3	660.7	255	3.11
HMF	1298.8	285.5	1013.3	238	5.46
HMG	1365.8	297.4	1068.4	242	5.64
ASS	119.9	0.1	119.8	521	0.25
Total	9566.4	1457.8	8108.6	Heat-treatment	450
Cost ($)	23389.17				

Based on the established baseline model, we implement the two-step method as shown in Fig. 3 in this case. In step

1, we first determine the initial threshold values and corresponding control policies that are used in GA as shown in Table VI. These values are suggested by plant engineer from their daily experience. The priority of ON/OFF control for the parallel stations is based on the comparison of electricity consumption per part production in Table V. For example, for three RM stations, the electricity consumption per part can be ranked as RMC, RMA, and RMB with an increasing order. Therefore, RMB has the highest priority to be turned off, followed by RMA and RMC.

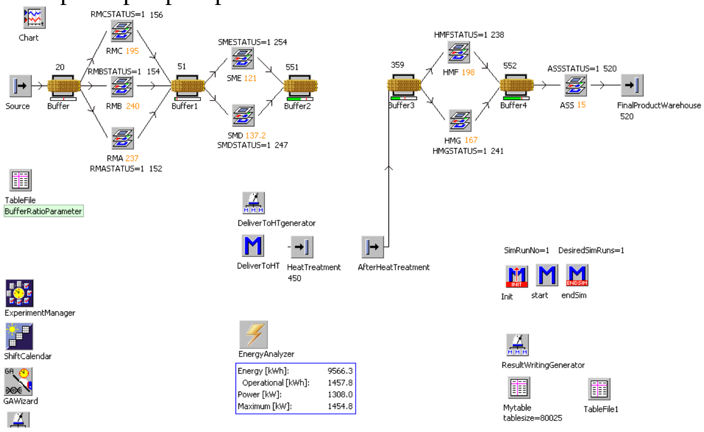

Figure 5: The simulation model of the baseline system

TABLE VI. INITIAL THRESHOLD VALUE AND POLICY

Process	Buffer	Condition	Action	Notes
RM	Buffer 1	Less than 67%	RMA, RMB, and RMC are ON	
		Between 67% and 83%	RMA and RMC are ON. RMB is OFF	
		Between 83% and 99%	RMC is ON. RMA and RMB are OFF	
		Larger than 99%	RMA, RMB, and RMC are OFF	
SM	Buffer 2	Less than 450	SMD and SME are ON	Otherwise, check Buffer 1
	Buffer 1	Less than 25%	SMD and SME are OFF	
		Between 25% and 49%	SMD is OFF. SME is ON	
		Larger than 49%	SMD and SME are ON	
HM	Buffer 4	Less than 75%	HMF and HMG are ON	
		Between 75% and 99%	HMF is ON. HMG is OFF	
		Larger than 99%	HMF and HMG are OFF	
ASS	Completed Product	Larger than 450	ASS is OFF	Otherwise, check Buffer 4
	Buffer 4	Larger than 25%	ASS is ON	
		Not larger than 25%	ASS is OFF	

TABLE VII. OPTIMAL THRESHOLD VALUES AND CONTROL STRATEGIES FOR COST-ORIENTED OBJECTIVE

Process	Buffer	Condition	Action	Others
RM	Buffer 1	Less than 67%	RMA, RMB, and RMC are ON	
		Between 67% and 80%	RMA and RMC are ON. RMB is OFF	
		Between 80% and 99%	RMC is ON. RMA and RMB are OFF	
		Larger than 99%	RMA, RMB, and RMC are OFF	
SM	Buffer 2	Less than 450	SMD and SME are ON	Otherwise, check Buffer 1
	Buffer 1	Less than 25%	SMD and SME are OFF	
		Between 25% and 46%	SMD is OFF. SME is ON	
		Larger than 26%	SMD and SME are ON	
HM	Buffer 4	Less than 58%	HMF and HMG are ON	
		Between 58% and 99%	HMF is ON. HMG is OFF	
		Larger than 99%	HMF and HMG are OFF	
ASS	Completed Product	Larger than 450	ASS is OFF	Otherwise, check Buffer 4
	Buffer 4	Larger than 31%	ASS is ON	
		Not larger than 31%	ASS is OFF	

The optimal threshold values and corresponding control actions for each station for cost-oriented and energy-oriented objectives are obtained using GA as shown in Table VII and Table VIII, respectively. The information of the computer we use to implement GA is as follows: Intel(R) Core™2 Quad CPU Q9650 @3.00GHz 2.99GHz processor, 8.00GB memory, and 64 bit operating system. The number of generations in GA is 50 and the size of the generation is 10. The computational time is about 48 minutes.

TABLE VIII. OPTIMAL THRESHOLD VALUES AND CONTROL STRATEGIES FOR ENERGY-ORIENTED OBJECTIVE

Process	Buffer	Condition	Action	Others
RM	Buffer 1	Less than 59%	RMA, RMB, and RMC are ON	
		Between 59% and 72%	RMA and RMC are ON. RMB is OFF	
		Between 72% and 89%	RMC is ON. RMA and RMB are OFF	
		Larger than 89%	RMA, RMB, and RMC are OFF	
SM	Buffer 2	Less than 450	SMD and SME are ON	Otherwise, check Buffer 1
	Buffer 1	Less than 25%	SMD and SME are OFF	
		Between 25% and 49%	SMD is OFF. SME is ON	
		Larger than 49%	SMD and SME are ON	
HM	Buffer 4	Less than 51%	HMF and HMG are ON	
		Between 51% and 89%	HMF is ON. HMG is OFF	
		Larger than 89%	HMF and HMG are OFF	
ASS	Completed Product	Larger than 450	ASS is OFF	Otherwise, check Buffer 4
	Buffer 4	Larger than 25%	ASS is ON	
		Not larger than 25%	ASS is OFF	

The results of production and energy consumption of the buffer-based control by using optimal threshold values obtained in step 1 are summarized in Table IX.

In Step 2, we utilize the results obtained from Step 1 with two different objectives to implement the optimization. In this step, for each objective, we examine two different buffer utilization policies, i.e., empirical buffer policy, and extreme buffer policy. The bounds of the buffer for these two policies are illustrated in Table X. The number of generations in GA is 50 and the size of the generation is 10. The computational time is about 49 minutes for each combination of objective-buffer policy pair.

TABLE IX. THE IMPROVEMENT OF BUFFER BASED CONTROL MODEL

	Baseline	Cost Oriented	Improvement	Energy-Oriented	Improvement
Electricity (kWh)	9566.4	8137.8	14.93%	7676.4	19.76%
Operational (KWh)	1457.8	1207.3	17.18%	1089.4	25.27%
Demand (kW)	1382.8	1247.9	9.76%	1262.31	8.71%
Cost ($)	23389.17	21058.24	9.97%		
Throughput	521	456		456	
Heat treatment	450	450		450	

TABLE X. BUFFER BOUNDS FOR TWO BUFFER POLICIES

	Extreme Policy	Empirical Policy
Raw Material Buffer	0-900	0-100
Buffer 1	0-900	0-300
Buffer 2	0-1000	300-900
Buffer 3	0-1000	360-900
Buffer 4	0-800	360-800

The results of the cost-oriented objective and the energy-oriented objective are shown in Table XI and XII, respectively. It can be seen that the energy consumption cost or energy consumption can be significantly reduced without influencing the production target. The extreme policy can generally achieve higher reductions for the current planning horizon compared to empirical policy. Intuitively, we can infer that the extreme policy may be more suitable for the situation of one-time reduction, while the empirical policy is more suitable for the long-term reduction objective.

TABLE XI. THE IMPROVEMENT OF THE RESULTS OF COST ORIENTED OBJECTIVE

	Baseline	EX	Improvement	EM	Improvement
Electricity (kWh)	9566.4	4398.8	54.02%	6578.9	31.23%
Operational (KWh)	1457.8	741	49.17%	991.1	32.01%
Cost ($)	23389.17	12724.35	45.60%	17116.72	26.82%
Demand (kW)	1382.8	766.22	44.59%	1019.34	26.28%
Throughput	521	505		475	
Heat treatment	450	450		450	

TABLE XII. THE IMPROVEMENT OF THE RESULTS OF ENERGY ORIENTED OBJECTIVE

	Baseline	EX	Improvement	EM	Improvement
Electricity (kWh)	9566.4	3472.8	63.70%	6470.8	32.36%
Operational (KWh)	1457.8	654.4	55.11%	960.9	34.09%
Demand (kW)	1382.8	854.05	38.24%	1254.5	9.28%
Throughput	521	521		475	
Heat treatment	450	450		450	

IV. CONCLUSIONS

In this paper, we review the commercial products related to industrial energy efficiency and management for manufactories. An advanced decision-making method for industrial energy management to optimize both economic and environmental performance metrics in smart manufacturing systems is proposed and discussed. As a proof-of-concept, a case study based on a real auto part manufactory is presented to illustrate the benefits brought by the proposed method, quantitatively, and feasibility of the proposed method as well.

The proposed method takes advantage of prior knowledge, such as days ahead, of production order and electricity rate. For the future work, we need to implement the proposed method on a commercial Manufacturing Execution System (MES) to examine its feasibility in practice. The decision-making methods that can be used for production runtime control on a real time basis also needs to be investigated. Furthermore, we can conduct sensitivity analysis to examine the influence of two different buffer policies on the overall cost and the production throughput on the following production horizons.

REFERENCES

[1] Energy Information Administration, Annual energy outlook 2014, Washington D.C., U.S., 2014. Last Access (5/25/2014) http://www.eia.gov/forecasts/aeo/pdf/0383%282014%29.pdf

[2] S. B. Gershwin, *Manufacturing Systems Engineering*. Prentice-Hall, Engle Cliffs, NJ, U.S., 1994.

[3] J. M. Alden, L. D. Burns, T. Costy, R. D. Hutton, C. A. Jackson, D. S. Kim, K. A. Kohls, J. H. Owen, M. A. Turnquist, and D. J. V. Veen, 2006, "General Motors increases its production throughput," *Interfaces*, vol. 36, pp. 6–25, 2006.

[4] J. Li, and S. M. Meerkov, S.M., *Production Systems Engineering*. Springer, 2009.

[5] Department of Energy, President Obama sets a target for cutting U.S. greenhouse gas emissions, Washington D.C., U.S., 2009. Last Access (5/25/2014) http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=15650

[6] M. Shahbazpour, and R. H. Seidel, 2006, "Using sustainability for competitive advantage," in *Proc. 13th CIRP International Conference on Life Cycle Engineering*, Leuven, Belgium, 31 May 2006 - 02 Jun 2006, pp. 287-292.

[7] D. Brandl, What is ISA-95? Industrial best practices of manufacturing information technologies with ISA-95 models, 2008. Last Access (5/25/2014) http://apsom.org/docs/T061_isa95-04.pdf

[8] Rockwell Automation, Manufacturing execution systems for sustainability, extending the scope of MES to achieve energy efficiency and sustainability goals, 2013.

[9] Rockwell Automation, Asset Management, FactoryTalk EnergyMetrix, 2014. Last Access (5/25/2014) http://www.rockwellautomation.com/rockwellsoftware/assetmgmt/energymetrix/index.html

[10] H. Makita, Y. Shida, and N. Nozue, Factory energy management system using production information, Mitsubishi Electric ADVANCE December 2012, pp. 7-11.

[11] Schneider Electrics, MES software solution-Ampla, 2014. Available Online, Last Access (5/25/2014) http://www.schneider-electric.com.au/sites/australia/en/products-services/automation-control/products-offer/range-presentation.page?c_filepath=/templatedata/Offer_Presentation/3_Range_Datasheet/data/en/local/automation_and_control/ampla.xml

[12] Schneider Electrics, Enhance operational performance while driving energy and cost savings, StruxureWareTMPlant Operation AmplaTM, 2013. Available Online, Last Access (5/25/2014) http://download.schneider-electric.com/files?p_File_Id=88358839&p_File_Name=998-1194843_GMA-GB%281%29.pdf

[13] GE, Accelerator manufacturing energy management solution®, 2014. Available Online, Last Access (5/25/2014) http://www.ge-ip.com/products/accelerator-manufacturing-energy-management-solution/p3426

[14] H. I. Gultekin, D. Wei, Y. Lu, and M. A. Jafari, Method for energy demand management in a production flow line, Patent Publication number, WO2014039290A3, 2014.

[15] S. Mechs, J. P. Muller, S. Lamparter, and J. Peschke, "Networked priced timed automata for energy-efficient factory automation," in *Proc. American Control Conference*, Montr´eal, Canada, 2012, pp. 5310–5317.

[16] S. Mechs, S. Grimm, D. Beyer, and S. Lamparter, S., "Evaluation of prediction accuracy for energy-efficient switching of automation facilities," in *Proc*. IECON 2013 - 39th Annual Conference of the IEEE, Vienna, 10-13 November, 2013, pp.6928–6933.

[17] O. Herr, and A. Goel, "Comparison of Two Integer Programming Formulations for a Single Machine Family Scheduling Problem to Minimize Total Tardiness," in *Proc*. 2nd CIRP Robust Manufacturing Conference, vol. 19, pp. 174-179, 2014.

[18] J. Xu, Y. Yin, T. C. E. Cheng, C-C. Wu, and S. Gu, "A memetic algorithm for the re-entrant permutation flowshop scheduling problem to minimize the makespan," Applied Soft Computing, vol. 24, pp. 277-283, 2014.

[19] Siemens, Tecnomatix Plant Simulation, 2014. Available Online, Last Access (5/25/2014) http://www.plm.automation.siemens.com/en_us/products/tecnomatix/manufacturing-simulation/material-flow/plant-simulation.shtml