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Data-driven modeling and real-time distributed control for energy efficient manufacturing systems

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A B S T R A C T

As manufacturers face the challenges of increasing global competition and energy saving requirements, it is imperative to seek out opportunities to reduce energy waste and overall cost. In this paper, a novel data-driven stochastic manufacturing system modeling method is proposed to identify and predict energy saving opportunities and their impact on production. A real-time distributed feedback production control policy, which integrates the current and predicted system performance, is established to improve the overall profit and energy efficiency. A case study is presented to demonstrate the effectiveness of the proposed control policy.

1. Introduction

Conventionally, improving production efficiency, flexibility and responsiveness has been the primary research focus of production management, while energy consumption has received little attention. As concerns mount about long-term energy availability and climate change, energy consumption and energy efficiency improvement are becoming companies' top issues.

To achieve the goal of reducing energy use from manufacturing plants by twenty percent to fifty percent for the next three to ten years [1], critical technical challenges must be solved. First, there is a lack of rigorous modeling method for real-time system level monitoring, identification and prediction of energy waste and energy saving opportunities. While information about production systems has becoming increasingly transparent, detailed, and real-time, the utilization of this information for energy efficiency improvement and cost reduction has been lagging behind. The traditional methodologies for production system analysis and control are mostly based on steady state analysis and long-term performance measurements. Hence, the advantage of detailed sensor data, which is critical to improve responsiveness of the real-time system control, is mostly ignored. The vast amounts of time series data generated by distributed sensors have to be analyzed in real-time and converted to actionable knowledge that can be fed to process monitoring, control, and optimization algorithms [1]. The challenge now is to disseminate and interpret the information collaboratively through data-driven modeling for intelligent control such that the entire plant floor operations and energy consumption are well coordinated, connected, and timely reconfigured with the goal of achieving higher energy efficiency and sustainability for the entire system.

Second, there is a lack of real-time intelligent control method for manufacturing energy optimization. There is a long history of research in control theory but the manufacturing domain has not in general been a target for this research [1]. Consequently, most of the current energy optimization and control methods focus on heuristic rules or require computationally expensive time horizon algorithms, such as dynamic programming algorithm, where an optimal solution is obtained through an exhaustive numerical search. This will seriously hinder the effectiveness of the control in real-time advanced manufacturing environment. Due to the stochastic and non-linear properties of production systems, it is a big challenge to establish a control policy to enable a fast response to

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random disturbances and unexpected changes with the goal of improving overall economic benefit and energy efficiency.

This paper is devoted to address the above challenges. The main contributions of this paper are in: 1) establishing a data-driven mathematical model through available sensor data; 2) developing a system diagnosis and prognosis methodology based on the data-driven model to identify and predict the system performance and energy saving opportunities; 3) establishing a novel automated distributed control scheme which integrates real-time feedback control and collaborated control to improve overall system profit and energy efficiency.

The rest of the paper is organized as follows: literature review is provided in Section 2. Section 3 introduces the assumptions and notations applied in the paper. In Section 4, a mathematic model for a continuous flow stochastic production system is developed. Energy saving opportunity and system performance identification and prediction are discussed in Section 5. Section 6 describes the automated distributed control scheme based on the stochastic model of the production system. Section 7 studies the energy and production economics of the manufacturing system. A case study is presented in Section 8. Finally, conclusions and future research are given in Section 9.

2. Literature review

The existing production management studies are mostly focused on improving production efficiency, flexibility, and responsiveness [2–9]. There have been substantial research efforts in the analysis of the production system dynamics and performance evaluation [10–16]. Both simulation and analytical methods are utilized to study the properties of production system. Computer simulation is known to be a useful tool in analyzing the dynamics of production system. However, it may suffer from long model development time and intense computational effort to obtain useful conclusions. For analytical methods, exact analytical results only exist for the two-machine-one-buffer system and systems with infinite buffer capacity or without buffers [10,11]. Decomposition and aggregation methods are utilized with Markov chain models to estimate the performance of longer lines and assembly systems [10,12]. However, most of the existing analytical studies evaluate the system steady-state performance and make optimizations on long-term production system schedule plans [10,12,19]. Chen et al. derive the mathematical model and closed-form expressions for transient performance evaluation of synchronized serial production lines with geometric machines [20]. However, the method only provides some basic properties such as settling time monotonicity, while the transient throughput and work-in-process are actually derived based on approximation.

Recently, with the wide adoption of distributed sensors in production systems, more real-time detailed sensing information is available that is potentially very useful in identifying system real-time performance [13,15–18,21,22]. Analysis of downtime impacts and the cost of disruption incidents for multi-stage manufacturing systems are studied in Refs. [13] and [16]. Reference [21] develops a real-time disruption recovery model for two-stage production-inventory systems to obtain the optimal recovery plan based on the real-time influence of the system disruptions. However, these studies mainly focus on real-time system diagnosis without further prognosis for potential system performance in future time. A system identification method is desired to provide quick and accurate diagnosis and prognosis for system performance.

There is an increasing interest in the research of improving energy efficiency in manufacturing plant floor operations [23–30]. Previous efforts in this area mainly focus on isolated or mutually independent machines or processes [23–26]. Schudeleit et al. compare the general energy efficiency test methods (i.e., reference part method, reference process method, specific energy consumption method, and component Benchmark method) for testing machine tools' energy efficiency using a multiple criteria decision-making technique and find the most promising candidate for ISO14955 series [25]. However, the following property is shared in modern manufacturing systems: the system exhibits highly complex dynamics since the operation status of each machine is determined not only by itself, but also by other machines and buffers. Therefore, it is indispensable to consider the interactions within production systems for effective energy management.

Energy optimization and control methods have also been developed and applied to improve energy efficiency at the system level [27–31]. Deif et al. focus on a system model for the new green manufacturing paradigm, which captures various planning activities to migrate from a less green into a greener and more eco-efficient manufacturing [27]. Reference [31] proposes a system approach for time-of-use based electricity demand response for sustainable manufacturing systems under the production target constraint. It is noted that these efforts are more focused on heuristic rules or expert knowledge due to the lack of mathematical theory and computational implementations that are sufficiently flexible and robust to deal with the complex nature of production systems.

Conventionally, researchers try to treat the production system as one process or system to be controlled. Due to the difficulty of a single central controller to deal with production system complexity, one widely used solution has been to distribute decisional capabilities to decisional entities, leading to non-centralized control system [32]. The control architecture is semi-heterarchical or fully heterarchical, and the control decision has been distributed to local entities. Chung et al. develop a modified genetic algorithm approach to deal with the distributed scheduling models with maintenance consideration, aiming to minimize the makespan of the jobs [33]. Reference [34] proposes a domain-based factory loading allocation problem for the conceptualization of a multi-site manufacturing supply chain, and a decision propagation structure incorporating with a connectionist approach is developed based on the concept of constraint heuristic search to facilitate the exploration of solution spaces. A systematic control scheme based on mathematical model is much desired.

3. System description

Continuous flow models are used in this paper because the production dynamics can be conveniently described by integral or differential equations [10,16]. Continuous flow models assume the quantity of jobs in the buffer varies continuously from zero to its capacity. Consider a serial production line consisting of M machines (represented by the rectangles) and $M-1$ buffers (represented by the circles) as shown in Fig. 1. The following notations are used in this paper:

- S_i denotes the i^{th} machine, where $1 \le i \le M$;
- B_i denotes the i^{th} buffer, where $2 \le i \le M$;
- $s_i(t)$ denotes the actual processing speed of machine S_i at time t;
- $b_i(t)$ denotes the buffer level of buffer B_i at time t;
- K_i denotes the power rating of machine S_i;

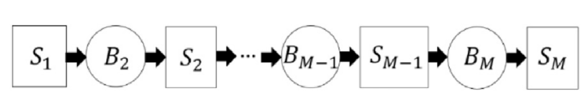

Fig. 1. General serial production line.