Energy 86 (2015) 164–174

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A modeling method for hybrid energy behaviors in flexible machining systems

Yufeng Li [a], Yan He [a,*], Yan Wang [b], Yulin Wang [c], Ping Yan [a], Shenlong Lin [a]

[a] State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400030, China
[b] Department of Computing, Mathematics and Engineering, University of Brighton, UK
[c] School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

ARTICLE INFO

Article history:
Received 2 November 2014
Received in revised form
1 March 2015
Accepted 28 March 2015
Available online 23 May 2015

Keywords:
Energy consumption
Energy behavior
Flexible machining system
Petri net

ABSTRACT

Increasingly environmental and economic pressures have led to great concerns regarding the energy consumption of machining systems. Understanding energy behaviors of flexible machining systems is a prerequisite for improving energy efficiency of these systems. This paper proposes a modeling method to predict energy behaviors in flexible machining systems. The hybrid energy behaviors not only depend on the technical specification related of machine tools and workpieces, but are significantly affected by individual production scenarios. In the method, hybrid energy behaviors are decomposed into Structure-related energy behaviors, State-related energy behaviors, Process-related energy behaviors and Assignment-related energy behaviors. The modeling method for the hybrid energy behaviors is proposed based on Colored Timed Object-oriented Petri Net (CTOPN). The former two types of energy behaviors are modeled by constructing the structure of CTOPN, whist the latter two types of behaviors are simulated by applying colored tokens and associated attributes. Machining on two workpieces in the experimental workshop were undertaken to verify the proposed modeling method. The results showed that the method can provide multi-perspective transparency on energy consumption related to machine tools, workpieces as well as production management, and is particularly suitable for flexible manufacturing system when frequent changes in machining systems are often encountered.

1. Introduction

Energy is a vital input for industrial sectors. With increasing industrial activities in a country, the demand for energy is also increasing [1,2]. Manufacturing industry plays an indispensable role in the global economy and dominates industrial energy consumption [3]. According to the most recent estimates of the International Energy Agency, manufacturing accounts for about 79% the global coal consumption, more than one third of global gas consumption and also uses 41.7% of all electricity produced [4]. As a result of climate change conventions and energy policy, stringent regulations to reduce carbon dioxide emissions and improvement of energy efficiency have been imposed globally, which have become an important influential factor in the manufacturing industry for energy reduction (particularly electric energy) [5,6]. In manufacturing industry, machining systems are conceived as machining workshops that are composed of computerized numerical control (CNC) machines or manual machine tools for producing workpieces. Machining, a manufacturing process to removal extra materials of workpieces is wasteful in use of energy and very inefficient [7–10]. To move toward energy efficient manufacturing, it is paramount for designers and engineers to be able to access detailed information about the environmental impacts of the manufacturing processes [11], thus effectively modeling of energy behaviors for machining systems is essential.

Energy behavior modeling for machine tools has so far been extensively studied and reported. Based on energy component breakdown of machine tools [12–14], energy behaviors of each component have been modeled for energy estimation of machine tools [15–20]. These models are certainly highly necessary but not sufficient for understanding energy behaviors at the machining systems level. To this end, the early research has studied the relationship between the energy consumption of machining systems and their operational states which is taken as the main factor for construction of the basic model. The model is very generic, thus, its capability to explicitly analyze energy consumption related to

* Corresponding author.
E-mail address: heyan@cqu.edu.cn (Y. He).

http://dx.doi.org/10.1016/j.energy.2015.03.121

products is limited [21]. Other researchers made efforts on energy modeling related to products or production tasks. For example, Rahimifard et al. introduced a novel approach to breakdown of energy required to produce a single product throughout a manufacturing system [22]. At the production operational level, a process chain simulation method was used to model energy consumption influenced by production management measures [23]. Smith and Ball developed guidelines to model the energy consumption based on facility related process flow employing an event graph method [24], and energy characteristics for alternative machining processes of tasks were analyzed using the method [25].

Although these presented methods modeled energy behaviors from production system level, energy behaviors were analyzed from a relatively single perspective. For example, the method proposed by Dietmair and Verl [21] was primarily focused on operational states of machine tools, while production processes for a product were mainly based on the research undertaken by Rahimifard et al. [22]. As a result, there are some limitations on overall transparency for the hybrid energy behaviors in manufacturing systems. Weinert et al. proposed an EnergyBlocks methodology for energy consumption in production systems. This methodology modeled production process chains by arranging the segments of specific energy consumption taking into consideration of operating state of equipments as well as process chains of parts. So the results can provide three different views of energy behaviors including equipment perspective, product perspective and production system perspective [26]. However, if process chains of production systems are changed, the segments of specific energy consumption need to be rearranged. Therefore, the proposed EnergyBlock methodology is not effective for energy modeling of flexible machining systems, where production process is dynamic and changeable.

In terms of energy modeling of flexible machining systems. Diaz and Dornfeld presented a methodology for analyzing energy behaviors related with routing flexibility in a flexible manufacturing system, the results of which was used to optimize energy consumption for machine tool scheduling [32]. Fang et al. also focused on the same issue, and proposed a scheduling method considering energy optimization in a flexible manufacturing system [33,34]. To address the limitation on dynamic and flexibility of the previous methods, Zhang et al. further presented a dynamic scheduling method for energy efficiency in a flexible manufacturing system [35]. The authors also proposed a method to optimize energy considering machine tool selection and operation sequence in flexible machining job shops [36]. Most of the above research on energy in a flexible manufacturing system were primarily concentrated on energy behavior analysis from operational production perspective, and the obtained results were specific to energy-optimization scheduling problem.

Energy behaviors in flexible machining systems have hybrid characteristics, which not only depends on the technical specification of machine tools and workpieces, but also are greatly linked to production scenarios. Understanding how to effectively deal with the hybrid characteristic is a key for predicting energy behaviors in flexible machining systems. To this end, this paper proposes a modeling method to predict hybrid energy behaviors in flexible machining systems. The method decomposes hybrid energy behaviors into Structure-related energy behaviors, State-related energy behaviors, Process-related energy behaviors and Assignment-related energy behaviors. Furthermore, CTOPN is used to model the hybrid energy behaviors for flexible machining system since it integrates the merits of Petri nets and object-oriented programming, [27,28]. While Structure-related energy behaviors and State-related energy behavior were modeled using the structure of CTOPN, the Process-related energy behaviors and Assignment-related energy behaviors are simulated employing colored tokens and their associated attributes. The proposed modeling with CTOPN method can be used to predict and analyze energy behaviors from multiple perspectives, which offers an overall transparency on energy consumption taking into account the structure of machine tools, machining processes of workpieces, as well as operational state and assignment in production processes. The proposed methodology will provide a basis for energy optimization in terms of operational production management, and facilitating potential energy saving exploration by environmental conscious engineers.

2. Hybrid energy behaviors in flexible machining systems

The dynamic and changeable production processes of flexible machining systems has led to the hybrid characteristic of the energy behaviors. In order to provide an overall transparency on energy consumption at the system-wide level, energy behaviors should be analyzed from multiple perspectives [26].

Although there are no widely recognized methods to decompose the comprehensive energy behaviors in machining systems, three general aspects of energy behaviors are often utilized including machine tool [15–20], workpiece (product) [21–22] and operational production processes [23–25]. Based on these, the hybrid energy behaviors are further brokendown into Structure-related energy behaviors, Processes-related energy behaviors, State-related energy behaviors and Assignment-related energy behaviors. The former two items are based on machine tool perspective and product perspective, which could provide useful information to support equipment designers and maintenance engineers, and process planners whist the late two items are related to operational production perspective, which is specifically useful for production managers to support decision-making.

1) Structure-related energy behaviors.

This kind of energy behaviors describes energy consumption relevant to the structure properties of machine tools and workpieces, such as energy-consuming components of machine tools, material and features of workpieces. These Structure-related energy behaviors are determined based on technical specification of machine tools or workpieces. For example, Abele et al. specifically focused on the analyses of a machine tool spindle unit structure and identified potentials for increasing the energy efficiency. They presented a way to increase energy efficiency of machine tools by developing an energy optimized spindle unit with an adapted electoral drive train [29].

2) State-related energy behaviors.

The State-related energy behaviors are used to analyze energy consumption related with operational states of flexible machining systems. The factors in production operation of flexible machining systems play an important role on this kind of energy behaviors, such as production planning, workpiece types and batch of production order. As reported by Herrmann and Thiede, two machining lines for producing the same quantity but different batch sizes of internal gear for automotive industry were simulated to show the effect of batch size on energy behaviors. Different batch size allocation was considered, such as 100 batch size and 25 batch size, and 24.29 kW h difference in energy consumption was observed for producing the same quantity parts with different batch size [23].

3) Process-related energy behaviors.

For machining a batch of workpieces, different process planning results in different energy behaviors in flexible machining systems. Process-related energy behaviors denote energy behaviors affected by both process routing and process parameters. According to the experiments conducted by Draganescu et al. for face milling of