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An energy-responsive optimization method for machine tool selection and operation sequence in flexible machining job shops

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A B S T R A C T

The environmental burden caused by energy consumption during the use phase of machine tool systems is widely acknowledged and hence ways must be found to use energy more efficiently. There is potentially a significant amount of energy savings that could be realized by selecting alternative machine tools and reducing the idle energy consumption through better scheduling. This paper proposes an energy-saving optimization method that considers machine tool selection and operation sequence for flexible job shops. The former seeks to reduce the energy consumption for machining operations, and the latter aims to reduce the idle energy consumption of machine tools. A mathematical model is formulated using mixed integer programming and the energy consumption objective is combined with a classical objective, the makespan. A Nested Partitions algorithm, which has proved to be robust for NP-hard problems, is utilized to solve the model. The proposed method is evaluated in a test case by two scenarios with different energy optimization schemes as well as the classical makespan objective. The results show that the proposed method is effective at realizing energy-savings for a flexible machining job shop.

1. Introduction

The global manufacturing industry sector is responsible for 31% of primary energy consumption and 36% of CO_2 emissions (Bruzzone et al., 2012). In manufacturing, machine tools consume an enormous amount of energy as they physically transform raw materials into finished products. Reducing the energy consumed by machine tool systems has been identified as one of the strategies to improve sustainability in manufacturing (Pusavec et al., 2010). The environmental impact of the use phase of a machine tool is more important than that of the other life cycle stages of a machine tool and resides mainly in the amount of energy consumed (Dahmus and Gutowski, 2004). With approximately 83% of the total impact, the use stage systematically is considered as the dominant contributor to the total life cycle environmental impact of machine tools (Duflou et al., 2012).

Against the background, energy consumption during the use phase of machine tools has received much research attention, and significant energy waste has been observed. The energy breakdown of machine tools has shown that only 10% of energy is used for actual material removal (Dahmus and Gutowski, 2004; Drake et al., 2006), and the rest of the energy is consumed by the auxiliary functions and components of machine tools. Moreover, substantial energy waste is associated with the idle phase of machine tool operation. At Toyota, it was reported that 85.2% of the energy was used for operations not directly related to the production of parts (Gutowski et al., 2005). Bladh (2009) also reported that the energy savings potential was 10–25% through the reduction of the time used waiting or in the start-up mode.

To reduce these energy wastes, some energy-focused optimizing methods have been proposed for production operation of machine tool systems. For a single machine system, energy-focused optimizing methodologies have been proposed to reduce idle energy or energy during peak periods. Mouzon et al. (2007) investigated the problem of scheduling a single machine to minimize the idle energy consumption using several dispatching rules. They also proposed a framework to incorporate energy consumption into consideration while making scheduling decisions to optimize objectives such as total tardiness. According to previous investigations, proposed optimization methods were used to reduce

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idle energy consumption for a single machine. Liu et al. (2014a) focused on a single machine system and the consumed energy of the machine when it stays idle. An optimization model was proposed to minimize the carbon dioxide emissions based on the arrival time and the processing time of each product. Moreover, energy cost optimization was modeled by Fadi et al. (2014) for single machine production scheduling during production processes. Based on the model, the reduction in energy costs is achieved by avoiding high-energy price periods.

Some studies have been carried out to address on energy optimization for production operation of flow shops. Herrmann and Thiede (2009) proposed process chain simulation to foster energy efficiency in manufacturing. Using the method, energy efficiency can be improved by the combination of quantity allocation and lot size of parts across two production lines. Some researchers focus on energy-efficient scheduling problems in flow shops, and presented mixed integer programming models for different energy-related objectives. Bruzzone et al. (2012) introduced a mixed integer programming model to minimize the shop floor power's peak. Fang et al. (2011a) and Dai et al. (2013) proposed a multi-objective optimization model considering both productivity (i.e., makespan) and energy (i.e., peak load, unload and carbon footprint). Besides these, Chen et al. (2013) studied specifically on productivity and energy performance in Bernoulli serial lines with machine startup and shutdown, and they utilized Markovian analysis method to discuss the effect of machine startup and shutdown schedule on system performance. These energy-focused methods for flow shops are not efficient for energy reduction in flexible job shops where significant flexibility involving both process routings and alternative machine tools exist for jobs.

Only a few methods for energy optimization in flexible job shops have been reported in the literature. Weinert et al. (2011) proposed the EnergyBlocks methodology for integrated energy-efficiency criteria with evaluation and decision processes during production system planning and scheduling in job shops, the limit of which is that the evaluated job planning or scheduling is known *a priori*. He and Liu (2010) introduced an energy conscious method for machine tool selection for machining jobs. They assumed each job required only one operation and the idle energy waste of machine tools was not considered during the investigation. Fang et al. (2011b) proposed a scheduling model that considered energy consumption for machining operations of jobs; however, no attempt was made to reduce the idling portion of machine tool operation. Furthermore, Liu et al. (2014b) developed a multi-objective scheduling method with reducing energy consumption as one of the objectives. The model focused on non-processing electricity consumption which only includes the idle power consumption of machine tools.

This paper proposes a method for optimizing energy efficiency that integrates machine tool selection and operation sequence selection for flexible job shops. To reduce idle time/energy, the mentioned method seeks to reduce the energy for machining operations through optimized selection of machine tools, and the choice of operation sequence.

The rest of the paper is organized as follows: The problem for the energy-aware machine tool selection and operation sequence in flexible machining job shops is described and a simple example to demonstrate the problem is shown in Section 2. In Section 3, the mathematical model which considers energy consumption as well as the classical objectives makespan is formulated. In Section 4, the Nested Partitions algorithm for solving the mathematical model is presented. Also, a test case to evaluate the proposed method using two scenarios with different energy optimization objectives as well as the classical makespan objective is demonstrated in Section 5 and finally concluding remarks are presented.

2. Description of the problem

It was reported by Dahmus and Gutowski (2004) that energy consumption depends on specific machine tools utilized, even for machining the same job. They reported that when machining steel on four different milling machines, the specific cutting energy may be as high as 60 kJ/cm^3 or as low as 10 kJ/cm^3. Even for the same machine tool type and size, the specific energy can vary by 50% which was also reported by He and Liu (2010). Different machine tools performing the same job with identical process parameters, may consume different amounts of energy. Fig. 1 presents an energy comparison for machining the same job with the same process parameters. And two different lathes which were made by Chongqing No. 2 Machine Tool Works company. There is 42% energy savings by selecting the C2-6136HK NC lathe to machine the job instead of the C2-6132HK/1 NC lathe. Accordingly, from a production operation perspective, energy consumption can be optimized by selecting the best available machine tool to perform a job.

Energy wasted through excessive machine idling energy waste can also be reduced. Mouzon and Yildirim (2008) observed that there is massive idle energy waste of machine tools in production operations. Great energy-savings can be realized by reducing the idle time, especially for machine tools with a high running power. This idling can be reduced by optimizing the operation sequences of jobs.

Based on the above observations, this paper proposes an optimization method for improving energy efficiency that integrates machine selection and job operation sequence (EMS/OS) in flexible machining job shops. Here, we present a simple example with two jobs and two machines to explicitly describe the EMS/OS problem. Table 1 shows the processing time and energy consumption for the jobs on different machines. The idle power of machine M_1 and machine M_2 are respectively 650W and 950W.

The operation precedence constraints and the machine tool alternatives are shown in Fig. 2. For job 2, operation O_{21} is the predecessor of operation O_{22} (O_{ij} refers to the j^{th} operation for the i^{th} job). Suppose that the release time of both jobs is zero; two feasible schedules are shown in Fig. 2. The makespans of both solutions are equal to 10 min while the total energy consumption of the first solution is 14.4% less than the energy required for the second solution.

As shown in this example, the objective of the EMS/OS problem is to determine an optimal schedule with machine tool selection

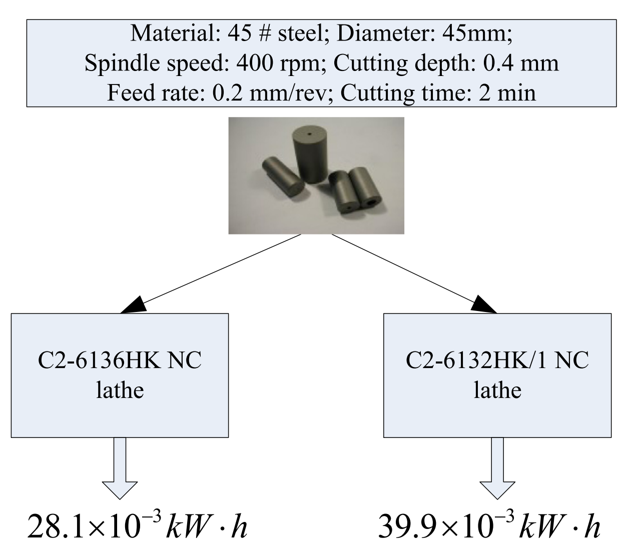

Fig. 1. Energy consumption comparison for two machine tools.

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