Journal of Cleaner Production xxx (2014) 1–16

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

A systematic approach of process planning and scheduling optimization for sustainable machining

S. Wang, X. Lu, X.X. Li, W.D. Li*

Faculty of Engineering and Computing, Coventry University, Priory Street, Coventry CV1 5FB, UK

ARTICLE INFO

Article history:
Received 17 July 2014
Received in revised form
3 October 2014
Accepted 4 October 2014
Available online xxx

Keywords:
Sustainable manufacturing
Computer numerical control machining
Process planning
Process scheduling
Intelligent algorithm
Machining feature

ABSTRACT

The lack of effective process planning and scheduling solutions for the sustainable management of machining shop floors, whose manufacturing activities are usually characterized by high variety and low volume, has been crippling the implementation of sustainability in companies. To address the issue, an innovative and systematic approach for milling process planning and scheduling optimization has been developed and presented in this paper. This approach consists of a process stage and a system stage, augmented with intelligent mechanisms for enhancing the adaptability and responsiveness to job dynamics in machining shop floors. In the process stage, key operational parameters for milling a part are optimized adaptively to meet multiple objectives/constraints, i.e., energy efficiency of the milling process and productivity as objectives and surface quality as a constraint. In the consecutive system stage, to achieve higher energy efficiency and shorter makespan in the entire shop floor, sequencing/set-up planning of machining features/operations and scheduling for producing multiple parts on different machines are optimized. Artificial Neural Networks are used for establishing the complex nonlinear relationships between the key process parameters and measured datasets of energy consumption and surface quality. Several intelligent algorithms, including Pattern Search, Genetic Algorithm and Simulated Annealing, are applied and benchmarked to identify optimal solutions. Experimental tests indicate that the approach is effective and configurable to meet multiple objectives and technical constraints for sustainable process planning and scheduling. The approach, validated through industrial case studies provided by a European machining company, demonstrates significant potential of applicability in practice.

1. Introduction

Paramount demands for new products have increasingly incurred more manufacturing activities. In order to balance the multi-faceted dimensions of economic growth and environmental protection, a series of regulations and guidelines on lifecycle energy/carbon-related management have been developed in recent years for product design and manufacturing enterprises to embrace "Competitive Sustainable Development" (Jovane et al., 2008) and shoulder "Extended Producer Responsibilities (EPR)" (Mayers, 2007). For instance, the lifecycle carbon labeling scheme, outlined by the ISO 14040: 2006, ISO 14044: 2006 and Publicly Available Specification 2050 (PAS 2050), has been introduced with a bid to stimulate energy efficiency improvement and carbon emission reduction during product lifecycle. Among the various stages of product lifecycle, manufacturing processes are energy intensive making the stage one of the primary energy consumption and carbon footprint generation sources. Manufacturing processes in factories, in which motors, compressors and machine systems need to be powered, and adequate heating, ventilation and air conditioning equipment need to be maintained, contribute to over 24% of total European energy consumption (O'Driscoll and O'Donnell, 2013). Therefore, the effective implementation of manufacturing sustainability is prevalent. The roadmap research of intelligent manufacturing towards 2020, conducted by an international consortium consisting of researchers from Europe, Japan, Korea and the United States has summarized that the energy efficiency indicators of manufacturing on a national or sectional level have been defined, but sustainable process management solutions for single companies have not been effectively implemented, and the research is highly imperative (EU FP7 project IMS2020 (Bunse et al., 2011)). Machining such as milling is one of the important manufacturing processes. Co-operations between machining companies and their

* Corresponding author. Tel.: +44 (0)7557425332.
E-mail address: weidong.li@coventry.ac.uk (W.D. Li).

http://dx.doi.org/10.1016/j.jclepro.2014.10.008
0959-6526/

customers are more project-specific, customer-centric and flexible, the jobs/orders are likely to be diversified and many of them are urgent. As thus, there are many uncertainties and adjustment requirements in shop floors as part of the day-to-day operation planning in companies (Tolio et al., 2011). However, effective process planning and scheduling solutions, which are adaptive to dynamics in both the machining process and machine system levels, and multiple criteria like sustainability, product quality and productivity are systematically incorporated in the solutions, are lacking.

In order to address the above issue, an innovative approach of sustainable process planning and scheduling for machining multiple parts using multiple Computer Numerical Control (CNC) machines has been developed. The approach focuses on the milling process, and addresses dynamics in machining processes from the following two aspects: (1) it optimizes the key milling parameters of individual machines for producing individual parts to meet constraint-based multiple objectives, in terms of energy efficiency, surface quality and productivity; and (2) based on the optimized milling process parameters, an optimized solution of process sequencing, setting-up and scheduling for machining multiple parts using multiple candidate machines in a shop floor is achieved by considering the criteria of energy consumption and makespan of the machine system.

The innovations of the approach are summarized below:

- The approach provides a systematic, adaptive and efficient means to optimize machining companies' multi-objectives such as sustainability, productivity and makespan, and to meet technical constraints such as the required surface quality and precedence constraints among machining features/operations;
- Machining feature-based sustainable process planning and scheduling is highly desirable as machining features have been used as essential building blocks in modern Computer Aided Manufacturing (CAM) software. This approach supports intelligent decision making processes for feature-based sustainable process planning and scheduling, and based on that a practical way is paved for the approach to be integrated into modern feature-based CAM systems.

The rest of the paper is organized as follows. In Section 2, a literature survey on sustainable machining processes especially milling processes is given. In Section 3, the system framework of the research is presented. In Section 4, the constraint-based multi-objective optimization of key milling process parameters are presented. Based on the optimized parameters of individual machines for individual parts, the multi-objective optimization process of a machine system in a dynamic shop floor is described in Section 5. In Section 6, case studies and experimental tests are described. Finally the research is concluded in Section 7.

2. Related work

In the past decades, research on manufacturing process planning and scheduling has been extensively conducted, and comprehensive surveys can be found from (Wang and Shen, 2010). This paper focuses on energy efficient process planning and scheduling, and the related state-of-the-art research is summarized below.

2.1. Energy consumption modeling based on key machining parameters

The European Machine Tool Builder Association indicates that the machine tool industry has shown strong interests on developing energy efficient manufacturing systems. To support the industry to achieve sustainability, a self-regulatory initiative for identification of measurements for energy performance and resource efficiency of machine tool systems has been proposed by the Association (Duflou et al., 2012). Aiming at implementing the initiative effectively, researchers have been actively investigating the energy consumption profile of machine tool systems during execution and identifying the key process parameters that affect the consumption profile. Based on that, optimization strategies are applied for process and system improvement in terms of energy saving.

Abele et al. summarized the total energy demand of a machine tool system during production as: $E_{total} = E_{th} + E_{additional} + E_{periphery}$, where E_{th} is the active energy theoretically needed to obtain the physical process effect, $E_{additional}$ and $E_{periphery}$ stand for the additional energy demands of the machine tool (e.g., energy to cover efficiency losses, or energy for machine functions such as central control) and peripherals (e.g., cutting fluid pump) respectively (Abele et al., 2005). Among the energy consumption of a machine tool system, the unit energy consumption demand of a machining process is remaining a challenging research issue. Gutowski et al. (2006) classified related energy consumption of manufacturing into the following categories:

- Fixed energy: energy demand of all activated machine components ensuring the operational readiness of the machine;
- Operational energy: energy demand to distinctively operate components enabling the cutting as performed in air-cuts;
- Tool tip energy: energy demand at tool tip to remove the workpiece material;
- Unproductive energy: energy converted to heat mainly due to friction during the material removal.

Series of research work were carried out to detail the energy profile for the aforementioned categories. A summary of the work is given in Table 1. Mori et al. (2011) developed an empirical model, in which several processes are considered such as positioning and acceleration of the spindle, tool changes, machining, and stop of the spindle. Newman et al. (2012) developed empirical models to establish the relationship between cutting parameters, such as depth of cut, feedrate and number of cuts, and power consumption. Two case studies of finish cutting and semi-finish cutting of Aluminum were used to verify the models. In Hu et al. (2012)'s work, a torque sensor was mounted onto the cutter and active power consumed by a machining process was calculated, while the total input power to the machine tool system was measured by a power sensor. Based on experimental data, an empirical model was established to estimate the total power and active power for machining, which are used to support the on-line monitoring system. The Taguchi method was introduced to analyze the relationship among cutting parameters, energy consumption, and surface roughness in order to determine the suitable cutting parameters leading to the minimum energy consumption and the best surface roughness (Camposeco-Negrete, 2013). A Grey Relationship Analysis method was developed for establishing relationships among Material Removal Rate (*MRR*), machining power and surface roughness minimization, the Response Surface Methodology (*RSM*) and the Taguchi method were used for factor effect analysis (Yan and Li, 2013). Winter et al. (2014) investigated the energy performance of a grinding process. The Sensitivity Analysis method was applied to illustrate how cutting parameters, including cutting depth, cutting speed and dressing speed affect the energy consumption in order to achieve multi-objective optimization.