Journal of Cleaner Production xxx (2015) 1–12

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Energy conservation in manufacturing operations: modelling the milling process by a new complexity-based evolutionary approach

A. Garg [a], Jasmine Siu Lee Lam [a, *], L. Gao [b]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
[b] The State Key Laboratory of Digital Manufacturing Equipment and Technology, 1037 Luoyu Road, Huazhong University of Science and Technology, Wuhan 430074, China

A R T I C L E I N F O

Article history:
Received 5 March 2015
Received in revised form
10 June 2015
Accepted 10 June 2015
Available online xxx

Keywords:
Environmental sustainability
Energy conservation
Energy consumption
Machining
Computational intelligence
Milling process

A B S T R A C T

From the perspective of energy conservation, the notion of modelling of energy consumption as a vital element of environmental sustainability in any manufacturing industry remains a current and important focus of study for climate change experts across the globe. Among the manufacturing operations, machining is widely performed. Extensive studies by peer researchers reveal that the focus was on modelling and optimizing the manufacturing aspects (e.g. surface roughness, tool wear rate, dimensional accuracy) of the machining operations by computational intelligence methods such as analysis of variance, grey relational analysis, Taguchi method, and artificial neural network. Alternatively, an evolutionary based multi-gene genetic programming approach can be applied but its effective functioning depends on the complexity measure chosen in its fitness function. This study proposes a new complexity-based multi-gene genetic programming approach based on orthogonal basis functions and compares its performance to that of the standardized multi-gene genetic programming in modelling of energy consumption of the milling process. The hidden relationships between the energy consumption and the input process parameters are unveiled by conducting sensitivity and parametric analysis. From these relationships, an optimum set of input settings can be obtained which will conserve greater amount of energy from these operations. It was found that the cutting speed has the highest impact on the milling process followed by feed rate and depth of cut.

1. Introduction

The subject of energy conservation is being extensively studied by climate change experts. This is because one of the factors contributing to drastic climate change is the extensive amount of energy consumption from the various sources (household appliances such as air conditioner, industry, vehicles). Therefore, for conservation of energy, reducing energy consumption from these sources is a problem of national interest. Among these sources, the energy consumption from the industry contributes significantly. It is learnt that the industry sector accounts for about one-half of the world's total energy consumption which has been doubled over the past 60 years (Fang et al., 2011). This is because with the world witnessing growth in manufacturing industries for meeting the stringent demands of customers, the demand of energy for driving the essential operations including machining processes (turning, drilling, grinding, and milling) has significantly shot up. This leads to an unfavourable environment due to the release of toxic gases in the atmosphere (De Soete et al., 2014; Egilmez et al., 2014a, Kreiger et al., 2013). Among these operations, machining is widely focused and performed in the manufacturing industries. Excessive use of energy used in driving the machining operations has adverse impacts on the environment. It is known that machining processes have an efficiency of below 30% (He et al., 2012) and 99% of the environmental impacts is from the electrical energy consumed by tools in processes such as milling and turning (Kant and Sangwan, 2014; Li et al., 2011). The consequences are soil, air and water pollution which may render environmental and social problems. From this perspective, saving of energy can result in higher environmental performance and productivity (Lam and Lai, 2014). Performing the manufacturing operations for higher economic prosperity with least environmental impact has led to a new manufacturing paradigm of environmental conscious manufacturing (ECM) or sustainability manufacturing or green

* Corresponding author. Tel.: +65 6790 5276.
E-mail address: SLLam@ntu.edu.sg (J.S.L. Lam).

http://dx.doi.org/10.1016/j.jclepro.2015.06.043
0959-6526/

manufacturing (GM) (Bhushan, 2013; Balogun and Mativenga, 2013).

Survey studies (Davim, 2011; Garg et al., 2013a; Chandrasekaran et al., 2010) conducted on the applications of modelling methods in machining operations reveal that the main attention was on reducing the implementation cost of the machining operations by optimizing the surface roughness (manufacturing aspects) of the machining operations (Aykut et al., 2007; Li et al., 2000). Among the machining operations, the modelling of milling process received less attention. To the best of authors' knowledge, comparatively, very little emphasis was paid in optimizing the environmental aspects (energy consumption and cutting forces) of the machining operations (Siddique, 2012; Tatàno et al., 2012; Egilmez et al., 2014b). It is known that energy is consumed during the different stages of machining such as during the machining, post machining and in idle condition to drive motors and auxiliary components. Machine tool is designed based on the peak energy requirement, which is significantly higher than the non-peak energy requirement of the machine tools. This results in lower energy efficiency of machine tools. Optimization of energy component in machining operations can result in wide application of lower energy rated motors/auxiliary components and thus can prevent wastage of energy and improve the environmental impacts of the machining operations (Garg and Lam, 2015; Kant and Sangwan, 2014).

The performance of any industry is accessed by the quality of products being manufactured, tool life and energy efficiency of the machining operations. It is known that the efficiency of machining operations is lower than 30%, with almost 99% of the environmental impacts are from energy consumption (Kant and Sangwan, 2014). Lowering the product quality or the tool life does result in a reduction of energy consumption. However, it imposes a greater risk to the rejection of products and thus a threat to its reputation and sustainability in market. Therefore, there is a need to find a balance between energy consumption and manufacturing aspects (product quality, tool life, etc.) by effectively determining the appropriate input process parameters of the machining operation (Kant and Sangwan, 2014). In context of optimization of machining operations, the formulation of models representing the functional relationship between the outputs (manufacturing and environmental aspects) and inputs (input process parameters) is vital. Due to the complexity of the process, it is difficult to formulate models based on partial knowledge about its physics behind the process (Armarego et al., 2000; Ahilan et al., 2012; Bhushan, 2013). Some of the useful works in this aspect was done by López de Lacalle et al. (2005, 2006). López de Lacalle et al. (2005, 2006) developed the diagnostics tool for researchers to detect and solve two unexpected problems during milling of complex parts. A data acquisition system was set up to record the position of tool and cutting forces simultaneously by dynamometric plate so as to correlate the geometry of surface machined and the cutting forces in three axes (X, Y and Z). The first problem is by changing the feed rate continuously; the correlation between cutting forces and part geometry was observed. Second is detection of engagement of unexpected tool engagement coming from previous semi-finishing operations in machining of complex parts. Zulaika et al. (2011) also proposed an integrated approach for design of productive and light weight milling machines. In this approach, the interactions between the process and machine was measured by a stability model which resulted in identification of mechanical design parameters that limit the productivity and must be met to target the desire productivity. The approach when applied to the re-design of the actual milling machine resulted in above 100% productivity and 13% less energy consumption due to mass reduction of above 20%. Similarly, an integrated framework for achieving the optimization of cost and energy consumption of manufacturing systems was proposed by Tolio et al. (2013).

Also, authors have studied the literature review on modelling the manufacturing and environmental aspects of the machining operations by the statistical and optimization based methods. It was learnt that the most widely used method is RSM because it can be applied on the limited set of experiments (Yan and Li, 2013; Campatelli et al., 2014; Sarıkaya and Güllü, 2014). Further, the analysis of variance (ANOVA) model is constructed to estimate the amount of impact of the input parameters on the outputs (Cetin et al., 2011; Camposeco-Negrete, 2013; Emami et al., 2014). However, these statistical methods hold the assumptions such as structure of a model before the problem in hand, normality of residuals, non-correlated residual error values, etc. the significant input process parameters identified using the ANOVA model is not the same for all performance characteristics (Fratila and Caizar, 2011; Hanafi et al., 2012). The reason can be attributed to the use of different material in every machining operation. Since each performance characteristic is vital, there is a need for a model that can comprehensively predict all the performance characteristics based on the given input process parameters. Thereby optimization of this model can optimize the given machining process efficiently. The models developed using such methods may not be generalized for a given input sample outside the training range. Optimization methods (Taguchi method and desirability analysis) used was the traditional ones. It can be interpreted that the research on CI methods in modelling the environmental and manufacturing characteristics has not yet attained its modernisation. Therefore, more and thorough investigation is needed to observe the influence of input parameters on the environmental aspects of the machining operations by formulation of a generalized explicit relationship between the process parameters.

Alternatively, the evolutionary based multi-gene genetic programming (MGGP) which generates the model structure and its coefficients automatically can also be applied (Garg et al., 2015a,b,c). Based on the previous applications of MGGP conducted by authors (Garg et al., 2013b; Garg and Tai, 2013a,b), the *complexity of the MGGP model* is not accurately defined. Complexity of the evolved models during the evolutionary stages of MGGP is generally defined by number of nodes of the tree. This implies that $\mathrm{Sin}\,(x)$ and $-x$ will have same complexity as they both have 2 nodes, but it is not at all true. This is a critical issue because the complexity term is a component of the fitness function which monitors the evolutionary search and the convergence rate towards achieving the optimum solution. Therefore, determining its correct value is essentially important for the effective functioning of the algorithm by driving the evolution to its direction of global minimum. This issue also requires a thorough investigation and therefore forms a motivation for authors in developing a framework that can result in evolution of generalized models in effectively studying the impact of input process parameters on the energy consumption.

In the present work, a new complexity measure based evolutionary framework of MGGP (COM-MGGP) is proposed to formulate the functional relationship between energy consumption and the three input process parameters (cutting speed, feed rate and depth of cut) of the milling process. Procedure of formulation of the energy consumption model is shown in Fig. 1. Experimental data obtained from the milling operation is further fed into the proposed evolutionary framework. In this new framework, the complexity of the models generated during the evolutionary stage is computed by number of basis functions that best fits the model. Performance of modified evolutionary framework is compared to that of standardized MGGP. The sensitivity and parametric analysis is conducted on the proposed model to understand the physics behind

Please cite this article in press as: Garg, A., et al., Energy conservation in manufacturing operations: modelling the milling process by a new complexity-based evolutionary approach, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.06.043