Journal of Cleaner Production 102 (2015) 246–263

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Improving environmental sustainability by formulation of generalized power consumption models using an ensemble based multi-gene genetic programming approach

A. Garg, Jasmine Siu Lee Lam*

School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form
6 March 2015
Accepted 20 April 2015
Available online 29 April 2015

Keywords:
Environmental sustainability
Power consumption
Product quality
Machining
Surface roughness
Genetic programming

ABSTRACT

Environmental sustainability is an important aspect for accessing the performance of any machining industry. Growing demand of customers for better product quality has resulted in an increase in energy consumption and thus a lower environmental performance. Optimization of both product quality and energy consumption is needed for improving economic and environmental performance of the machining operations. However, for achieving the global multi-objective optimization, the models formulated must be able to generalize the data accurately. In this context, an evolutionary approach of multi-gene genetic programming (MGGP) can be used to formulate the models for product quality (surface roughness and tool life) and power consumption. MGGP develops the model structure and its coefficients based on the principles of genetic algorithm (GA). Despite being widely applied, MGGP generates models that may not give satisfactory performance on the test data. The main reason behind this is the inappropriate formulation procedure of the multi-gene model and the difficulty in model selection. Therefore, the present work proposes a new ensemble-based-MGGP (EN-MGGP) framework that makes use of statistical and classification strategies for improving the generalization ability. The EN-MGGP approach is applied on the reliable experimental database (outputs: surface roughness, tool life and power consumption) obtained from the literature, and its performance is compared to that of the standardized MGGP. The proposed EN-MGGP models outperformed the standardized MGGP models. The conducted sensitivity and parametric analysis validates the robustness of the models by unveiling the non-linear relationships between the outputs (surface roughness, tool life and power consumption) and input parameters. It was also found that the cutting speed has the most significant impact on the power consumption in turning of AISI 1045 steel and the turning of 7075 Al alloy- 15 wt% SIC composites. The generalized EN-MGGP models obtained can easily be optimized analytically for attaining the optimum input parameter settings that optimize the product quality and power consumption simultaneously.

1. Introduction

In today's world, the growth of manufacturing industries has resulted in an increase in the demand for energy. In industry, several manufacturing operations such as machining (turning, drilling, grinding and milling), and 3-D printing processes (fused deposition modelling, selective laser sintering, selective laser melting, etc) are carried out which draw the (electrical) energy from the power grid (Kuram et al., 2013). Among these operations, machining is widely used in the manufacturing industries. Since energy is an essential and expensive component for driving the machining operations, the saving of energy would result in higher environmental performance and productivity. For example, if the energy is drawn from the thermal power station, lowering the energy consumption would result in the lower emission of harmful gas, and would result in saving of water resources, if the route chosen is drawn from hydraulic plants (Bhushan, 2013; Balogun and Mativenga, 2013).

Survey studies (Chandrasekaran et al., 2010; Garg and Tai, 2012; Garg et al., 2013, Mukherjee and Ray, 2006) reveal that an extensive focus has been paid in optimizing the machining operations based on the two components: cost and productivity. To the best of authors' knowledge, less focus has been paid in optimizing the

* Corresponding author.
E-mail address: sllam@ntu.edu.sg (J.S.L. Lam).

http://dx.doi.org/10.1016/j.jclepro.2015.04.068

environmental/energy efficiency of the machining operations. 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 power requirement, which is significantly higher than the non-peak power 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 power rated motors/auxiliary components and thus can prevent wastage of energy and improve the environmental impacts of the machining operations (Kant and Sangwan, 2014).

The product quality, tool life and energy efficiency are the important standards for accessing any manufacturing industry. It is known that the efficiency of machining operations is lower than 30%, and almost 99% of the environmental impacts are from the energy consumption. Lowering the product quality or the tool life does result in a reduction of energy consumption. However, this also compromises the product's marketability and imposes a greater risk to the firm's reputation in the market (Lam and Lai, 2014). Therefore, there is a need to find a balance between energy consumption, product quality and tool life by effectively optimizing the input process parameters of the machining operation (Kant and Sangwan, 2014). In context of optimization of machining operations, the formulation of mathematical model representing the relationship between the outputs (power consumption and tool life and product quality) and inputs is vital. Due to the complexity of the process, the physics-based models may not be able to reveal the nature of effect of these parameters on the outputs. Therefore, this problem has indeed shifted the focus and motivated scholars towards pursuing the research on modelling of machining operations using statistical methods, including regression analysis, response surface methodology (RSM), Taguchi method, analysis of variance (ANOVA) and grey relational analysis.

Authors have conducted the literature review on modelling the machining operations using the statistical methods in Table 1 in the Appendix as follows:

From the works described, it is clear that the most widely used method is RSM because it can be applied on the limited set of experiments. Further, the analysis of variance (ANOVA) model is constructed to estimate the amount of impact of the input parameters on the outputs. However, these statistical methods hold the assumptions such as structure of a model before the problem in hand, normality of residuals, and non-correlated residual error values. 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 were the traditional ones. In addition, in most of the works, the set of input parameters having influence on the outputs are found to be different. The reason can be attributed to the use of different material in every machining operation. Therefore, more investigation is needed to observe the influence of input parameters on the environmental impacts from the machining operation. There is also a need of formulation of a generalized explicit relationship between the output parameters (power consumption, tool life, surface roughness) and the input process parameters.

Alternatively, several well-known computational intelligence (CI) methods such as genetic programming (GP), artificial neural networks, fuzzy logic and support vector regression can also be applied (Lam and Gu, 2013; Garg et al., 2015b). Among these methods, GP possesses the ability to evolve the model structure and its coefficients automatically. The most popular variant of GP used recently is multi-gene genetic programming (MGGP). Despite having a good number of applications in the manufacturing field, MGGP generates models that may not give satisfactory performance on the test data. The poor model performance on the test data is undesirable and is likely to give false information about the process (Garg et al., 2013, 2014a, 2015a). It is primarily due to two main reasons: the inappropriate formulation procedure of the MGGP model and the difficulty in model selection. Since the procedure of combination of genes in formulation of MGGP model is random, therefore, the gene of poor performance can get regressed with the other genes of higher performance and degrade the performance of model. Secondly, the difficulty in model selection is an issue since MGGP is based on evolution of models of varying accuracy. Generally, the best model is selected based on the minimum training error. By conducting few applications of MGGP (Gandomi et al., 2009; Gandomi and Alavi, 2012; Garg et al., 2014a, 2014b), it is observed that this best model may not perform best on the testing data. There are other models in the population that perform better than the best model with a little compromise on training error. These two issues responsible for poor generalization of MGGP is a motivation for developing a framework that can evolve models which evaluate the environmental impacts from the machining operations accurately.

In the present work, an ensemble-based-MGGP (EN-MGGP) framework is proposed in formulating the models for estimating power consumption, tool life and surface roughness. Formulation of problem of modelling the power consumption and product quality is shown in Fig. 1. Experiments on turning conducted under operating conditions are referred from the previous studies. The proposed EN-MGGP approach is applied on the data obtained from the experiments and its performance is compared to those of the standardized MGGP approach. Furthermore, the proposed model is validated via. sensitivity and parametric analysis by unveiling dominant input variables and the hidden non-linear relationships.

2. Experimental details of two turning processes

In this section, the two turning operations are referred from an earlier study conducted by Kant and Sangwan (2014) and Bhushan (2013) on evaluating the two sets of outputs (surface roughness and power consumption, tool life and power consumption) respectively. The materials used in the experiment and set-up details of each are given in the following subsections.

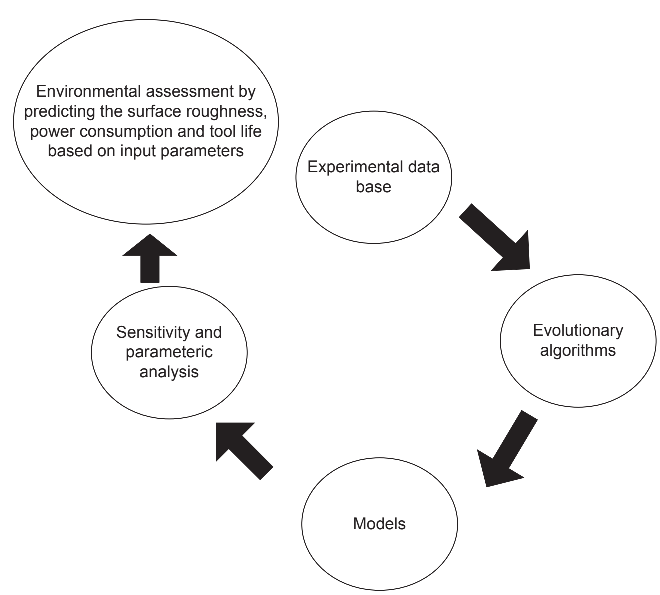

Fig. 1. Study of environmental impacts using the models formulated by evolutionary algorithms.