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Design of robust energy consumption model for manufacturing process considering uncertainties

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ABSTRACT

In view of environment degradation, sustainable manufacturing has become a major focus in the production industry. Energy consumption is one of the key factor in sustainable manufacturing and also responsible for an increase in production cost. It is found that machining parameters have a considerable influence on both energy consumption and product quality. One way to optimize the energy consumption is to establish the relationship between the machining parameters. Thus, developing robust and accurate energy consumption models for manufacturing process is an urgent need to ease negative environmental impacts. In this context, an evolutionary approach of Gene Expression Programming considering uncertainties is proposed. Two case studies are carried out to validate the effectiveness of proposed approach. Uncertainties during the modeling process are considered and handled with a designed set of experiments. Experiments are further performed to validate the robustness of the models. Further, 2D and 3D plots are employed to analyze the relationship between the given machining parameters. Optimization of the designed models is then carried out to determine the optimum set of inputs that minimizes the energy consumption.

1. Introduction

1.1. Background and motivations

Sustainable manufacturing is paid special attention from the production industry due to the deterioration of the environment and shortage of resources. Energy consumption plays a vital role in sustainable production whose levels are closely related to the environmental impact of manufacturing (Kara and Li, 2011). Moreover, energy is a fundamental resource for any kind of production activity, not to mention that the production industry contributed a total of 31% energy consumption over the world (EIA, 2011). On the other hand, energy consumption also yells a considerable part of production cost. In context of energy saving, great efforts have been put on both electricity distribution such as smart grids development (Amini et al., 2013) and demand side management where technics are employed to reduce energy consumptions (Palensky and Dietrich, 2011). In order to reduce the production energy costs, a robust and accurate energy consumption model is essential (Peng and Xu, 2014) so that a wide range of optimization methods can be used to fine tune the machining parameters in the model to achieve an optimum balance between production efficiency and energy cost. To achieve this, it is vital to find a reliable modeling approach which performs well in terms of efficiency and generality.

The methodologies used for energy consumption modeling are mainly focused on machining theory, empirical formulas, simulation and Artificial Neural Network (ANN). Bayoumi et al. (1994) formulated an energy consumption model in metal cutting based on a closed form mechanistic force model for milling operations. Li and Kara (2011) developed an empirical model for turning operation through power measurements under various cutting conditions. Lu et al. (2016) established a multi-objective multi-pass turning operation model considering both energy consumption and machining quality and applied multi-objective metaheuristics for optimization. Guo et al. (2015) proposed an operation-mode based method for energy consumption prediction of machining processes by performing simulation on material removal mechanism. Kant and Sangwan (2015) developed a face milling energy

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consumption model by utilizing ANN technique and identified the processing time as the main impact factor in milling process. A detailed review of energy consumption modeling can be found in (Zhou et al., 2016). However, interpretable models such as those based on the machining theory lacks accuracy while ANN provides a relative precise and accurate model in a form of black box. The finite element models based on simulation are time consuming and computational intensive. This motivated us to look for a methodology which is capable of developing models having good precision and interpretability.

Gene Expression Programming (GEP) is an evolutionary approach introduced by Ferreira (2002) and has been successfully applied for modeling of manufacturing processes. Yang et al. (2013) used GEP for cutting force prediction in face milling. A collaborative evaluation modeling method is employed to evaluate the performance of the obtained model in actual productions. In (Kök et al., 2011), GEP is applied to model the surface roughness of abrasive water jet machining. Experimental results show that the GEP model is in good agreement with actual observations. Yang et al. (2016) proposed a variant of GEP and applied it to model the energy consumption of the milling process. The vital input factors during the milling process are also analyzed.

Similarly, Genetic Programming (GP), from where GEP is derived, has also been applied in manufacturing modeling. Göloğlu and Arslan, (2009) used GP for surface roughness prediction in zigzag milling process and compared the GP models with ANN models in terms of accuracy. Milfelner et al. (2005) applied GP in cutting force modeling of milling process and achieved an approximately accuracy of 96.5%. In context of energy conservation, Garg et al. (2015) proposed an energy consumption modeling approach based on GP. In this study, orthogonal basis functions are introduced for model complexity evaluation which has significant influence on the performance of the algorithm. Statistics analysis shows that the accuracy of prediction models can be enhanced by considering model complexity in the objective functions of GP. It is found from the review that the uncertainties occurred during the modeling process are ignored. The settings of the GEP algorithm affect the performance of the modeling process which can be regarded as uncertainties and should be further explored.

1.2. Objectives

Face milling and drilling operations are common process frequently used in manufacturing industry. To achieve the goal of sustainable manufacturing, the energy utilization level of these processes should be improved via a reliable and precise model in terms of machining parameters and energy consumption. This study aims to perform modeling and optimization of machining processes to achieve sustainable manufacturing for energy conservation (energy consumption minimization). In this study, GEP will be adopted to formulate the energy consumption models and applied on two case studies on sustainable manufacturing. In the first case study, the main objective is to minimize the energy consumption of face milling process involving machining parameters such as the cutting speed, the depth of cut and the feed rate. To optimize the energy consumption, the traditional trial-and-error procedure may be too costly in some cases (Charoen et al., 2017) and thus makes it more preferable to formulate a robust and precise mathematical model. In this circumstance, the evolutionary approach of GEP is employed to formulate energy consumption model and the 2D and 3D surface analyses are then applied to give in-depth understanding of how machining parameters have impact on the energy efficiency. For the drilling process, temperature, feed and rotational velocity are considered as the inputs to model the mechanical strength and drilling time. Energy consumption is evaluated indirectly through study of individual factors such as the mechanical strength and operation time. The optimum parameters can be then obtained to minimize the operation time while ensure a satisfactory mechanical strength of the work piece.

In actual practice, there exist a few uncertainties in applying GEP. Three main factors, head size, number of generations and selection of objective function are considered as the uncertainties, which have noticeable effect on the performance of algorithm. In order to distinguish how these factors influence the models generated by GEP, multiple comparisons are made with different level of variations. This test shall guide us to tune the algorithm and reduce the uncertainties, thereby, achieving a robust and precise mathematic model. Finally, the best models obtained by GEP can be optimized using various existing optimization methods.

Hence, the present work aims to explore the ability of GEP in robust modeling for energy consumption of two manufacturing processes taking the uncertainties into account. Two widely used manufacturing (machining) processes, namely face milling and drilling, are studied to validate proposed methodology. A brief description of problems being considered is shown in Fig. 1.

The contributions of this paper may be reflected in energy consumption modeling and experimental analysis through case studies.

- A modeling scheme based on evolutionary approach of Gene Expression Programming, which takes uncertainties into account is proposed. Unlike the existing theoretical models, models generated by GEP are explicit, accurate and do not require any pre-assumption of their forms.
- Uncertainties during the modeling process are analyzed based on case studies of two widely used machining processes. Different settings of parameters are compared individually and tuned for generation of models with better performance.
- Step-by-step experimental studies are carried out to verify the effectiveness of proposed modeling approach. The best models are chosen and further analyzed in terms of performance and validity. The models are then optimized to determine the best parameter settings of the two machining processes that minimize the energy consumption and improve the energy efficiency.

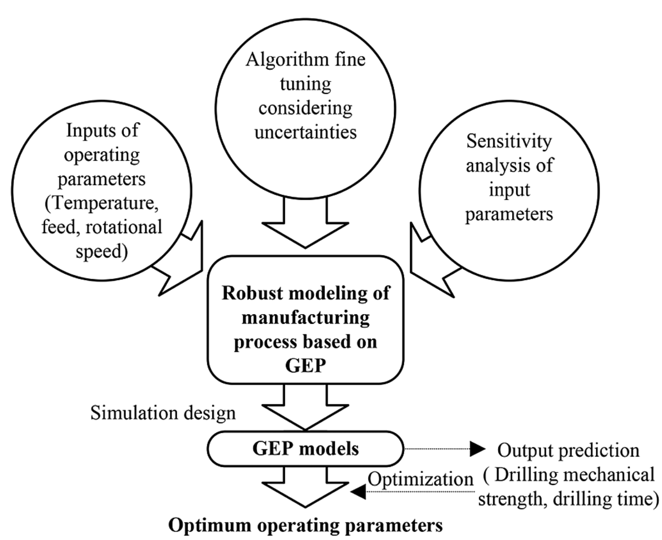

Fig. 1. Illustration of research problems undertaken.