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Simulation-based model for the optimization of machining parameters in a metal-cutting operation

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ABSTRACT

To achieve a certain measurable performance in cutting machines, the machine parameters need to be optimized. Several constraints determine the possible values that these parameters can take. Although parameters are usually assumed to be deterministic, in practice, it is common to find variations on the characteristics of the products or the processes. Modeling machining parameters as stochastic factors provides a more realistic representation of cutting operations. Moreover, multiple operational objectives are of interest, in many real situations, these multiple objectives are conflicting. Consequently, the problem of setting the parameters becomes a trade-off situation. This paper presents a novel Simulation-based Multi-Objective Optimization (SimMOpt) solution procedure. The procedure is divided into two phases: (1) finding initial solutions and, (2) using a simulated annealing-based method for finding neighboring solutions. In the first phase, non-linear goal programming is used for finding high quality initial solutions. The second phase incorporates Pareto Archive Evolution Strategy (PAES) and hypotheses testing for searching near-optimal solutions for a set of stochastic parameters (i.e., cutting speed, feed rate, and depth of cut) in metal cutting operations. Three objectives are optimized (i.e., operation time, operation cost, and quality of the product). The results from implementing this procedure are analyzed and compared to a baseline methodology based on the Multi-Objective Simulated Annealing (MOSA) algorithm. The analysis demonstrates that the proposed method outperforms the Genetic Algorithm (GA), which was the benchmark algorithm, in terms of the solution quality of all the objectives. More importantly, the solutions from using the SimMOpt procedure outperform those obtained from using an enhanced MOSA-based approach (i.e., 4.71% improvement in the hypervolume approximation).

1. Introduction

In a Flexible Manufacturing System (FMS), the Computerized Numerical Controlled (CNC) machining system is used to control the individual machine tools. At the workstation control, the parameters are defined so the quality of the product is ensured at a minimum cost [1].

Measurable responses, such as quality characteristics, costs per unit, cycle times, among others are subject to variations for specific values of the parameters. Several methods have been developed to determine these values while ignoring these variations. Hence, the main contribution of the present work is to develop a Simulation-based Multi-Objective Optimization

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(SimMOpt) method that considers the stochastic behavior of the factors that intervene in the setting of machining parameters.

Particularly, this work extends the problem of setting the parameters of a machining operation studied by Cus et al. [2]. The formulation of the problem is extended by adding two key aspects: (1) the stochastic nature of the operating conditions and (2) the optimization of multiple objectives (e.g., operation time, operation cost, and quality of the product).

The plausibility of the proposed SimMOpt method is evaluated by using a case study and comparing our results to (1) results previously obtained from solving a deterministic problem using the Genetic Algorithm (GA) presented by Cus et al. [2], and (2) results obtained from solving a problem with low variation on the values of some parameters using the MOSA-based approach presented by Chavez and Castillo-Villar [3]. It is worth mentioning that the simulated annealing metaheuristic has successfully been used for setting parameters of equipment [4,6]. The quality of the solutions is assessed by comparing the results from the SimOpt when solving the stochastic case study considering large variation of the values of the parameters with the results from the MOSA-based approach [3].

This paper is structured as follows: Section 2 presents a literature review on (a) models for setting the parameters of machining equipment, (b) multi-objective optimization methods, and (c) simulation optimization methods. Section 3 shows the mathematical formulation of the problem. Section 4 presents the proposed SimMOpt model and discusses some of its most important characteristics. Section 5 describes the case study and provides the nominal values of the parameters. The levels of the SA schedules considered during the experimentation stage are also described in Appendix A. Section 6 considers the low deviation version of the problem to verify the plausibility of the solutions found by using the SimMOpt method. Section 7 presents the results for the problem with large variation from the nominal values on the parameters included in the formulation. Section 8 and 9 discuss the quality of the set of non-dominated solutions and future algorithmic improvements to reduce the computational cost.

1.1. Main contributions of the SimMOpt to the optimal setting of the parameter of a machine

The proposed SimMopt provides a novel method for finding near-optimal solutions to the problem of setting the machining parameters with the following characteristics in its formulation:

- Multiple competing objective functions.
- The coefficients that are used to model the parameters of the system follow continuous probability distributions that represent the realistic stochastic behavior of the real system.
- The objective functions are modeled by using *non-linear equations*.
- The constraints include non-linear inequalities.

2. Literature review

Fig. 1 describes the limitations and strengths of the models and methods that belong to the groups further discussed in Sections 2.1, 2.2, and 2.3. It also presents some techniques used by each group to overcome some specific limitations. Table 1 shows some of the classifications mentioned in Fig. 1 and how specific modeling techniques fall into different categories depending on the classification approach.

The SimMOpt method is proposed for finding a set of solutions to competing objective functions in complex systems. This method is based on replicated evaluations of the equations that model the objectives and uses the Simulated Annealing (SA) metaheuristic to search near-optimal values for the decision variables. From Table 1, it can be concluded that the proposed method for setting the parameter of a machine can be classified as non-conventional simulation-based method that uses a modern metaheuristic technique (i.e., SA) (refer to cells containing “X” in Table 1). Section 2.4 discusses some important features to be considered when using SA while modeling the stochastic behavior on some elements of the system.

2.1. Models for setting the parameters of machining equipment

This section discusses some of the recent research work intended to model the parameter setting of machining equipment. Yusup et al. [4] enlisted 41 papers that proposed techniques based on GA, 11 on SA, 25 on PSO, 5 on ABC Optimization, and 3 on ACO. The implementation of modern techniques such as ABC to solve the problem of setting the parameters of machining equipment started in 2009 [4]. Yusup et al. [4] concluded these optimization techniques were mostly used for solving problems involving specific equipment: (1) ABC for modern machining such as wire electrical discharge machine (WEDM), and electrochemical machining (ECM), (2) GA and PSO for multi-pass turning, (3) SA for end milling and abrasive waterjet (AWJ), and (4) ACO for end milling, turning and multipass turning. The authors also concluded that the most common performance indicators considered in research are: surface roughness, machining/production cost, and material removal rate (MRR). This paper considers surface roughness, production time and production cost.

It can become difficult for the practitioner to select the appropriate optimization technique for a particular metal cutting process given the characteristics of the process and cutting conditions. Mukherjee and Ray [5] provide a generic framework for process parameter optimization in metal cutting process problems. The framework is presented in two categories: (1) process input-output and in-process parameter relationship modeling, and (2) determination of optimal or near optimal