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# A novel two-stage optimization approach to machining process selection using error equivalence method

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ABSTRACT

The selection of a machining process involves the choice of machine tools, fixture elements, and fixture locator layout, as well as the allocation of tolerance in each operation. In practice, manufacturers frequently choose identical machine tools and fixture elements for each operation to reduce purchase cost. As such, fixture layout and tolerance allocation are critical in selecting or designing appropriate manufacturing processes. Conventional research deals with robust fixture layout design and simultaneous tolerance allocation for multiple types of error source separately. However, fixture layout design could also affect tolerance stackup caused by multiple error (not only the fixture error) sources. Therefore, considering the interaction between fixture layout and other types of error source is critical in the process selection to improve the process selection strategy. In this paper, a two-stage framework is proposed to optimize the process selection based on our previously developed error equivalence model, which transforms multiple errors into equivalent errors that occur on a fixture. In the first stage, a process is selected by determining the allowable tolerance for an aggregated base error given a fixture layout. In the second stage, a computer experiment model is established to search for the globally optimal fixture layout by exploring a large number of fixture layout alternatives. A real-world case study based on a two-operation machining process demonstrated the effectiveness of the proposed strategy in controlling manufacturing cost while ensuring product quality via proper fixture layout design.

## 1. Introduction

Machining process selection involves choosing machine tools, fixture elements, and fixture locator layout, as well as allocating tolerance for multiple tools in each manufacturing operation. Given that manufacturers frequently select identical machine tools and fixture elements to obtain increased discounts from vendors, the process selection can be simplified into two problems, namely, fixture layout and process tolerance design.

Fixture layout design involves the automated generation of a robust fixture layout that reduces the influence of fixture variation on product quality. The early approaches to fixture layout design are deterministic [1] because they do not consider fixture variations, such as those caused by worn or loose locating pins. Recent research on fixture layout design investigates the robustness of fixtures [2–4] with optimization aiming to minimize the sensitivity of the fixture layout. The optimal fixture layout design for multi-operation assembly processes was investigated by Kim et al. [5]. A fixture layout design for a machining process was developed by Huang and Shi [6] by using a 2D case study. Fixture layout optimization was also addressed by using metaheuristics, such as evolutionary techniques [7] and augmented ant colony algorithm [8]. These studies on fixture layout design mostly focused on kinematic analysis to reduce potential quality problems induced by fixture errors (e.g., clamping and locator inaccuracies).

Process tolerance design involves estimating tolerance stackup and allocating tolerances corresponding to multiple error sources to ensure quality or robustness at reasonable manufacturing cost. In this line of research, the focus is on the simultaneous optimization of assigning candidate processes to operations or parts, allocating process or product tolerances, and/or designing process parameters. Nagarwala et al. [9] solved the tolerance design problem in process selection by using a slope-based approach, which exhibits high computational efficiency.

*Abbreviations:* EFE, Equivalent fixture errors; NP, Non-deterministic Polynomial; FDM, Fused deposition modeling; CAD, Computer Aided Design; LH, Latin Hypercube; RMSE, Root-mean-square error; MSE, Mean square error

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**Nomenclature**

| | |
|---|---|
| $\sigma_\gamma$ | Standard deviation of cutter path orientation |
| $\sigma_\theta$ | Standard deviation of part orientation due to fixture error |
| $\mathbf{x}_i$ | Error source $i$ |
| $\mathbf{s}_i$ | The $i$th candidate layout in the explored design space for LH sampling in computer experiments |
| $\mathbf{w}$ | The fixture layout in the unexplored design space |
| $\mathbf{w}^*$ | The globally optimal fixture layout |
| $\mathbf{K}_i$ | Transformation matrix in EFE. |
| $\mathbf{\Gamma}_j$ | Mapping matrix that reflects the impact of process errors on the jth quality feature (also called a sensitivity matrix) |
| $\mathbf{y}_j$ | The $j$th quality feature deviation |
| $\mathbf{u}(k)$ | The aggregated process error at the $k$th operation |
| $\varepsilon(k)$ | Noise term at the $k$th operation |
| $\mathbf{I}$ | Identity diagonal matrix |
| $\Sigma_{\mathrm{u}(k)}$ | Covariance matrix for the process error $\mathbf{u}(k)$ |
| $\Sigma_{\mathrm{y}_j(k)}$ | Covariance matrix for the deviation of feature $j$ |
| $\mathbf{\Theta}$ | A vector of the process errors for tolerance allocation |
| $\boldsymbol{\sigma}\Theta$ | The standard deviations of process errors $\mathbf{\Theta}$ (process tolerance) |
| $\mathbf{C}^T$ | The coefficient matrix |
| $\mathbf{c}$ | A row vector in matrix $\mathbf{C}$ with the highest dimension to compute overall cost |
| $\mathbf{b}_1$ | The upper bound of the variation components of surfaces or dimensions |
| $\mathbf{b}_2$ | The upper bound of tooling variations |
| $\mathbf{F}^c$ | The reaction force between the workpiece and the fixture locator |
| $\mathbf{f}_i$ | The positions of the fixture locators |
| $\mathrm{Y}(\mathbf{w})$ | The response given the input $\mathbf{w}$ |
| $Z(\cdot)$ | Zero-mean Gaussian |
| $R(\cdot,\cdot)$ | Correlation function between the responses |
| $D$ | The number of the design variables |
| $\mathbf{Y}_j$ | The quality features $j$ |

Qin et al. [10] proposed a unified point-by-point planning algorithm for machining fixture layout by considering practical degrees of freedom and determining the location of the locating pins. A tolerance design approach based on the Shapley value method was developed by considering the demands of manufacturing cost and product quality [11]. Other approaches developed for process selection considering tolerance design include functional group approach [12], exhaustive search methods [13,14], simulated annealing [15], genetic algorithms [16], and artificial intelligence techniques [17]. Optimization problems in previous studies target a certain manufacturing cost as their sole objective function. Wang and Liang [18] developed a dual-objective optimization approach to simultaneously assigning processes to operations, determining machining parameters, and designing product dimensional tolerances. Andolfatto et al. [19] proposed to allocate geometrical tolerances by solving a multi-objective optimization problem, aiming to minimize the cost and the nonconformity of the assembly plan. Comprehensive reviews of the tolerancing strategy for process selection were also conducted [20,21].

Most studies on process selection separately investigate the problems of fixture layout optimization and process tolerance design, and do not directly consider the influence of the fixture layout on the allocation of tolerance for multiple error sources. For example, tolerance allocation is optimized in a fixed fixture layout only. Such studies are only reasonable when multiple error sources are independent of each other.

This study provides additional insights into process selection by considering the interactions between the fixture layout and the tolerance allocation for non-fixture errors. The significance of such interactions is illustrated in Fig. 1, in which a 2D prismatic part is installed on a fixture and milled on the top surface. For simplicity of illustration, we assume that the machine tool error occurs rotating around the $z$ direction (denoted by angle $\gamma$). In fixture layout 1 (Layout 1 in Fig. 1[a]), in which two locating pins are close to each other, the variation in the top surface is more sensitive to the fixture error. Thus, a tight tolerance ($\sigma_{\gamma 1}$) for the machine tool error is required to ensure product tolerance (i.e., thickness). By contrast, only a loose tolerance ($\sigma_{\gamma 2}$) is necessary for the machine tool error in fixture layout 2 (Layout2 in Fig. 1[b]) because the influence of the fixture error on the surface variation is small. Process selection can be improved by considering the mechanism by which the fixture layout affects the tolerance allocation for multiple error sources. Therefore, properly identifying the link between fixture errors and other types of error sources is important for tolerance stackup modeling.

Only limited research has been conducted on the joint optimization of fixture layout and tolerance design. For instance, Li [22] implemented a dual-objective optimization problem to obtain a robust fixture layout while minimizing the cost associated with the tolerances caused by fixture errors. A study on tolerance synthesis showed that fixture layout might have a significant influence on tolerance stackup because of the fixture, machine tool, and datum errors [6]. In the said study [6], a two-step optimization procedure was proposed, and a sensitivity analysis was conducted by using a 2D example; however, the fixture layout was not optimized.

Through a review of the literature, the following research gaps are identified:

- Studies on the relationship between the problems of fixture layout and process tolerance allocation are few. As mentioned, the fixture layout significantly affects the process tolerance allocation. However, prior research studied the two problems separately. For example, tolerance allocation was optimized in a fixed fixture layout only. Thus, the potential to improve the optimization process further is missing.
- A comprehensive understanding of how different types of process error interact to affect the process tolerance allocation problem is lacking. Prior research deals with the tolerance allocation for multiple types of process errors, such as machine tool, fixture, and datum errors, independently without considering their interaction effects on the process selection problem.

This paper is the first to provide insights into the relationship between the two problems based on an error equivalence model and present a method for jointly optimizing process tolerance and fixture layout design for process selection. Considering an error equivalence mechanism by which multiple types of error source result in identical

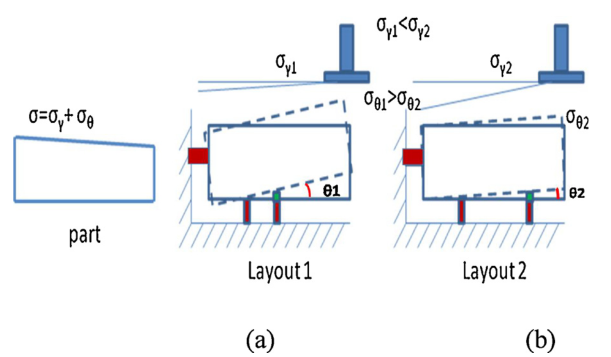


**Fig. 1.** Impact of fixture layout on tolerance allocation for a machine tool.