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Technical paper

Optimal determination of the process means, process tolerances, and resetting cycle for process planning under process shifting

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ABSTRACT

A proper process planning can significantly improve a producer's competitiveness in regard to delivering high-quality and low-cost products with short development-cycle time. Because of process shifting, the produced quality may change during a production run and lead to early product failures. Hence, to compensate for such process shifting, there is a need to determine the optimal resetting cycle before the next setup as well as the initial settings at the beginning of a production run. As the process tolerance is one of the key elements in the production process, determination of the process tolerance must also be considered. Due to the interdependence among decision variables, a model for process planning is proposed to simultaneously determine the initial setting, process tolerance, and resetting cycle, so that the average total cost, in a period of resetting cycle, which includes the setup cost, quality loss, failure cost and tolerance cost, is minimized under process-capability limits, functionality requirements, and conforming rate restrictions.

1. Introduction

A certain amount of variation will exist in any production process, regardless of how well it is designed or how carefully it is maintained. This variation is the cumulative effect of many essentially avoidable or unavoidable causes [1]. The variation in quality characteristics usually arises from three sources of error: improper process establishment, operator errors, or defective raw materials. The various errors from improper process establishment will result in poor, inaccurate, and defective parts, including random deviation and systematic deviation from the design target.

During the process design, parameter design determines the process setting, thereby reducing the susceptibility of unit-to-unit variation. The need for further reduction in process variation is generally considered after sensitivity to noise has been minimized. This is related to the process selection, in order to achieve a certain required process capability, namely process tolerance determination. To achieve product functionality, process engineers should specify the process tolerance at a value less than design tolerance to ensure manufacturing feasibility. Because the design tolerance exceeds the process tolerance, additional space for process distribution provides for a possible shift within the specification limits. The process mean may be set at various positions within the specification limits for further quality improvement and cost reduction.

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That is, the process mean and process tolerance are two decision variables that have to be determined simultaneously because of the dependence existing between the mean and tolerance values during process planning [2,3]. In other words, a simultaneous determination of the process mean and process tolerance for a true optimization of process planning is necessitated. However, previous research only focuses on process mean and process tolerance determination under the situation that process shifting does not exist during the production process.

It is possible that a shifting process may occur during the production process. For example, in metal cutting operations, the machining tool is subject to both wear and random shocks. If modification for process shifting is not made during a production run, the risk of product failure increases and the quality of product performance decreases, resulting in a large proportion of nonconforming items [4–8]. For modification, the process mean is adjusted to an initial setting with additional setup cost to compensate for the process shifting over the resetting cycle. In regard to the shifting process, Jeang et al. also developed a time-based tolerance design model that considers component deterioration due to wear, when designing the product's life application [9]. However, the relevant previous works mainly focused on finding the optimal process mean and process tolerance independently with the optimal use time (production run length) for a deteriorating process. As pointed out in the above discussion, a simultaneous determination of the process mean and process tolerance is required for true process optimization. In these regards, Jeang further developed a concurrent optimization of a time-based parameter and tolerance design for an assembly [8]. Thus, there is a motivation to extend

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a time-based parameter and tolerance design for an assembly to a time-based parameter and tolerance design for process planning in this study.

The loss function is an expression which estimates the cost of quality value versus target value and the variation in product characteristics in terms of monetary loss due to product failure in the view of the consumer [10,11]. Quality-related production costs usually increase as the value of the process tolerance becomes tighter, due to the need for more refined and precise operations as the output ranges are reduced. Generally, a low quality loss (good quality) implies a high quality-related production cost (tight tolerance) and a high quality loss (poor quality) indicates a low quality-related production cost (loose tolerance) [12]. Other than quality loss and tolerance cost, there is a possibility that failure costs may occur when the quality values fall outside the specification limits.

In addition, due to process shifting, the process mean is reset at the end of the resetting cycle with a given setup cost, which may influence the appropriate tolerance value being selected. Hence, the quantitative analysis model should minimize the average total cost, for the period of the resetting cycle, and contain the setup cost, quality loss, failure cost, and tolerance cost, with the initial setting, process tolerance, and resetting cycle to be simultaneously determined for further quality improvement and cost reduction.

This paper is written in eight sections. Section 1 is the introduction; Sections 2–5 describe the related background information employed for reference in this research; Section 6 presents the model development; Section 7 provides an application; and a summary is given in Section 8. Appendix A proves the dependence between process mean and process tolerance. Appendix B presents the formulation of conforming rate requirements.

2. Design target, design tolerance, process mean and process tolerance

The primary objective of quality engineering efforts is the systematic reduction of variation in product-quality values. At the product-design stage, the design of each parameter and its tolerance determines the best values of the design target and design tolerance, respectively, so that the non-conforming rate or the variation of the product-quality value is reduced to a minimum. Then, at the process-design stage, process engineers should specify the process mean and the process tolerance with reference to the design target and the design tolerance obtained at the product-design stage so that production feasibility can be guaranteed. If the design tolerance is smaller than the process tolerance, no functional product can be produced in the production process, i.e. the manufacturer should aim for a high process capability with a small process tolerance; this always results in a high production cost. However, if the design tolerance exceeds the process tolerance, additional space for the process distribution allows for flexibility within the design tolerance. This flexibility is necessary as the process mean changes due to process shifting or component deterioration and it permits adjustment of the process mean to improve product quality, reduce costs, and increase endurance. Eventually, longer process times with reliable product performance can be achieved with the least amount of quality loss, failure cost and tolerance cost. Therefore, a functional relationship is provided mathematically in Eq. (1), to link the design target T, design tolerances S_1 and S_2, process mean U, and process tolerance t [3]:

$$T - S_1 + t \leq U \leq T + S_2 - t. \tag{1}$$

In this paper, $T - S_1$ and $T + S_2$ are called the lower and the upper specification limit, respectively. As a decision variable, the process tolerance t is constrained by the process capability, which depends on the available tools, methods, and the techniques applied in a given production environment. The benefits of the above-presented mathematical link for product and process design are (i) revealing manufacturability for all feasible combinations of design target, design tolerance, process mean, and process tolerance; (ii) increasing selection flexibility of the design target, design tolerance, process mean, and process tolerance; and (iii) reducing the amount of precision required to control the process, thus obtaining lower costs with higher quality.

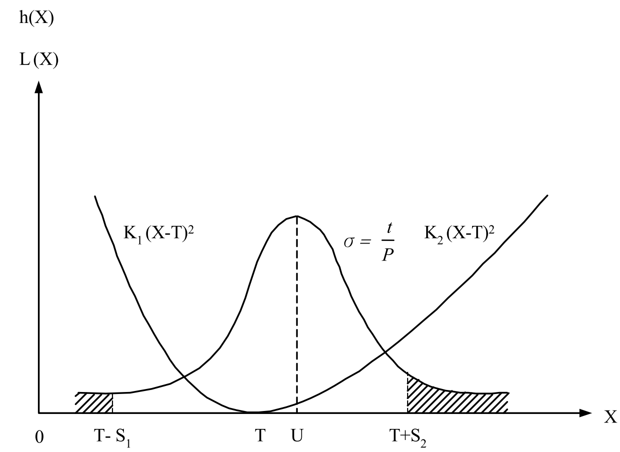

Fig. 1. Relationship between the design target T, design tolerances S_1 and S_2, process mean U, and process tolerance t.

3. Quality loss, failure cost and tolerance cost

Quality loss is an expression that represents the difference between the process mean and the design target and the variation of product-quality value in terms of economic loss due to product failure in the eyes of a consumer. The main quality loss functions include the nominal-the-best, the smaller-the-better, the larger-the-better and the asymmetric loss function [10,11].

In this paper, the asymmetric loss function is applied. The quality loss experienced by consumers varies in both directions around the design target, i.e. quality loss resulting from the deviation of product-quality value in one direction is unequal to the quality loss resulting from deviation in the opposite direction. In this case, the quality loss coefficient values K_1 and K_2 have to be allocated for the two directions of the design target. Thus, the loss function $L(X)$, given in Fig. 1, can be represented as

$$L(X) = \begin{cases} K_2(X - T)^2 X & X \geq T \\ K_1(X - T)^2 X & X < T \end{cases} \tag{2}$$

where X is the product-quality value and T is the design target.

Due to design aspects, the product-quality value may vary between the upper and lower specification limits of the functional performance as well as the quality requirement. For example, the thermal cracking of a product may result from a faulty assignment of the specification limits. This problem occurs because the two assembled components are made from different materials with disparate thermal expansion coefficients. The unbalanced expansion is usually more harmful to a product's performance as one component expands in one direction than the other in another. In this regard, we have assigned specification limits: the lower specification limit is $T - S_1$, and the upper specification limit is $T + S_2$. The quality value of a product within specification limits will be accepted by consumers, but when product-quality value does not meet specification limits, the product is deemed unfit and should be rejected, to be either repaired or discarded. If the product-quality value falls below $T - S_1$, failure cost C_1 will incur. On the other hand, if the