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Integrating the continuous improvement of measurement systems into the statistical quality control of manufacturing processes: A novel link

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ABSTRACT

Reliability in measurements is a requirement for quality-oriented organisations. A novel link is presented in this work for the integration of the continuous improvement loop of measurement systems into the statistical quality control of manufacturing processes. The proposal is based on the Index of Contamination of the Capability (*ICC*) and the Golden Rule of Metrology. It is expressed through clear-cut decision rules that consider the uncertainty of measurement, the intended use of the measurements and the risk of inaccurate measurements. The proposal makes it possible to improve production quality. To facilitate its application, an equivalent graphical approach is provided.

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1. Introduction

Reliability in measurements is a necessary requirement for all quality-oriented organisations looking to efficiently control manufacturing processes. In fact, Six Sigma methodology, which is one of the most important methodologies for controlling and improving process and product quality, considers the assessment of measurement systems as one of its main objectives for success.

Metrology should be understood as an integral part of the production process that must be optimised as a whole [1]. The international standard ISO 10012:2003 [2], which guides the implementation of measurement management systems, is useful for the control and the improvement of measurement activities and of product quality as well as for meeting metrological requirements. To integrate the continuous improvement loop of measurement systems that is consistent with such a standard into the statistical quality control of manufacturing processes, a novel link is proposed in the present work. Among the main novelties introduced in this paper, the following are indicated: the new link is based on a combined application of the *ICC* (Index of Contamination of the Capability) parameter [3] and the Golden Rule of Metrology [4]; the proposal provides clear-cut decision rules that make it possible to improve production quality; to make the implementation of this novel link easier, an equivalent graphical approach is established. The proposal considers the intended use of the measurements, among other characteristics. In particular, manufacturing process capability determination is considered as the final end of performed measurements. This represents a fundamental activity in programs for process quality improvement, such as the Six Sigma methodology mentioned above, and thus, the proposal in this paper is of great practical interest to manufacturing industries. Furthermore, the decision rules provided take into account the measuring equipment metrological characteristics — the uncertainty of measurement [5] in concrete — when assessing the quality of manufacturing processes, as suggested by previous research [6].

2. Background

2.1. Previous works

The clear-cut decision rules of the novel approach are formulated in terms of the *ICC* parameter, which considers the effect of measurement uncertainty on the assessment of the production process capability. This effect has been researched by some authors in recent years. Mittag detected that systematic and random measurement errors can substantially affect the evaluation of process capability indices [7]. Donatelli et al. [8] developed equations by simulation, with one for each analysed process capability index, which makes it possible to estimate the worst capability values that are consistent with given measurement conditions. The research of Weckenmann and Rinnagl [6] pioneered the consideration of the measurement errors present within global and international metrological parameters, using the uncertainty of measurement [9]. The authors proposed a graphical method to eliminate the influence of the measurement system in the evaluation of the process capability index C_p. Bordignon and Scagliarini [10] studied the statistical properties of the estimators of the capability indices C_p and C_{pk}, and Scagliarini [11] examined the case of autocorrelated data. Baldo and Donatelli [12] showed through simulations that the measurement effect on C_p and C_{pk} can be more important than the sample size effect in many cases, considering the uncertainty values accepted in industry. From all of these studies, it is possible to conclude that measurement uncertainty can considerably affect the results of a process

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capability assessment. Therefore, the measurement uncertainty cannot be neglected when evaluating manufacturing process capability and establishing decisions about the process and the product, especially in areas such as coordinate metrology, because there are numerous influencing factors that can affect the measurement results [13].

2.2. Continuous improvement loop of measurement systems

The loop of three phases in Fig. 1 can be conceived based on the ISO 10012:2003 standard [2]. The activities included in these phases are involved in the statistical assurance of measurement systems, which is needed to achieve the continuous improvement of such systems as well as of the manufacturing processes that they measure. This continuous improvement loop works as follows. The metrological confirmation process (phase 1) ensures that the metrological characteristics of the measurement system meet the metrological requirements of the measurement process. To this end, it is necessary to evaluate the uncertainty of measurement [9]. Once the measurement equipment is confirmed for a given measurement process that is used to ensure the quality of a manufacturing process, the measurement uncertainty ensures the reliability of the measurement results. Then, measurements are obtained, and due to the overlap of the measurement and manufacturing processes, an analysis of the measurement system capability is needed (phase 2). Risk analysis and gauge repeatability and reproducibility studies [14] are typical tools used for this aim. Performing measurement system monitoring (phase 3) is also important to ensure its effectiveness and continuous improvement. The activities of this phase are the post-process indicators for metrological confirmation and control charts for repeated measurements on the same unit to determine the stability of the measurement system [15]. Measurement system analysis often provides useful information to improve the quality of measurement uncertainty estimation. Furthermore, these studies must be performed each time the manufacturing process improves (decreases its variation) because a capable measurement system could stop being capable. Then, both estimation processes are reappraised periodically and fed back to the system, promoting the continuous improvement of the measurement system.

3. Integrating measurements and statistical quality control of manufacturing processes

3.1. Presentation of the ICC parameter

In the statistical quality control of manufacturing processes, the production process capability is described through the capability indices C_p and C_{pk}. To take into account measurement uncertainty when evaluating manufacturing process capability and establishing decisions on the process and the product, Villeta [3] has proposed the *ICC* parameter. The error model of Eq. (1):

$$Y = X + \varepsilon \tag{1}$$

was assumed, where *Y* is the observed result of a measurement, *X* is the true value of a product quality characteristic, ε is the error due to the measurement inaccuracy, and *X* and ε are independent and normal $N(\mu, \sigma_P^2)$ and $N(0, \sigma_M^2)$, respectively. From this model — due to the superposition of the production and measurement processes, and that the coverage factor $k_{1-\alpha}$ in *U* is $z_{\alpha/2}$ due to normality hypothesis — approaches to the observed process capability (Eq. (2)) and to the capability that the process actually has (Eq. (3)) were developed considering the capability C_p:

$$\hat{C}_{p,obs} = \frac{z_{\alpha/2}\hat{C}_{p,real}}{\sqrt{z_{\alpha/2}^2 + [6(U/T)\hat{C}_{p,real}]^2}} \tag{2}$$

$$\hat{C}_{p,real} = \frac{z_{\alpha/2}\hat{C}_{p,obs}}{\sqrt{z_{\alpha/2}^2 - [6(U/T)\hat{C}_{p,obs}]^2}} \tag{3}$$

where $z_{\alpha/2}$ is the value of a standard normal distribution with a probability $\alpha/2$ on the right, *U* is the expanded uncertainty [5], and *T* represents the manufacturing tolerance (*T* = USL − LSL). Furthermore, equivalent expressions for the capability index C_{pk} were obtained. For both capability indexes C_p and C_{pk}, it is known that a capability lower than that which the production process actually has is observed due to the measurement uncertainty such that the greater the uncertainty, the greater the difference between the observed and the real capabilities. This difference is more marked for manufacturing processes with less variability. Additionally, it was shown that the uncertainty of measurement has a similar effect on both production capability indices when the error model of Eq. (1) is considered. Furthermore, the ISO standard 10012:2003 [2] suggests the establishment of indicators that show the effectiveness of measurement processes, depending on the intended use of the measurements. With these results and to quantify the contamination effect due to the uncertainty of the measurement system in process capability indices C_p and C_{pk}, the *ICC* parameter has been proposed [3]:

$$ICC = \frac{\hat{C}_{p,obs}}{\hat{C}_{p,real}} \times 100 = \frac{\hat{C}_{pk,obs}}{\hat{C}_{pk,real}} \times 100 \tag{4}$$

This equation shows that the higher the contamination effect of the measurement uncertainty on the capability of the manufacturing process, the lower the value of the *ICC* parameter. Fig. 2 illustrates the behaviour of the *ICC* parameter (α = 0.05) based on the observed capability $\hat{C}_{p,obs}$ for different uncertainty-to-tolerance (*U*/*T*) scenarios. Fig. 2 shows the decrease of the *ICC* parameter with the increase of the observed capability. This decrease is more pronounced when the *U*/*T* ratio increases. These facts can also be observed in Table 1, which presents the *ICC* parameter value obtained from concrete values of the observed process capability $\hat{C}_{p,obs}$ and values of the *U*/*T* ratio.

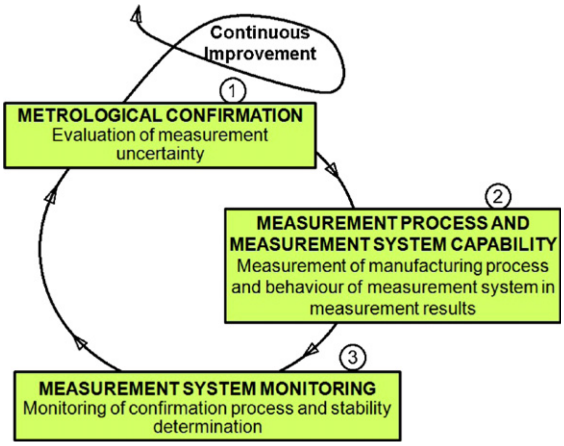

Fig. 1. Overview of the continuous improvement loop of measurement systems consistent with ISO 10012:2003.

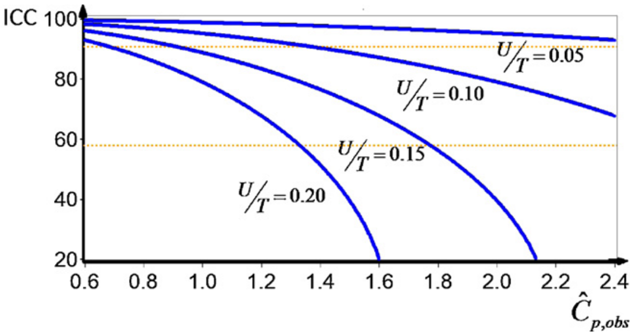

Fig. 2. Behaviour of the *ICC* parameter.

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