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Short Run Production Process Capability Analysis in Machine Production

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ABSTRACT

Statistical Process Control (SPC) is an important tool for monitoring productions processes. Process capability analysis aims to compare and find the proportion of process tolerance and process variation. Both SPC and Process capability indices are widely used within manufacturing environments. This article deals with monitoring low volume production process in bakery industry and reports the results of a statistical quality improvement programme. Calculated capability indices (Cp, Cpk) and subsequent process modification are discussed in relation to a specific short run and small mixed batch pro-duction. The purpose of the paper is to present that conventional under-standing that SPC and process capability analysis are or can be performed only on high volume processes is rebutted by applying high volume theory to a low volume production process.

KEYWORDS: Capability indices, Machining Industry, Mixed Batch Production, Process Capability, Short Run Production

I. Introduction

Capability indices are often used in industrial practice. Customers require the vendor to periodically assess process capabilities and the suppliers themselves can use the values of the indicators as a basis for designing activities to improve processes or as a measure of the effectiveness of the changes made. The results of the capability analysis can be used not only to verify the ability of the process to meet specified criteria and to estimate the risk of inappropriate products, but also, for example, when designing or modifying tolerance limits. According to [1], if the process capability is high, it is possible to reduce the cost of output control or the costs of statistical process control (SPC).

The SPC has become not only a tool for analysing quality improvement, but also a method for assessing the ability of the process to repeatedly produce quality products. The process illustrates the ability to produce products within the specifications required by the customer. Control charts are used during production to ensure the minimization of non-conforming products and histogram is used as an essential tool for assessing the data collected.

Capability indices have been developed to provide quantitative value for a process to assess their ability to produce components not only centred around the nominal value, but also to assess how many components are produced as non-compliant.

It is important to understand the assumptions that lead to a valid statistical analysis when using capability indices. Most indices assume that the process is under control, with common causes of deviations. By using control charts in designing processes, special causes can be removed that statistically minimize the probability of variations.

The purpose of this article is to identify the process capability indices for low production volumes and small mixed batches and to consider the relevance of the data thus obtained.

II. Research Problem and Objectives

Process capability analysis is one of the most common methods in the field of processing and evaluation of industrial data [2]. By analysing the capability, we determine not only whether the regulated variable exceeds the specification, but also what is the reserve against the specifications, respectively to what extent the process under review is technically relevant.

Capability analysis in short run production and in small mixed batches combines data from several production cycles into one analysis.

The goal of this phase of the research is to define process capability Cp, Cpk and process performance Pp, Ppk in short run production with mixed batches. In practice, in the production of precision stainless steel cylinders (rollers) it means knowing how many of different cylinders produced have a dimension within the specified limits or how well we manage to comply with the specifications, but also whether the mixed production itself is effective.

III. Literature Review and Theoretical Framework

In the literature various examples of the calculation of process capability indices can be found, depending on whether we evaluate only the variability of the process and its location, whether tolerance limits are set, whether the target value is in the middle or whether we can assume a normal distribution of the monitored characteristics [1]. To have a good validity of calculated variable, data collection must be correctly performed. It is also necessary to provide a sufficient number of measured values for assessment of normality and so for estimation a standard deviation describing the inherent fluctuation of the process. Important is the length of the production process tracking period in which we evaluate the behaviour of the process.

Bakery industry and precise machining: In the bakery industry, production lines and equipment are based on customer specifications, which need to be addressed flexibly, tailor-made and adaptable to any type of requirement. The bakery equipment itself is based on dough sheeting function. Thanks to sheeting the dough it is possible to shape it into multiple shapes and species. A joint sheet of dough is produced first to get its resulting shape during line operation. This is possible through different types of units that use moulding methods such as cutting, rolling, tilting or bending the baking dough. The production of such equipment is a precision engineering that meets strict standards for the manufacture of equipment used in the food industry. Components that come in direct contact with the dough are made of stainless steel, often with specific surface treatment, and food grade plastic parts intended for the food industry.

Process capability analysis: Research in the field of short run production and small mixed batches was in the past focused mainly on products, less focused on processes and hence the implementation of SPC and the process capability mainly concerned product control. In literary sources and professional practice, by the end of the last century, mostly terms like "piece production" and "small batch production" were used, which were characterized by the number of pieces produced in a batch [3]. Examples are in the publications [4] [5] where the following terms can be found: "one-off and small batch production" and "small batch and piece production".

According to Montgomery [6], the quality level is inversely proportional to variability, and since variability can only be described statistically, statistical methods are the basis for continuous improvement of a product or process. In the design phase of the product, it is expected that the attribute, for instance the dimension will be assigned a specification that will include all the quality characteristics of the final product. Walter Shewhart designed control charts in 1920 to graphically monitor process changes in Bell Laboratories [7]. The control charts used data subgroups with calculated means ($\bar{X}$) and range (R), that were plotted in the charts. From the collected data and by comparing with given product specifications, a series of upper (UCL) and lower (LCL) regulatory limits could be derived. Samples are taken during production and the required product characteristics are measured and the data are recorded sequentially in time dependence to the chart. The operator is responsible for changing the process, if necessary.

Process capability analysis is performed through statistical techniques during development phase, in pre-production stages, during the production cycle, in the variability analysis in relation to the requirements or specifications of the product, in facilitating the development and production while eliminating or significantly reducing this variability.

Process capability concerns its unity, uniformity and stability. Two views are known to consider the process variability [6]:

- natural (inherent) variability at a specific time (instant variability),
- variability over time.

Basic techniques are used in the capability analysis: histogram (or probability plot), control charts, design of experiments. These techniques are a visual assessment of process capability, which in the past provided reason for numerical expression and the basis for the development of process capability indices.

Capability indices are used in conjunction with control charts to assess the ability of the process to produce acceptable products [8]. Before developing and understanding the capability indices, it is necessary to verify that the process is stable. Since most indices assume a normal distribution, it means that the process is under control. The indices used for the case study are as follows [6]:

$$Cp = \frac{USL - LSL}{6 \times \sigma} \tag{1}$$

$$Cpk = \left(\frac{USL - \mu}{3 \times \sigma}, \frac{\mu - LSL}{3 \times \sigma}\right) \tag{2}$$

Eq. 1 estimates the capability of a process (Cp) based on the Upper Specification Limit (USL), Lower Specification Limit (LSL) and Standard Deviation (σ). Eq. 2 determines process capability when the mean is centred within the specification limits. Cp can overestimate the capability of off-centred processes.

Higher values of Cp indicate a centred production process and a higher ability of the process to adhere to the tolerance limits USL and LSL. Figure 1 shows centred processes that differ in variability, i.e. processes with different values of standard deviation σ.

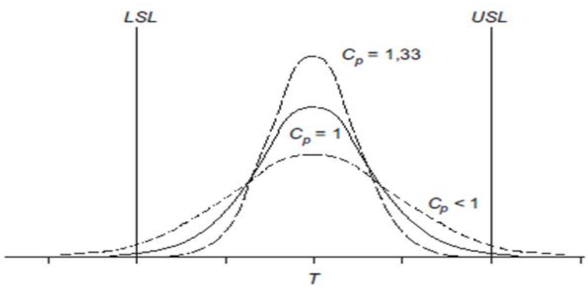

Fig. 1 The relationship of capability and variability [1]

Process standard deviation (σ) is defined as the square root of variance and is calculated if we have a complete set of possible process states. The sample standard deviation (S) is defined as the square root of the sample variance and is calculated from the selection made. That is, if we do not have a complete set of possible states, but only a selection of them [9].

Process capability indices are designed to match their higher values with the higher capability of the process. Values close to zero or below zero indicate the status of the process beyond the desired target or with a large deviation. If the process is centred, the Cpk value is the same as the Cp value. If the process is reversed from the nominal value, Cpk is always lower than Cp.

Process capability study usually measures performance parameters or characteristics that are sensitive to product quality, not the process itself. A real process capability study is one in which it is possible to directly monitor the process and at the same time to control or monitor the activity of collecting data, because through data collection management and by knowing the time sequence of the data, several conclusions can be drawn about the stability of the process over time. This article presents a study on the process capability in short run production with small mixed batches for bakery industry.

IV. CASE STUDY

Methods: To assess the ability of the process to produce conforming parts, resp. acceptable parts, capability indices are used most often in conjunction with control charts and this is preceded by verification of process stability. These actions were processed in [10] during the process of precise turning of three types of stainless steel cylinders, which differ in the length of the shaft and the length of the pipe. Their common sign is the same shaft diameter Ø50 h6 ($50^{+0.000}_{-0.016}$ mm).

After providing and verifying normal production conditions it was possible to start with process monitoring, i.e. to obtain subgroups with range of n = 3. The normality of the data was verified by the Shapiro-Wilk test, and continued with Hartley´s F_{max} homogeneity test. The results of the test led to the conclusion that there is no significant difference between variances, i.e. the data demonstrate homogeneity of variances and the variability of the precise diameter turning process is considered to be consistent.

Furthermore, it was necessary to ensure the conditions for SPC, i.e. steadiness of all known effects: temperature in the range of 16 °C – 20 °C; air humidity 50 % – 60 %, and material quality according to DIN 1.4301 (AISI 304) austenitic chrome-nickel steel. Period of data collection was January 2017 – November 2017. The number of diameter measurements is 150, with a range of subgroup 3 and the number of subgroups is 50. In [11] the short run and small mixed batch control chart $\bar{X}, R$ of measuring the precise shaft diameter (ϕ50 h6) applications are present.

Through $\bar{X}, R$ it has been verified that the production of all three types of rollers (400, 600 and 800 mm) is considered as statistically under control and all values of monitored characteristics are within the regulatory limits.

According to [12] SPC can be defined as the problem-solving process incorporating many separate decisions including selection of the control chart based on the verification of the data presumptions. There is no professional statistical software which enables to make such decisions in a complex way.

Lathe operation is a chip machining process where the workpiece performs a rotary movement and the tool is sliding. In machining, the surface of a component of the desired shape, dimensions and quality is formed by separating parts of the material in the form of chips, shapeless particles or droplets of molten metal [13]. From the technological point of view, lathe operation can be considered as the basic machining method. It is versatile because different surfaces, various external and internal rotary surfaces of cylindrical, conical and other can be machined.

In practice, the lathe operation (turning) of the diameter was performed on a 2-axis CNC-controlled lathe with X and Z axes. Such a lathe can perform external, internal, longitudinal and transverse turning operations. Dimensional tolerances are indicated by the allowed inaccuracy specified in the drawing. Fig. 2 presents tolerances for precise shaft diameter ($50^{+0.000}_{-0.016}$ mm) in the drawing of the cylinder. In the production process, it was necessary to determine the correct starting position for machining (laying and clamping). The material was removed by machining from the surface, that had the prescribed shape accuracy and roughness other than that achieved during the production of the intermediate product. Through turning, the component has taken shape, i.e. exact dimensions, required surface roughness and accuracy.

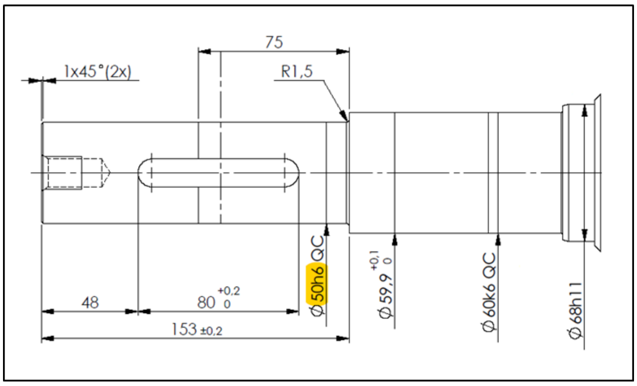

Fig. 2 The precise shaft diameter of turned cylinder

Lathe operation of stainless steel roller diameters has been monitored for 11 months. 150 data were gathered and grouped into 50 selections, each of which contained 3 pieces. The rolls varied in length and tube diameter. Their common sign was material and shaft diameter. Standard probability plot processed in [14] showed that data are from a normal distribution.

Upon completion of lathe operation, the rollers (400, 600, 800) were moved to the quality inspection centre and were subjected to dimensional inspection for the diameter to ensure that the products met specifications and are mountable.

Results and discussions: Data from measurements of precise shaft diameters were obtained during the inter-operational quality inspection. QI-Macros [14] was used to create histograms, process capability and process performance indices. Summary of the calculated Cp, Cpk and Pp, Ppk indices is shown in Table 1.

Table 1. Summary of results for Cp, Cpk and Pp, Ppk for acquired data

	Cp	Cpk	Pp	Ppk
Roller 400	0.316	0.027	0.317	0.027
Roller 600	0.297	-0.039	0.322	-0.042
Roller 800	0.305	0.042	0.317	0.044

Through indicator Cp it is possible to determine how the process is capable of repeatedly producing within the set tolerance, while the Cpk indicator also considers the position with respect to the average value and tolerance limits. If both capabilities are equal, the process can be described as centred.

After reviewing the measured data of precise shaft diameter, a trend was recorded. When turning the precise diameter of the rollers (400, 600, 800) the value of the upper tolerance of 50 + 0.000 mm has not been exceeded. However, the lower tolerance of 50 – 0.0016 mm was exceeded in 52 % of measurements, by 0.0060 mm on average. Since these values are lower than the required values of process capabilities, it was necessary to develop a plan to improve product quality to minimize the rate of repairs and to improve the repeatability of production.

Process analysis indicated that the precision of turning depends largely on initial machining when a component gets its shape, not dimensions. Only accurate turning results in precise geometrical dimensions with tolerance. To control the speed of metal removal during fine machining, the roughing tolerance was adjusted to 0.5500 mm.

After consultation with Research & Development of Products department, a mathematical data analysis was performed, and the tolerances of the shaft diameter were reviewed. A new diameter tolerance of $50^{+0.015}_{-0.055}$ mm has been established, which will further enable its assembly possibilities and functionality. New measurements and data analysis were performed. The results are recorded in Table 2.

Table 2. Summary of results for Cp, Cpk and Pp, Ppk for acquired data following improvement

	Cp	Cpk	Pp	Ppk	Cp 95% Confidence interval	Cpk 95% Confidence interval	Pp 95% Confidence interval	Ppk 95% Confidence interval
400	1.18	1.00	1.19	1.00	1.42	1.22	1.42	1.22
600	1.11	1.00	1.21	1.09	1.33	1.22	1.45	1.33
800	1.14	0.95	1.19	0.99	1.37	1.16	1.43	1.21

The significance level α was set to 0.05, which corresponds to a 95% confidence interval. We are 95% sure that Cp values exceed or are equal ≥ 1.33 and Cpk values are less than < 1.33.

The interval estimation is represented by the interval (G_d, G_h), which with a certain probability will contain the actual value of the estimated parameter. This probability is called the reliability of estimation and is indicated $1-\alpha$. The interval whose upper and lower limits are G_d and G_h (wherein $G_d < G_h$)is called the $100(1-\alpha)\%$-confidence interval of parameter G, using Eq. 3 [15]:

$$P(G_d < G < G_h) = 1 - \alpha \qquad (3)$$

The data obtained and presented show that process capability can be improved by verifying and re-setting of tools and process parameters. However, it should be noted that machining affects the final quality and determine the order of operations and the machining technology itself – turning, roughing before finishing operations, and other [16].

According to [17] the values for process capability measures (Cp, Cpk) indicate the ability to process improves or not. Whereas the requirement is to obtain Cpk values higher than >1.33, the assessed process is still not considered to be able to produce products repeatedly within the set tolerances.

According to [18] the Cp index is defined as the specification tolerance width divided by the process six sigma spread irrespective of process centring. The Cpk is the capability index that accounts for process centring error. It relates to the distance between the process mean and the nearest specification limit divided by one-half of the process spread (3σ).

The term “Sigma” is used to designate the distribution or spread about the mean (average) of the process. Examples of equivalences for capability indices are presented in Table 3.

Table 3. Examples of equivalence for capability indices [18]

Cp	Cpk	Sigma capability	Remarks
  1.00 1.00 1.33 2.00	 0.50 1.00 1.33 1.33	1.5 sigma 3 sigma 4 sigma 6 sigma	Process is not centred, and not capable. Process is centred, but not capable. Process is centred and capable. Process is not centred but is capable.

Based on data in Table 3, $C_p = 1.00$ and $C_{pk} = 1.00$ (i.e. 3 sigma) it is stated that the process is centred but not capable.

In statistical process control, data are collected in intervals, process capability over time and capability indices are determined, based on which the amount and frequency of data collection shall be determined. In the case of lathe operation of cylinder shafts, 100% of the data was used in the capability analysis to prevent large volumes of non-conforming products that would continue at the assembly site, which could result in non-installability or technical failure of the bakery equipment.

The use of 100 % control on the production of precision diameters in short run production and small mixed batches calls into a question the integrity of process capability indices in the submitted study. The resulting Cpk value, which is less than 1.00 indicates that the process is not statistically capable.

According to [19] histogram represents a graphic form of processing the results of mass discovery or a set of measurements. In quality management, it mainly refers to the frequency distribution of quality values or values related to production factors influencing the quality of the product. As can be seen through histogram in Fig. 3, the measured data for Roller 600 are off-centred, out of the tolerances set.

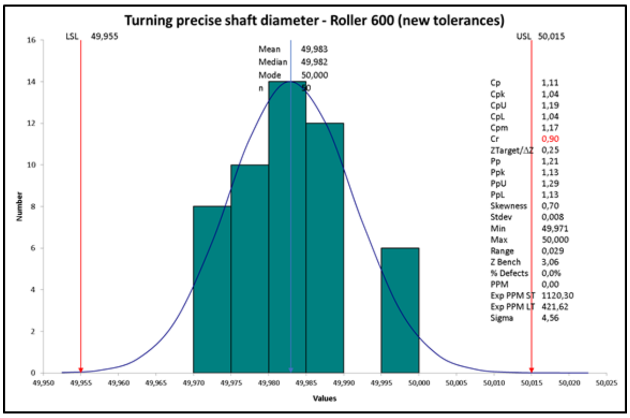

Fig. 3 Histogram and off-centred data of Roller 600

However, by changing the roughness tolerance and changing the tolerance for the precision of turning the diameter, a centred production process can be achieved while the repeatability of production is ensured (Fig. 4).

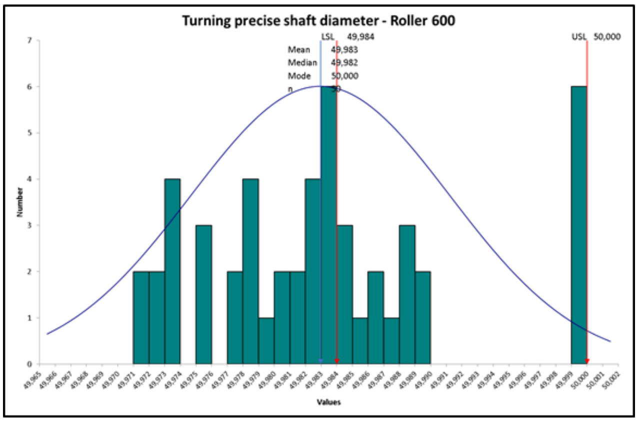

Fig. 4 Histogram and Process Capability indices of Roller 600 after improvement actions

According to Foster [20], the literature often states that SPC can only be used in conjunction with high-volume production. Improvements in quality and in productivity that can be obtained from the techniques outlined in this article are considerable.

Data acquired from the machining process and calculated capability indices enable the process of precise shaft diameter turning be categorized as capable.

V. Conclusion

Research in low volume and small mixed batch machinery production is based on a literature review and is targeted on demonstration that high volume theory is applicable on short run production process. Lathe operation of precise shaft diameter in the reporting period in small batch production was subjected to process capability review based on capability indices used in mass production. It has been found, that process capability for machining shaft diameter has been improved from an initial Cpk (0.027) to an improved Cpk (1.000) by modifying the tolerance for roughing and by implementing new tolerance to precise shaft diameter.

The challenge faced by many low-volume manufacturers is to determine whether the use of statistical indices has any relevance to applying in this type of process. Initially, the studied process showed low capability, but applying improvement actions have reduced the amount of non-conforming parts productivity and repeatability of production have increased.

Future research is required to determine whether it is more appropriate to assess the individual components and subject them to quality inspection than to rely on the statistical data and demonstrate acceptance.

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