PROCESS CAPABILITY INDEX: A BETTER WAY TO ASSESS EQUIPMENT CAPABILITY

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ABSTRACT

In the world of electronic assembly equipment, determining the true capability of the process equipment can be a daunting task to an average process engineer. While various customers have certain expectations regarding the capability of supplied equipment, there is no specific existing industry standard requiring the equipment manufacturer to report their equipment/process capability. Hence, it has become a game of "statistical gamesmanship". A current literature survey shows some manufacturers report equipment/process capability as accuracy of ± some dimension, while others report capability as repeatability or as a process capability index (C_p, C_{pk}, or others).

What is a process engineer to do? We suggest the use of a sound statistical approach to understand the process capabilities of their equipment/process before purchasing said equipment. In order to gauge the ability of an equipment/process to perform according to the product's design, process capability indices (C_p, C_{pk}, and others) can be used. Many process engineers are becoming aware, particularly through 6σ types of programs, of the ability of some of these statistical tools in determining process capabilities and to subsequently improve upon them.

There is an urgent need for building a bridge between product specification reported by an equipment manufacturer and the end user in respect to the process capability. This paper will present an overview of basic concepts and formulas to estimate equipment/process capability. More specifically, this paper will introduce a practical and simplified method of using statistical concepts and formulas to estimate process capability indices (C_p, C_{pk} and others) in the use of a stencil printer. A hypothetical example along with experimental data will be used to demonstrate key concepts.

INTRODUCTION

The electronic material deposition process is a process by which material, e.g., solder paste, adhesive, underfill, etc., is deposited onto the PCB for assembling and providing mechanical/environmental support to various components. In the early days of electronics assembly processes, demand on accuracy and repeatability was not as high as it is today due to the larger form factors of that time. As the technology in component packaging continues to advance with components and their spacing rapidly decreasing in size, material deposition is becoming highly critical to the electronic assembly process. Some of today's current examples are the following: 0.3mm CSPs, micro BGAs, miniature passives such as 01005 components, various displays and MEMS devices. The primary methods of depositing material for component assembly are printing and dispensing. For the sake of simplicity, this discussion will be limited to the printing method for solder paste deposition.

Typically, printing equipment manufacturers express printing capability as ± X. Where X is a dimension that is chosen by the machine supplier (example: ± 20 microns) without taking the specification (requirements) into consideration. In reality, the true machine capability should be expressed as a comparison of output of an "in-control" process to the specification limits.

PROCESS CAPABILITY INDICES

Many process engineers are becoming aware, particularly through 6σ types of programs, of the need for a sound statistical approach to understand the capabilities of their processes and are learning many of the tools that will enable them to determine those capabilities and to subsequently improve upon them. One such tool for determining the ability of a process to meet specifications on the product is to calculate what is known as a "process capability index" (PCI). While the practitioner may know the formula to use in order to calculate a process capability index, like C_p or C_{pk}, what that same practitioner may not realize is the fact that performing a process capability calculation on a single set of data may actually yield, depending on how the data are stratified, different results. For example, in a recent publication[1] a stencil printing study was performed on solder paste deposition for a QFP208 component. Thirty (30) prints (that were referred to as "boards") were studied and the data could be analyzed from the following points of view:

- Total number of deposits: 6,240;
- Total number of perpendicular (w.r.t. squeegee direction) deposits: 3,120;
- Total number of parallel deposits: 3,120;
- Each of the 208 pads had 30 deposits; and
- Each of the 30 boards had 208 deposits.

All the data were from the same process, however, depending upon how the data were viewed, different PCI values were obtained. Detail of this study can be found elsewhere[1].

PCIs compare the output of an "in-control" and normal process to the specification limits of the product to be produced. They basically determine the ratio between the spread of the product's specifications to the spread of the process values as typically measured by ±3σ where σ represents the standard deviation of the process. The fundamental PCI is known as C_p and it is often referred to as a measure of "inherent" capability and is calculated as follows:

$$C_p = \frac{USL - LSL}{6\sigma}$$

As most readers may know, the absolute minimum C_p value should be 1.00, with many companies requiring a hurdle of 1.33 or higher. However, C_p is referred to as "inherent" capability because it merely incorporates the spread of the process but not where the process mean is located. The centering of the process is quite crucial to yields – one can have very high C_p values, yet still have very poor yields if the centering of the process is not near the target value. To accommodate the centering of the process, the C_{pk} formula was developed and is calculated as follows:

$$C_{pk} = \min\{\frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma}\}$$

Because this index incorporates centering and spread of the process as compared to the specification limits, C_{pk} has been dubbed as the "actual" process capability.

While C_p and C_{pk} are the most fundamental and often used, other PCIs exist. For example, C_{pm} and C_{pmk} incorporate the target of the part's specification, C_{pw} is similar to C_{pm}, but incorporates a weighting function, and the Automotive Industry Action Group (AIAG) lobbies for the use of P_p and P_{pk} when the process is not known to be in a state of statistical control. The interested reader is referred to Montgomery[3] for a review of these indices.

A point we stress time and again is to make it clear to the practitioner that in all likelihood the actual process parameters of μ (mean) and σ (standard deviation) are unknown. This is something that is difficult for some younger engineers to wrap their minds around. Seldom, if ever, do we know the true population parameters of mean and sigma; however, we can get good estimates of them if we obtain large sample sizes from the process. But since they are estimates that we are using, $\bar{x}$ for μ and s for σ, what we actually are obtaining are estimates of C_p, C_{pk}, and other PCIs. And since we are obtaining estimates of these indices, we can and should place confidence intervals (CIs) around them[2]. The confidence interval for C_p is exact; Bissel's approximate CI is often used for C_{pk}[2]. In order to demonstrate the concept of process capability indices and their use, the following section examines a hypothetical process/product example followed by an example specific to a stencil printer.

HYPOTHETICAL EXAMPLE

For example purposes let us suppose we have a part with the following specifications: 110mil ± 10mil. In other words, the target value is 110mil, but a part from the process would be considered to be in specifications if it was between 100mil and 120mil (the lower and upper specification limits, respectively). Before determining PCI values, assume it is shown that the process is normally distributed (e.g., by use of histograms or normal probability plots), and that the process is shown to be in control (e.g., by use of control charts) – these are two important and necessary criteria for process capability analyses. Further let us suppose that 30 parts randomly drawn from the process yield a sample standard deviation of 2.35mil. With this information we can *estimate* the C_p value as follows:

$$\hat{C}_p = \frac{120 - 100}{6(2.35)} = \frac{20.0}{14.1} = 1.42$$

While that value appears to be a good one (e.g., > 1.33), we still recommend placing a CI around the estimate (the hat over the "C" indicates this is an estimate). Using the C_p CI formula, which is a function of the sample standard deviation, s, sample size, and confidence level[2,3] we obtain the following 95% confidence interval for C_p:

$$1.06 \le C_p \le 1.78$$

While the 1.42 initial estimate is a good one, it is important to realize that since the value is based upon a sample, it is possible that the C_p value (at 95% confidence) may actually be as low as 1.06 – a borderline value. Thus, when a manufacturer reports their C_p, C_{pk} or other process capability index, a knowledgeable process engineer should also ask for the confidence interval and corresponding sample size used to estimate the index!

ANALYSIS AND USE OF A PCI:

Although PCIs are dimensionless – the dimension of the numerator (e.g., mils, mil^3, inches, etc., is the same as the dimension of the denominator and thus cancel out) – their value lies in the ability to almost instantly equate them to defect levels. Table 1 provides a few C_p values and their associated defect counts in terms of parts-per-million (ppm) defects. The table does assume that the process is in control, is normally distributed, the process is centered on the target value, and that the specifications are two-sided.

Table 1. Process Capability Index versus Defect Level

C_p	ppm
0.5	133,614
1.0	2,700
1.3	96
1.7	0.34
2.0	0.0018

The interested reader may want to know that the defect levels are obtained by determining the area under a normal distribution curve that lies outside the specification limits. For example, if a process is centered on the target and its C_p value is 1.00, then that implies that the specification spread (the numerator) is equal to the process spread, $\pm 3\sigma$ (the denominator). The capable process engineer should be aware that $\pm 3\sigma$ of a normal distribution accounts for 99.73% of the area under the curve. Therefore the area outside of the curve (and outside specifications of a centered, C_p=1 process) is 0.27%. When translated to ppm, 0.27% = 2,700. More complete tables of PCI values as compared to defect levels can be found in many statistical texts[3].

EXPERIMENTAL – STENCIL PRINTING

A simple experiment was set up to test the theory in a real application environment on whether a stencil printer with a stated accuracy can guarantee good results (yields). Two printers, Printer 1 and Printer 2 were set up to run 10 boards under identical conditions. Both of these printers have a stated accuracy of $\pm$ 25 μ. The test vehicle for this experiment consisted of a 9" X 14", copper clad board with pre-printed fiducials. The stencil used in this test was a 5mil thick laser cut, electropolished stencil with a 3 X 6, 1mm^2 aperture matrix. Figure 1 shows the schematic of the stencil design. A commercially available type 3, lead free paste was used for this test. A Kho Young SPI system was used to characterize the print quality of both of the printers.

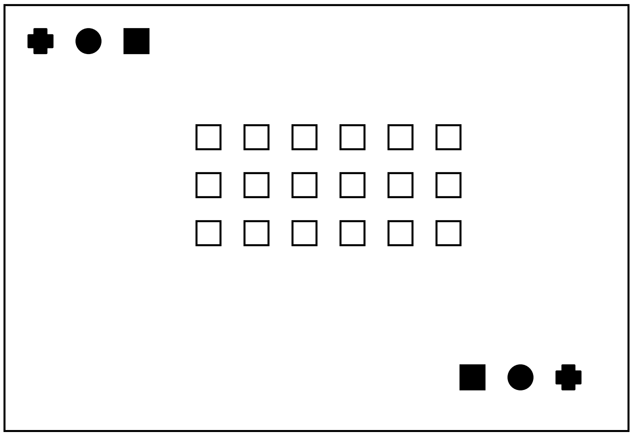

Figure 1. Schematic of the test stencil

RESULT AND DISCUSSION

The distribution plot for Printer 1 and 2, in respect to the Y offset is shown in Figures 2 and 3. Note that assumption of normality is reasonable due to the shape of the histograms. Hence, we can apply the process capability analysis to understand the actual capability of both of the printers. Process capability results from the Koh Young SPI inspection showing the Y offset is shown in Figures 4 and 5. As it can be seen from these plots, even though both the printers report to have a Y offset specification of $\pm$ 25 μ, Printer 1 (see Figure 2) is not capable at all.

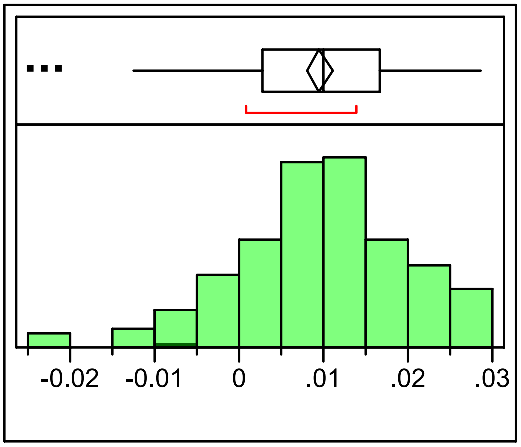

Figure 2. Y offset distribution plot for Printer 1.

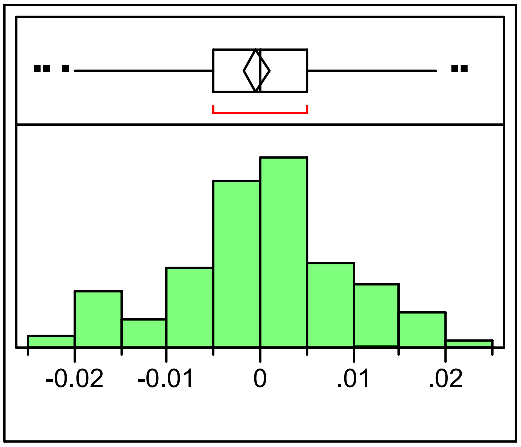

Figure 3. Y offset distribution plot for Printer 2

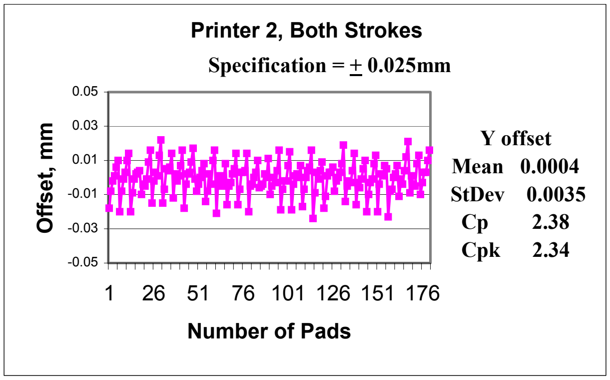

Figure 4. Process capability of Printer 2

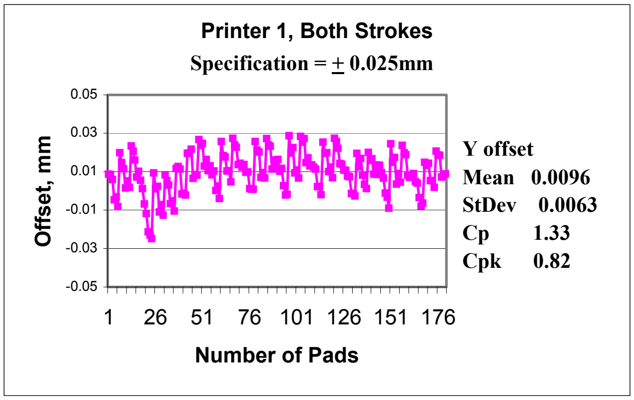

Figure 5. Process capability of Printer 1.

This example serves to illustrate that even though both printers have the same stated accuracy, they clearly do not perform similarly. It should be of interest to note that there are even examples in which a printer with a better stated accuracy (e.g., ± 10 μ) can be shown to be inferior to that of one with a poorer stated accuracy (e.g., ± 25 μ) when the application (specification range) is considered.

Returning to the above example, the sample standard deviations are such that the capability of each printer (before comparing to the specifications of the offset) concur with the stated accuracy of ± 25 μ. However, Printer 2 clearly has a superior centering and lower variability than Printer 1. The estimate of C_{pk} for Printer 2 (2.34) is much better than that of Printer 1 (0.82). Following the earlier suggestion, the 95% confidence intervals for each printer's C_{pk} appear below.

Printer 1: $0.72 \le C_{pk} \le 0.91$

Printer 2: $2.10 \le C_{pk} \le 2.59$

Even when a confidence interval is generated for each printer, Printer 1 is still inferior and incapable because the CI does not contain 1.0 (or a better hurdle of, say, 1.33). The reader should notice that it does have a good Cp estimate (1.33). However, because it is off-center (Y offset target = 0.000mm and it has a sample mean approximately equal to 0.010mm), this adversely affects the actual process capability (C_{pk}). When the CI is considered for Printer 2, its lower confidence limit is still above 2.00, indicating it to be an exceptional print process.

SUMMARY

In summary, we would like to stress the following points:

- A good process engineer should know how to calculate process capability indices (C_p, C_{pk} and others), but before doing so must assure that the process is in statistical control and the data are normally distributed,
- A good process engineer should understand how a process capability index value relates to defect levels,
- A good process engineer should realize that population parameters rarely, if ever, are used and therefore the resulting calculations are most likely based upon samples from a process; thus yielding estimated values of C_p, C_{pk}, etc.,
- A good process engineer should realize that one process can yield different PCI values, depending upon the sample sizes used and how the data are stratified[2],
- Since estimated PCIs are typically what are obtained, a good process engineer should be able to generate the confidence intervals for their PCI estimates,
- Similarly, when provided a PCI value, e.g., as from a supplier, then the process engineer should ask the supplier to either provide the CI, as well, or have them provide the data (sample mean, sample standard deviation, and sample size) so that the process engineer can, himself or herself, generate the CI and more fully understand how good the process is with respect to specifications,
- A good process engineer should "trust, yet verify". Even if a relationship with a supplier is good, it is important to make informed judgments based upon the data and the application and not simply rely upon stated specifications of a piece of equipment.

REFERENCES

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