PWI: Process Optimization Made Simple

By Jim Hall and Phil Zarrow

The process window index (PWI) can be used to quickly determine the impact of process changes and compare different process parameters.

Improving product quality in electronic assembly processes is important to profitability and is especially significant in the highly competitive electronics manufacturing services (EMS) industry. In practical terms, the foundation step is choosing a process setup that minimizes defects. A process setup consists of material selections, equipment configurations and assembly sequences. By adjusting the process setup, product quality can be improved or degraded.

Quality levels must be maintained throughout extended or multiple production runs. Maintaining quality requires robustness, which is defined as "the insensitivity of the product's functional characteristics to variations caused by noise factors."[1] Accordingly, the process setup chosen must be sufficiently robust so that defects do not result from any normal variation of setup parameters. Ideally, the process setup should also provide some protection from abnormal variations.

Specified Process Window

An excellent philosophy for reducing defects is the integrated sequence of Define – Measure – Improve (DMI). By following these three steps, deficiencies can be systematically identified and improvements achieved. The first step in the DMI approach is to define the process, ultimately in terms of quantitative specifications that are known to determine product quality.

Specifications are not single, discrete values. Instead, they are ranges consisting of a minimum value, a maximum value or, most commonly, both. Some examples are:

- each chip component must have a minimum contact of 95 percent on the pad
- the height of a solder paste deposit must be no less than 4 mils and no more than 8 mils
- the preheat slope of all solder joints must be less than 4°C/second during reflow.

These ranges are the process windows within which zero or minimum defects will be achieved. For some parameters, the minimum and maximum are true, binary statistical specification limits where any value inside the range is good and any value outside the range is a defect. The classic example of this type of specification limit is the pin in hole: Any pin less than the specified diameter fits in the hole, any pin larger does not.

Other specification ranges are more analog, exhibiting good quality for values within the range and increasing defects for values outside. The aforementioned 95 percent on-pad placement specification would be an example of this type and so would a percentage range for solder paste to pad coverage (Figure 1).

The process setup should be adjusted so that the average or mean parameter value falls as closely as possible to the center of the specification range. For statistical-based specifications, this approach provides the lowest probability that any product will fall outside the specification range and cause a defect. If statistical data are available, the lowest probability can be confirmed by calculating the process capability index (Cpk):

$$C_{pk} = \frac{USL - \overline{X}}{3\sigma} \text{ or } \frac{\overline{X} - LSL}{3\sigma}$$

(whichever is less)

where USL is the upper specification limit, LSL is the lower specification limit, X is the mean and sigma is the standard deviation. If the mean value is centered between the USL and the LSL, then both [USL-Mean] and

FIGURE 1: Example specification range for solder paste to pad coverage.

[Mean-LSL] are equal to [(USL+LSL)/2], and both equations yield the same value of Cpk. If the mean value is not centered, then one of these differences will be less than [(USL+LSL)/2], resulting in a lower Cpk.

For an analog-style specification, the lowest defects could exist at some value or sweet spot within the range but not at its center. However, this relationship would most certainly be very product-specific, so no general guidelines can be given. If such data are available for a specific product, then the process setup should be adjusted to move the mean closer to this sweet spot to produce less defects.

The impact of normal process variation on defects should still be considered. In most common assembly situations, because of the difficulty in identifying product-specific "sweet spots," all process parameters are typically centered within their specification ranges.

Obviously, a process cannot always be adjusted to bring a specific parameter exactly to the midpoint of its specification limits. Therefore, the decision must be made as to whether or not a process setup is good enough or which one of several setups is the best.

An excellent method of quantifying these decisions is to calculate a process window index (PWI). The PWI normalizes the specific data to a scale of 0 to 100 percent, linearly distributed between the center of the specification range and the closest limit (Figure 2). The scale can be calibrated with 100 percent either at the center of the range or at the limit. With 100 percent at the limit, the PWI grades the process by defining what percentage of the process window is consumed by the process setup. With 100 percent at the center of the range, the values indicate the allowable room for variation.

Converting parameter units to percentages provides several benefits. First, the impact of process changes can be easily understood. Second, the ranking of a process setup or improvements of specific parameters can be easily communicated and understood even by non-technical personnel. Finally, the percentage scale permits direct comparison of different parameters with unlike units and specification limits, an important advantage.

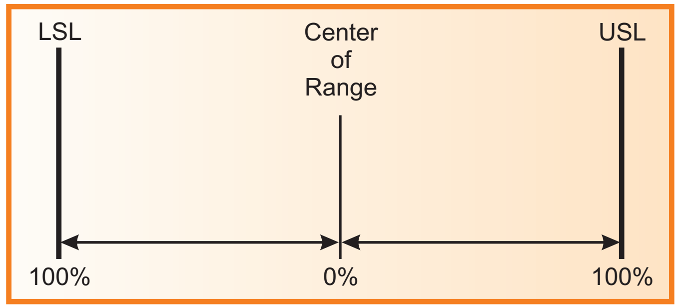

FIGURE 2: Process Window Index.

PROCESS VARIABLE	RANGE	UNITS
Paste Height	0.002 - 0.010	in (mm)
Paste Volume	10^{-9} - 10^{-5}	in^3 (mm^3)
Placement Registration (X,Y)	0.0001 - 0.01	in (mm)
Placement Registration (Θ)	0.01 - 1	° (degrees rotation)
Reflow Peak Temperature	200 - 260	°C
Reflow Liquidus Time	15 - 120	Seconds
Reflow Heating Slopes	0.5 - 4.0	°C / second

TABLE 1: Comparison of process variables.

A recent article discussing surface-mount placement and an online calibration system can be used to illuminate the basic application of PWI.[2] The article describes an assembly line scenario, with specification limits of ±50 µm, standard deviation of 8 µm, and placement offset before and after calibration of 18 µm and 4 µm, respectively. The impact of the calibration is presented by performing before and after calculations of Cpk; 1.33 and 1.92, respectively.

Using PWI, the benefits of this process setup optimization are shown by stating that the calibration improved the PWI from 36 percent to 8 percent. Thus, the advantage of PWI's percentage scale is clearly shown; the percentage scale is easily understood whereas Cpk is a rather sophisticated concept, and its scale (1=3s, etc.) is far from universal. In addition, this quantitative evaluation could be performed even if the statistical repeatability (standard deviation) of the process was unknown.

The PWI is a powerful tool for quickly evaluating the quality and robustness of a process setup for any parameter, and PWI is truly valuable for optimizing processes with multiple parameters. Successfully producing an electronic assembly, even one of minimal complexity, requires that many diverse specifications be simultaneously and sequentially accomplished. Three groups of materials are required—substrate, components and solder paste—and at least three assembly operations are needed: paste application, component placement and reflow. Each of these items affects one or more product level parameters, which can have a wide variety of limit values and measurement units (Table 1).

Evaluating all parameters by using the 0 to 100 percent PWI scale reveals the robustness of the entire assembly process. The most stringent method uses the highest individual PWI (0 percent = center of range) as a

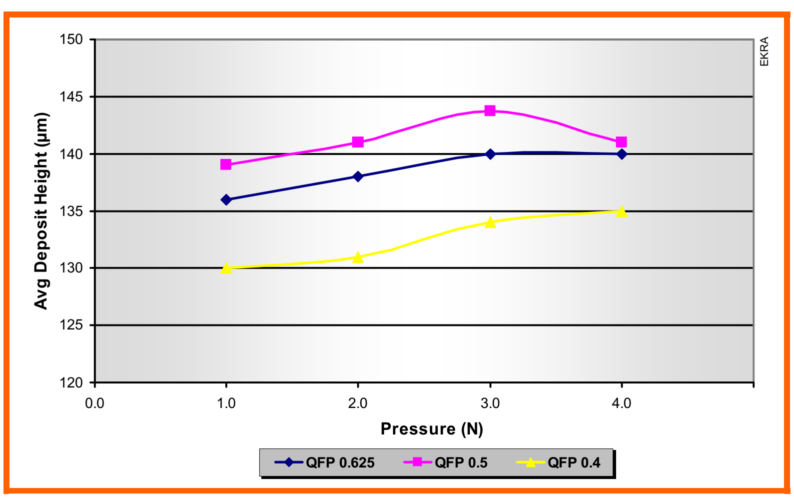

FIGURE 3: Example comparison of deposit heights and print pressure.

single grade for the entire process. This method maintains that any individual parameter that falls outside of its specification range will generate a defect; so, the entire process is only as strong as its weakest link. By assigning a single percentage value, the process setup can be easily evaluated and the impact of changes or adjustments can be immediately determined.

Using PWI

The following example illustrates the advantages of applying the PWI concept to parametric test results. The chosen board-level quality parameter was solder paste deposit height. The variables were squeegee pressure and aperture size, which is directly related to the gull-wing lead pitch on quad flat packs (QFPs). The specification limits are 130 to 160 µm.

Figure 3 depicts the actual data values, and Table 2 shows the PWI for each data point. Clearly, a squeegee pressure of 90 Newton's (N) with an overall PWI of 67 percent provides the best quality level when all three lead pitches (aperture sizes) are considered. This table is easy to set up using only simple arithmetic and a maximum function, yet it quickly generates a final result and facilitates comparison of the different pressures.

PWI's percentage scale can be used to compare process setups with different units of measurement. Table 3 shows solder joint liquidous times and peak temperatures for two process setups. These parameters are interdependent and often require a trade-off during optimization. The inconsistent units—seconds for liquidous times and °C for peak temperature—can obscure these comparisons of results. However, with PWI, whether or not an overall improvement has been achieved is immediately obvious.

The PWI analysis is quick and simple, permitting discrete evaluation of individual locations on the product, instead of averaging results to generate overall averages or standard deviations. This approach is consistent with the weakest link philosophy, where an out-of-specification value at any location constitutes a defect, regardless of the accuracy of all others; for example, solder paste height of individual deposits, location accuracy of individual components or reflow temperatures at different locations.

Figure 4 shows the effects of averaging post-print solder deposition heights at four discrete locations. Data from three locations are near the center of the specification range, while a fourth location is near the LSL. The average of all four is near the center of the range with a PWI of 17 percent, while the worst case location is 90 percent. The 17 percent averaged value should not be used as an overall value for the process because a deficient or excessive solder deposit at any location will generate a defect regardless of how accurate all other deposits are within the specification range.

The Optimal Solution

The technique of using PWI values to comparatively rank multiple parameters can be extremely valuable for setting up a process in which individual setup variables affect more than one product specification and trade-offs must be made to achieve the overall optimum performance. An example could be squeegee pressure in the stencil printer, which can impact paste volume, smearing and other print qualities. If the maximum PWI for all these parameters decreases when the pressure is adjusted, then the adjustment is beneficial to the overall process.

Squeegee Pressure (N)	PWI Values			
	Aperture Size (QFP Pitch, in.)			
	0.065	**0.050**	**0.04**	**Max**
30	53	40	100	100
50	47	20	93	93
70	33	13	80	80
90	33	20	67	67

TABLE 2: PWI example.

	Peak Temperature (°C)	Liquidus Time (sec)	Overall PWI
Spec Range	210 - 230	45 - 90	45 - 90
Recipe #1	213	60	60
Recipe #2	218	80	80

TABLE 3: Example comparison of recipe variables.

If a modeling algorithm is available for the process, then changes can be evaluated without actual physical experiments. Going one step further, the ultimate method for optimizing a process setup is to link the model to a search engine and check all setup combinations for the lowest overall PWI. The search engine would change all of the setup variables, using the model's algorithms to calculate the PWI for each combination.

Obviously, two fundamental requirements are needed for such a system to be successful. First, the model must be accurate over the full usable range of all setup parameters. Second, it should be able to self-correct based on confirmation test data versus results predicted by its algorithms.

Once the model predictions can be relied upon, the search engine must efficiently find the optimum process setup. It should evaluate the entire range of all parameters and all possible combinations in a reasonable time. For example, overnight computing is acceptable to optimize an entire assembly line. However, having the optimum result within a few minutes is much more desirable in a typical high-mix contract environment, especially because most companies will require a confirmation run of the final setup, before committing expensive materials to the assembly process.

An important requirement in many production situations is maximizing throughput. Often, when attempting to increase throughput, the impact of throughput on quality is difficult to determine. The overall PWI value provides an excellent metric for qualitatively evaluating processing speed adjustments. If the relationship between PWI and quality (defects) is clearly understood, an acceptable maximum PWI value can be established. Setup combinations can then be evaluated either by test or by modeling calculations, choosing the highest throughput that still meets overall PWI criteria. Again, a process model and a configurable search engine are extremely time saving.[3]

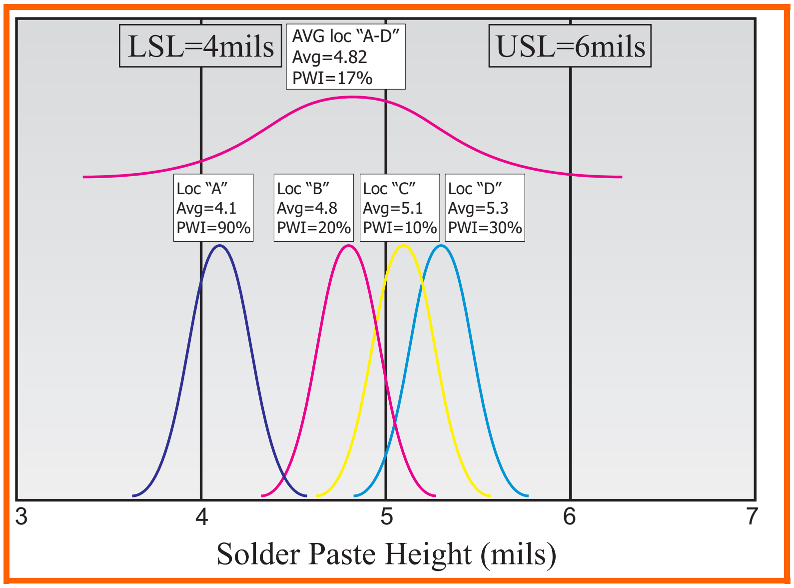

FIGURE 4: Example comparison of solder paste heights and PWIs.

If certain parameters are more critical to the overall process or more likely to cause defects, their priorities can be increased by tightening the limit values for the PWI calculations inside the actual specification limits. Mathematically, this approach causes the same value of PWI to fall closer to the center of the specification range, thereby reducing the probability of defects caused by the more critical parameters.

Conclusion

Improving product quality in the electronic assembly processes is key to profitability for both original equipment manufacturers and EMS providers. Quality levels must be attained and maintained throughout all production runs, which can only be achieved when the process setup is robust.

The PWI is a powerful tool for quickly evaluating the quality and robustness of a process setup for any assembly parameter. Of course, completing any electronic assembly requires that many diverse specifications are achieved.

The PWI is suitable for discrete analysis of individual locations on the product. The overall PWI value provides an excellent metric for qualitatively evaluating process speed adjustments. With a clear understanding of the relationship between PWI and defects, an acceptable maximum PWI value can be established. Using test or modeling calculations, setup combinations can then be evaluated and the highest throughput scenario that still meets overall PWI criteria can be determined. Hence, using PWI values to comparatively rank multiple parameters can be extremely valuable for setting up a process in which individual process setup variables affect more than one product specification. ■

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