Defining Placement Machine Capability by Using Statistical Methods

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1. Introduction

Modern placement machine's capability to place certain electrical components can be defined as a question of required accuracy. In six sigma methodology the discussion about accuracy is divided into accuracy and precision. Accuracy can be defined as the closeness of agreement between an observed value and the accepted reference value and it is usually referred as an offset value, see Fig.1. Precision is often used to describe the expected variation of repeated measurements over the range of measurement, see Fig.2, and can also be further broken into two components: repeatability and reproducibility (Breyfogle, 2003).

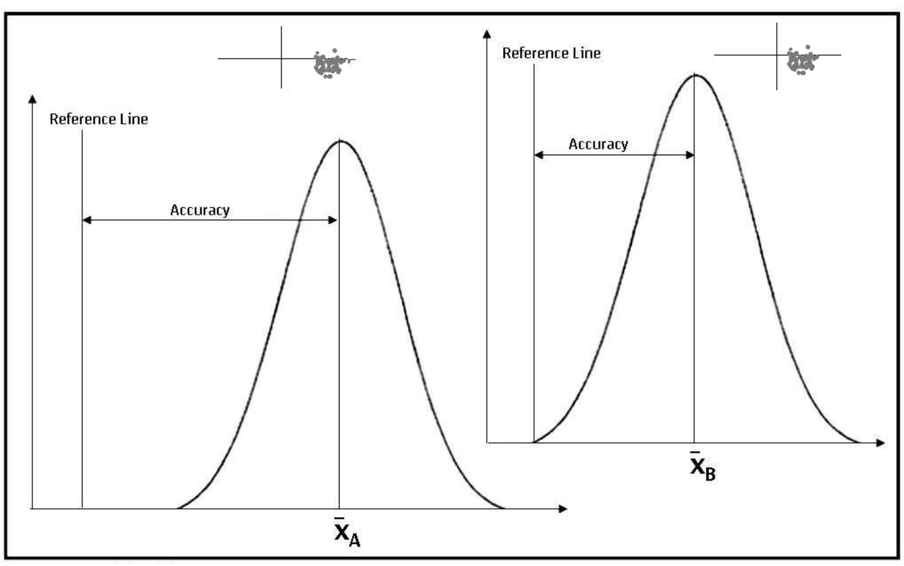


Fig. 1. Definition of accuracy: Process X_A has lower accuracy than process X_B i.e. process X_A has bigger offset from reference line. Both have approximately the same precision.

In common everyday language the word accuracy is often used to mean both accuracy and precision at the same time: machine is accurate when both its offset from reference and its variation are small. A rifle e.g. can be said to be "accurate" when all ten bullet holes are found between scores 9.75 and 10.00, but mathematically the shooting process, including also the shooter and conditions, is both accurate and precise.

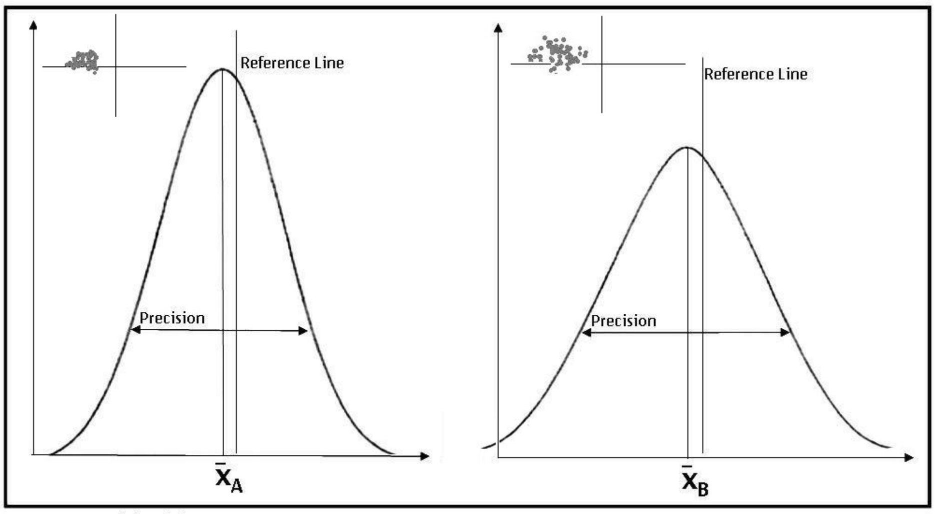


Fig. 2. Definition of precision: Process X_A has better precision (less variation) than process X_B. Both processes have approximately the same accuracy (same offset from reference line).

2. Placement machine accuracy and former studies

Rotary turret SMD (Surface Mounted Device) placement machine (Fig.3) has moving XY-table to transfer Printed Wiring Board (PWB) to correct position below the placement head. XY-table moves also in vertical direction to adjust placement height to various component thicknesses. Component feeders are arranged behind the machine in a table, which transfers the correct feeder below the placement head. Placement heads with various sizes of vacuum nozzles are arranged in the turret, which revolves and moves pickup nozzles from part pickup point to placement point in a continuos movement providing vision inspection and rotational correction on the way.

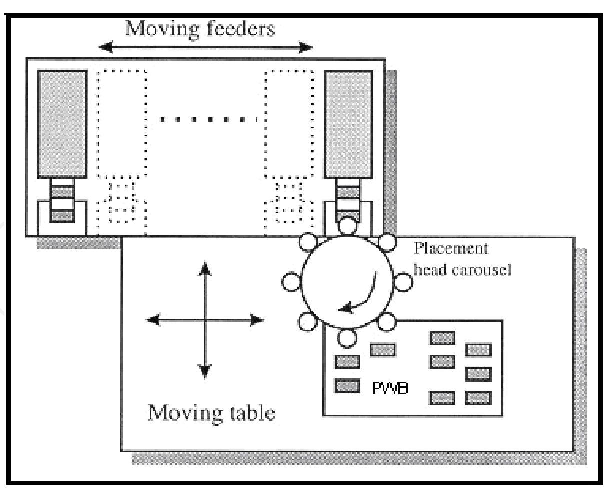


Fig. 3. Principle of a rotary turret placement machine (Johnsson, 1999).

Placement defects such as misaligned or missing parts on PWB are expensive when reworked after reflow soldering. Naturally good quality of the preceding solder paste printing process is crucial for successful component placement (Liukkonen & Tuominen, 2004). One cause for placement defect is poor placement accuracy of the placement machine

(Kalen, 2002; Kamen, 1998). Controlling of placement accuracy has a significant role in placement quality and becomes even more important when placement machines gain more operation hours (Liukkonen & Tuominen, 2003).

CeTaq GmbH provides placement capability analysis services for electronics manufacturing field. In order to reduce the extra variation coming from e.g. inaccurate materials CeTaq GmbH uses special glass components and glass boards, as well as dedicated camera based measuring device for the results (Sivigny, 2007; Sauer et al., 1998). In this six sigma study the purpose is to use commercial standard components and very simple FR4 type glas epoxy PWB. Problem with special materials is the extra cost and extra time needed to prepare and perform the test under the special circumstances. By using standard materials we can keep the cost down and also speed up the time needed for the testing when e.g. the same board thickness and size can be used as normally in the production line. This will make it easier for the line engineers to start the test when needed because it takes only 15-30 minutes. Kamen has studied the factors affecting SMD placement accuracy, but has put especially focus on effects coming from variations in solder paste printing, vertical placement force and different component types, whereas in this study they all are considered and kept more or less as constant (Kamen, 1998). Wischoffer discusses about correct component alignment and possible offsets after placement and points out four factors that affect the most: part mass, part height, lead area contacting solder paste and solder paste viscosity (Wischoffer, 2003). Baker studies also the factors affecting placement accuracy and highlights that limits used in placement machine parameters should be defined separately by each company and are based on economics on machine cost, process cost, overall production cost, repair cost and the cost having a defective or potentially defective product reach the customer (Baker, 1996). In this study the technical limits are set by the technical acceptance for the new technology requirements coming from the company.

CeTaq GmbH defines the purpose of capability measurements in three different customer groups as shown in Table 1 (CeTaq, 2010). For this project the main purpose well aligned with CeTaq's grouping can be found in Technical acceptance and machine qualification.

Equipment Manufacturer	**Retailer Distributer -After Sales Service -Electronic Manufacturer -OEM**	**Customer-Designer - Auditors**
-Design -Validation -DOE -Machine qualification before shipping …	-Technical Acceptance and machine Qualification -Line Configuration -Maintenance optimization -Statistical Process Control -Task force / Six sigma -Customer report on demand -Identify root-causes for Quality issues …	-Audits -Quality management systems -Design for manufacturability …

Table 1. Capability measurements defined in three customer groups (CeTaq, 2010).

3. The DEFINE phase in a Six Sigma project

This study was completed like a six sigma project including the identifiable DMAIC-process phases: Define, Measure, Analyse, Improve and Control (Breyfogle, 2003). However, because this project is quite short some phases like analyze and improve were combined partly together already in the beginning of planning the experiments. Design Of Experiments (DOE), a statistical tool used to screen the factors to determine which are important for explaining process variation (Montgomery, 2008), has been mostly presented in the Analysis chapters and the interactions found there are presented in Improve phase.

3.1 Selection of the project and the voice of the customer

Project selection is the most important part of a Define phase in a six sigma project. In this project the purpose was to find out what is minimum placement machine's Sigma Quality Level (later also referred as Placement Sigma Level, PSL) that still produces good placement quality when spacing between the components on the PWB will be decreased by 33%. Customer's plan to decrease component spacing by 33% may be too demanding for, at least, those machines which have a lower placement sigma level in placement accuracy, but are still assumed to be used in production for several years. This leads to the second important part of the Define phase, to the business case behind the selected project (Breyfogle, 2003): a lot of bad Quality may be produced if the most capable machines can not be selected. At the same time new investments in machinery can be postponed in the future which will bring additional economical value. Therefore ranking of the available machines is essential.

The smallest component to be assembled is 0402 size capacitor and resistor, where the nominal length of the component is 1mm and width 0.5mm. The height of a resistor is 0.3mm and that of the capacitor is 0.5mm. Because the required placement nozzle is wider than the 0402 component, , it may be necessary to place all resistors first before any of the taller capacitors to prevent the protruding nozzle hitting the components already been placed, i.e. place components according to their height. When component-to-component spacing is larger the problem arising from protruding nozzle does not matter. The kind of "forced" placement sequence will deteriorate free placement optimization and will then have negative effect on line output and also on placement quality as has been shown in previous publications (Liukkonen & Tuominen, 2003).

3.2 Problem Statement

It is essential to determine the project scope in relation to business case and also to available project resources. Primary target of this study is to rank the placement machines according to their capability to place high-density 0402s i.e. what is the minimum requirement in terms of sigma quality level? Secondary target is to verify the need for forced placement sequence: should all resistors be placed before any taller capacitors?

4. Process Exploration: the MEASURE phase

4.1 Response Variables and Metrics

In six sigma projects the monitored process outputs are divided into variable type data and attribute type data. Variable data is quantitative data (continuous data) where measurements are used for analysis, e.g. shaft diameter in millimeters. Attribute data is qualitative data that can be counted for recording and analysis. Examples include characteristics such as "missing" or "present", "good" or "bad", "accepted" or "rejected". Attribute data can also include characteristics that are inherently measurable but where results are finally recorded in a simple yes/no or go/no-go fashion (AIAG, 1995). According to six sigma the process output (response) is a function of process inputs (e.g. materials or process setup parameters) i.e. Y=f(X). In this study the following responses are monitored.

Attribute data type responses:
Placement errors

Referred later in Figures as Y1 e.g. missing, misaligned, skewed
- Specification used for category "Misaligned" in placement errors before reflow soldering: +/- 180 µm for 0402 components

Variable data type responses:
Placement position against nominal in X and Y axes i.e. ΔX, ΔY

X Mean (referred later in Figures as Y_{21})
X StDev (standard deviation, referred later in Figures as Y_{22})
Y Mean (referred later in Figures as Y_{23})
Y StDev (standard deviation, referred later in Figures as Y_{24})

Specification for Means: +/- 100 µm (at 3 sigmas, machine manufacturer's specification)
Specification for StDevs: +/- 33 µm (tolerance area /6, i.e. 200 µm / 6)

4.2 Measurement System Analysis

Measurement system description The optical-based AOI (automated optical inspection) system used in this study utilizes solid shape modeling to measure and characterize components and solder joints with lifelike 3D visualization. System has 20-25 µm/pixel resolution at all times with a single high-resolution digital camera and high-speed precision XY-robot. The very same AOI machine was used throughout the study and the machine was calibrated by the manufacturer before the study. Post-placement inspection tools are common sight in a modern SMT (Surface Mount Technology) production line today, and these in-line tools are very often also utilized in various placement accuracy tests and evaluations (Kamen, 1998).

Measurement system Gage

For repeatability test (precision) of the AOI five populated PWB panels were measured with pre-reflow AOI, each three times, totally including 13 680 observations. Gage test was based on two randomly selected components. Calculated Gage error result 1.09% was excellent (see Fig.4) and AOI seemed to be fully capable as a measurement system for the analysis in this study.

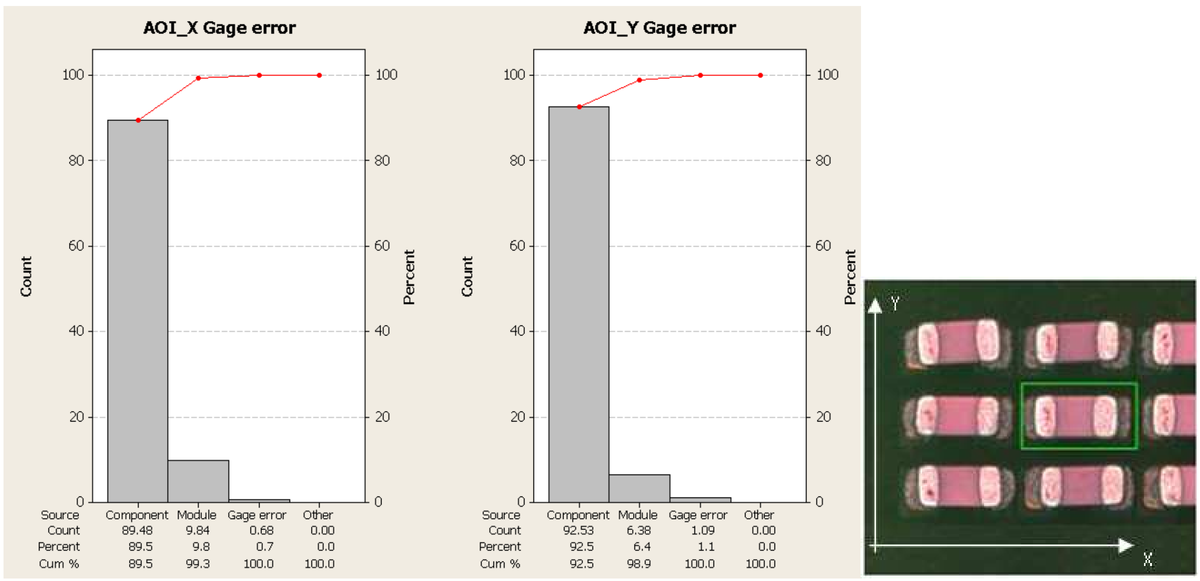


Fig. 4. On the **Left**: AOI Gage error result showing that 0.68% of inaccuracy comes from the AOI itself on X axis and 1.09% on Y axis. On the **Right**: Test boards' coordinate system and AOI screenshot of 0402 components in 0 placement angle.

For additional reliability a second gage test round was made. Measurements were taken from all the components separately using two randomly selected PWB panels and entered into a Boxplot chart. Boxplot is a tool that can visually show differences between characteristics of a data set. Box plots display the lower and upper quartiles (the 25th and the 75th percentiles), and the median (the 50th percentile) appears as a horizontal line within the box (Breyfogle, 2003). The analysis produced Fig. 5 where AOI deviation defined as X-Range (i.e. measured max ΔX value – min ΔX value separately calculated for each circuit reference) in X axis is large when placement angle 0 is used. Fig. 5 shows that X range is 80 µm with capacitors and 30 µm with resistors. See right part of Fig. 4 for clarification of placement angles and PWB coordinate system. AOI deviation defined as Y-range in Y axis is large when angle 270 is used. Fig. 5 shows that Y range is 60 µm with capacitors and 30 µm with resistors. Because this observed repeatability error was randomly distributed all over the board area and therefore could not be avoided by deleting certain references it was decided not to use Y axis data with 270 placement angle and X axis data with 0 angle in further analysis of this study. Fig. 5 also shows that X axis data with 270 angle and Y axis data with 0 angle is fully reliable and usable for this study. The gage problem originates from AOI's inability to detect component location accurately in its lengthwise direction with selected algorithm, especially with capacitors. AOI manufacturer was informed about the observed algorithm problem.

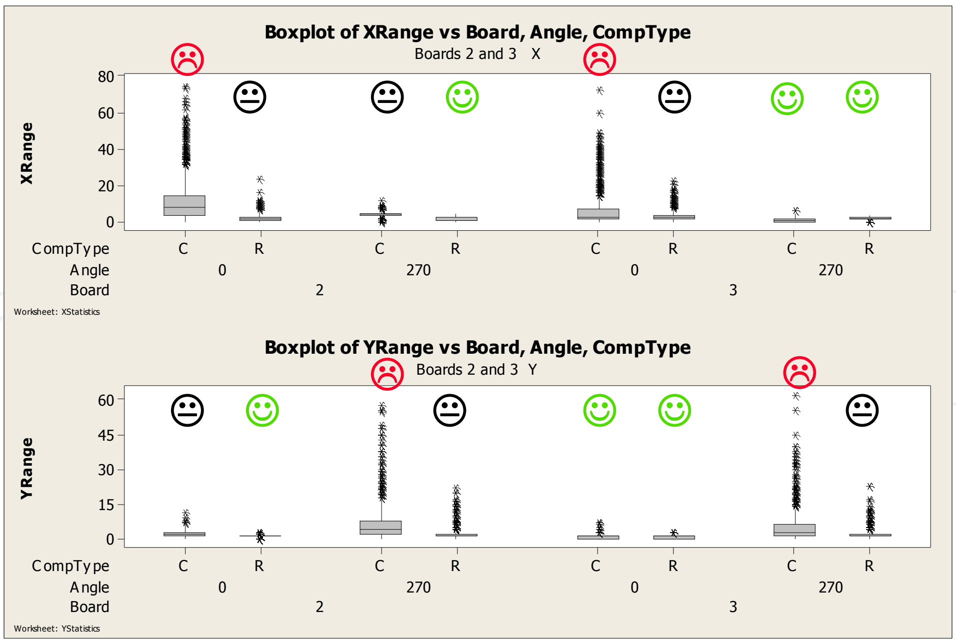


Fig. 5. Boxplot of range for ΔX (XRange) and ΔY (YRange) in relation to board, placement angle and component type, including categorization of repeatability results into "Good = Happy-Face", "OK = Neutral-Face" and "Not Used = Sad-Face" symbols showing the goodness levels. Range values shown in µm, angles in degrees. C=Capacitor, R=Resistor.

4.3 Process Map

It is advantageous to represent system structure and relationships using flowcharts. This provides a complete pictorial sequence of what happens from start to finish of a procedure in order to e.g. identify opportunities for improvement and identify key process input variables. An alternative to flowchart is higher level process map that shows only a few major process steps as activity symbols (Breyfogle, 2003). The process map of a turret type placement machine is shown in Fig.6. The two main areas where input parameters in this study are affecting the process are "X/Y table moves to placement position" and "head comes down to placement height". The process map is created by the six sigma project team.

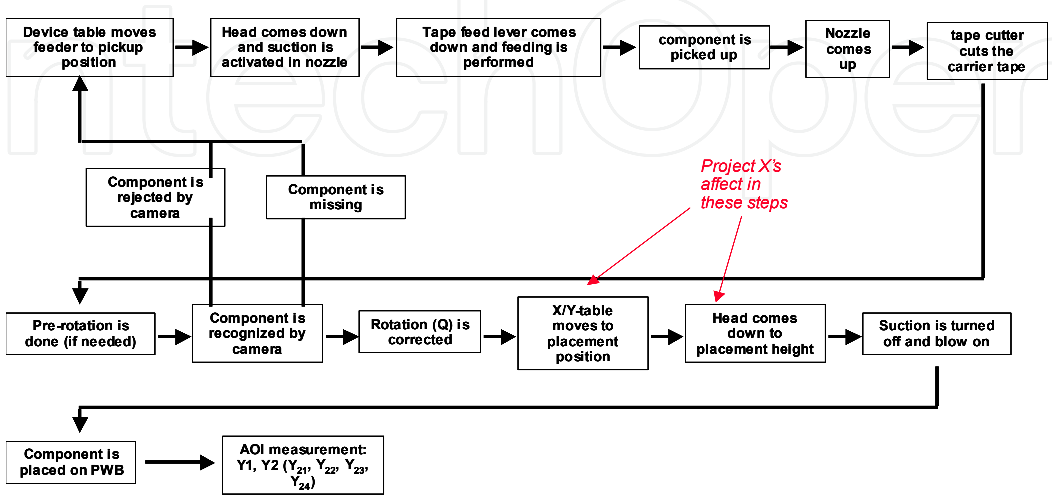


Fig. 6. Component pickup and placement process mapping.

4.4 Measuring basic machine capability with PAM-Board

In this study the purpose was to find out what is minimum placement machine's Sigma Quality Level that still produces good placement quality when spacing between the components is decreased by 33%.

Machines' Placement Sigma Level (PSL) were defined by placing 960 pcs 0402 size resistors and capacitors on sticky taped PWB called PAM-board using the original i.e. current component-to-component spacing (PAM, Placement Accuracy Measurement, see Liukkonen & Tuominen, 2003). Use of double sided sticky tape eliminates e.g. the possible variation caused by poor solder paste printing, and use of original spacing instead of coming tighter one ensures that the machine's measured original process capability is very reliable and fully comparable between the machines. The machine in question was fully calibrated according to manufacturer's specification prior to this PAM-board testing. Placement results were measured using the optical based AOI machine. Customized Microsoft® Office Excel macro for calculating and presenting PSL result is shown in Fig. 7.

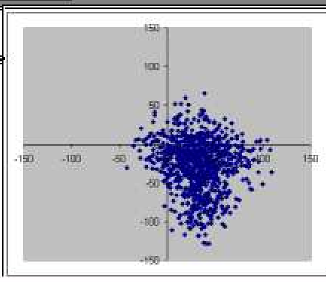
Placement machine has several placement nozzles arranged in a rotating turret head. To be able to test capability for the new spacing with machines which have different Placement Sigma Levels (i.e. measured through PAM-board testing) the offsets of each nozzle were manipulated manually to alter the total variation of the machine. Because the offsets of the nozzles were manipulated symmetrically this did not change the total accuracy (possible offset) of the machine, only total variation (precision). This step produced the simulation possibility for machines having Placement Sigma Levels 1, 2, 3 and 4, to be further studied.

0402 resistors are thinner (thickness 0.3mm) than 0402 capacitors (thickness 0.5mm). Vacuum pickup nozzle for 0402 is wider than the component which produces an expectation that the nozzle currently placing a resistor may hit an adjacent capacitor that has already been placed on the PWB earlier and thus cause a placement defect e.g. missing capacitor. This issue becomes even more critical when we remember that most often components are not picked up summetrically from the center because of free movement of some degree in the pocket of the component feeder. Generally the best placement sequence optimization is achieved when resistors and capacitors are placed mixed based on their location thus producing shortest process cycle time (Liukkonen & Tuominen, 2003). The use of smaller component spacing on PWB may require new placement sequencing so that all resistors are placed before any capacitors, which may deteriorate placement cycle time. The possible need to place resistors before capacitors was the second purpose of the study.

In PAM-Board testing the fixed tolerance area ±100 µm is symmetrical i.e. reference value 0 is in the middle, thus the result is calculated using the basic formula for Sigma Quality Level (Breyfogle, 2003) shown in Equation 1, where USL=100 µm (Upper Specification Limit).

$$\text{Sigma Total} = \frac{\text{USL-}|\mu|}{\text{s}}, \quad \textit{where}\ \mu = \text{mean, s} = \text{standard deviation, USL} = \text{Upper Specification Limit} \tag{1}$$

PAM-test information:	
Serial number:	
PAM-datafile:	
Placement started by head	A
Nickname of equipment:	
Line:	
Date:	06.03.2003
Import PAM data	Imports data from location in cell "PAM-datafile" B3
X and Y correction	Corrects the averages of the measured data to zero
X Correction:	0
Y Correction:	0
Comments:	



Correction values for machine Proper data						
Head	X-corr:	Y-corr:	Deviation X	Deviation Y:	Sigma X	Sigma Y
A-head	-1	2	2,2	4,0	4,0	2,1
B-head	-1	-1	2,6	3,5	3,5	2,5
C-head	-1	0	2,3	2,8	4,0	3,5
D-head	0	0	2,3	3,6	4,4	2,6
E-head	-1	0	2,3	3,5	3,8	2,7
F-head	1	0	2,4	3,3	3,9	2,9
G-head	-1	1	1,9	3,0	5,0	3,0
H-head	1	0	2,1	3,4	4,2	2,9
I-head	0	0	2,6	2,9	3,7	3,3
J-head	0	1	1,5	3,1	6,3	2,9
K-head	0	1	2,3	2,6	4,3	3,6
L-head	1	0	1,9	3,3	4,9	3,0
M-head	1	0	1,7	3,3	5,0	3,0
N-head	-1	1	2,3	3,1	4,0	2,9
O-head	1	-1	1,8	3,8	4,9	2,5
P-head	-1	1	1,9	2,8	5,0	3,3
Q-head	1	-1	2,4	3,2	3,8	2,9
R-head	0	-2	2,3	3,1	4,3	2,7
S-head	0	-2	2,4	2,2	4,1	3,5
T-head	0	0	1,5	2,7	6,3	3,6
Min:	-1,32	-2,18	Deviation total:		Sigma total:	
Max:	1,37	1,71	2,28	3,30	4,4	3,0

Fig. 7. Example of customized Microsoft® Office Excel macro for calculating and presenting PSL result. This placement accuracy measurement (PAM) procedure is generated using 0402 placements (with current component spacing) on sticky tape and on dedicated PAM-board (see Liukkonen & Tuominen, 2003).

4.5 Creating HD-Board in order to define capability for the new component-to-component spacing

Placement capability for the new spacing was measured with the machines having produced different PSL results. This step can also be regarded as representing basic process capability for the new technology requirement. Fig.8 and 9 show process capability distributions from placements using especially designed test PWB called HD-board ("High-Density" placement to highlight new tighter component-to-component spacing). HD-board has 5050 pcs 0402 components placed on wet solder paste and with new tighter component spacing. HD-Board is presented in Fig. 11. All machines of different placement sigma levels are placing the same kind of board using the same process. Subtitle "Placement Sigma Level = 1" in Fig. 8 and 9 means that PSL result of this particular machine has shown "Sigma total:" ~1.0 in original PAM-Board testing, subtitle "Placement Sigma Level = 2" means "Sigma total:" ~2.0 etc. respectively. Sigma Quality Level from HD-Board is presented with "Z.Bench" value in the Fig. 8 and 9, and specification limits (Z.USL, Z.LSL) for it are calculated automatically by Minitab® software from the data. Fig. 8 and 9 show roughly that process changes remarkably somewhere between PSL levels 2 and 3. Generally, instead of sigma level, process capability can also be defined using a Capability Index C_{pk}, value of which is one third of Sigma Quality Level value (Breyfogle, 2003). Analyse phase in the next chapters shows distributions from HD-Board analysed deeply against fixed specification limits.

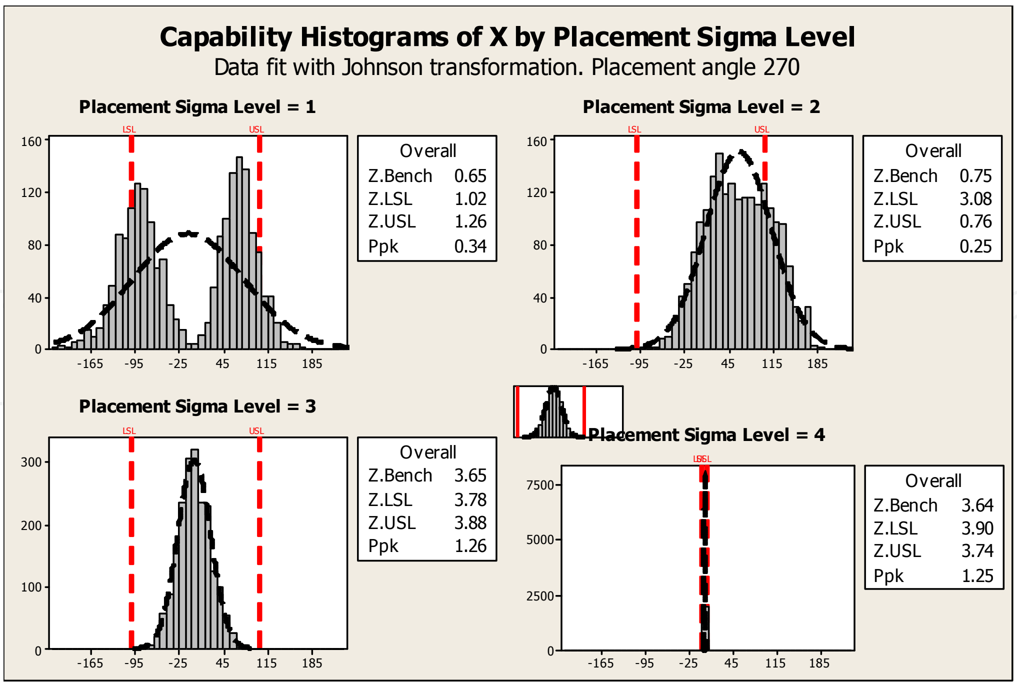


Fig. 8. Capability histograms of 0402 placements on X direction by different PSL values. ΔX values are presented in micrometers.

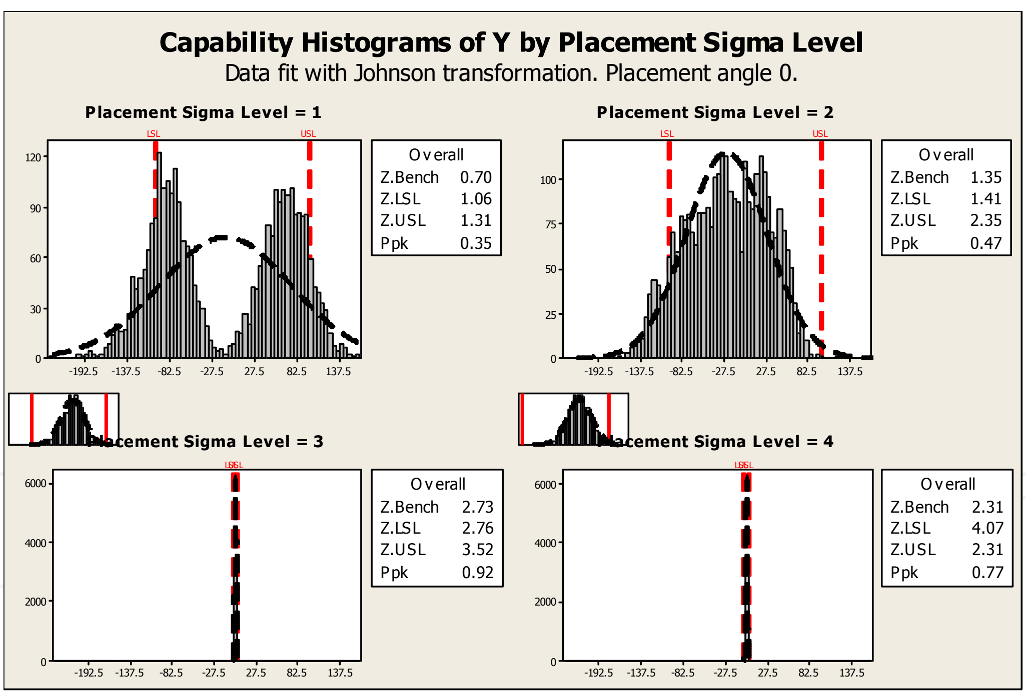


Fig. 9. Capability histograms of 0402 placements on Y direction by different PSL values. ΔY values are presented in micrometers.

Placement sigma levels 1, 2 and 3 are created manually by manipulating the parameters (the means of head groups in north-east, south-east, south-west and north-west directions) of the very same original machine and thus affecting the total deviation (precision) of the placement heads. Means (accuracy, offset) should however be approximately the same in every case, which should be seen in further analysis of distributions.

4.6 XY Matrix

Prioritization matrices are used to help to decide upon the order of importance of a list of items (Breyfogle, 2003). XY matrix is one of them and will take into account not only how often things might happen but also the severity of the effect it will create. Fig. 10 shows XY matrix on placement process key input variables. Prioritization matrices are often completed by the selected project team.

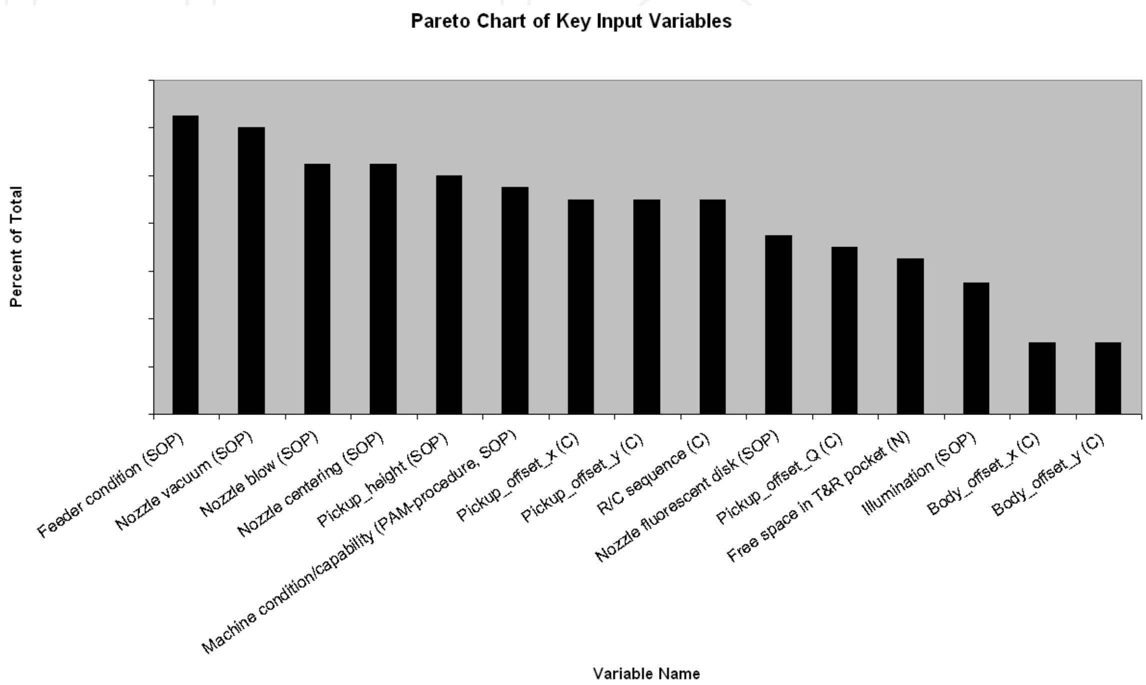


Fig. 10. XY matrix on placement process key input variables showing the relative importance and effect of each input variable X on response variable Y (pickup and placement error). SOP = Standard Operating Procedure, C = Controllable, N = Noise.

4.7 X's from Measure Phase

From measure phase three X's were identified and prioritized for the project scope by the six sigma project team.

1) R/C sequence

Placement sequence of resistors (R) and capacitors (C)
=> *this X is to be further studied*

2) Feeder condition

Elimination of X by using calibrated "error-free" feeder

3) Machine condition/capability

Elimination of X by using maintained/calibrated machine (i.e. machine is in good condition), but what machine placement sigma level from PAM-board is required?
=> *this X is to be further studied*

5. The ANALYSE phase

A DOE was performed with a dedicated HD-board test PWB. Picture of HD board is seen in Fig.11. The HD boards were first solder paste printed with a modern high-accuracy stencil printing machine. Then 0402 resistors and capacitors were placed on the boards by machines having placement sigma levels of 1, 2, 3 and 4 respectively. Totally four HD-boards were produced, one for each placement sigma level. Components were placed only on modules 1 and 3 of the HD-board panel (see Fig.11). Resistors and capacitors were placed on modules 1 and 3 using different placement sequence, which is described in Fig.11. AOI inspection was performed immediately after placement and totally 20 200 components were placed.

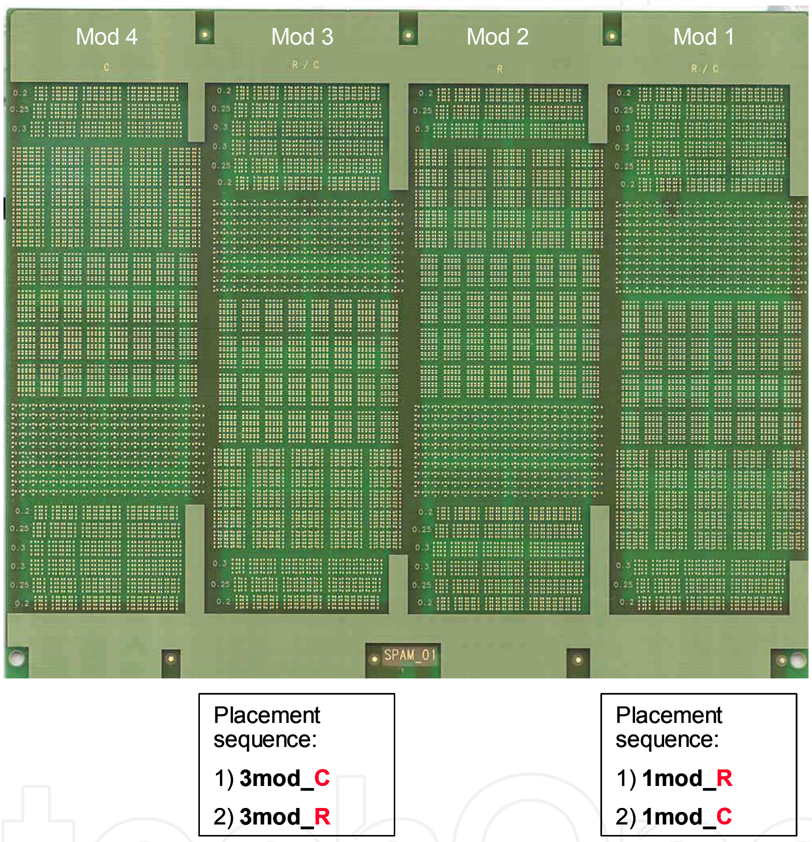


Fig. 11. HD-Board test PWB panel having four identical modules. Modules are numbered from right to left. On Module1 (1mod) all resistors were placed before any capacitors and on Module3 (3mod) all capacitors were placed before any resistors. Modules 2 and 4 were not used at all.

5.1 Graphical Analysis

Totally four HD-boards were produced, one for each placement sigma level. Basic process capability distributions from these boards were already shown in Fig.8 and 9 using specification limits calculated automatically from the data. In this chapter graphical analysis are made from the same data using Minitab® statistical software.

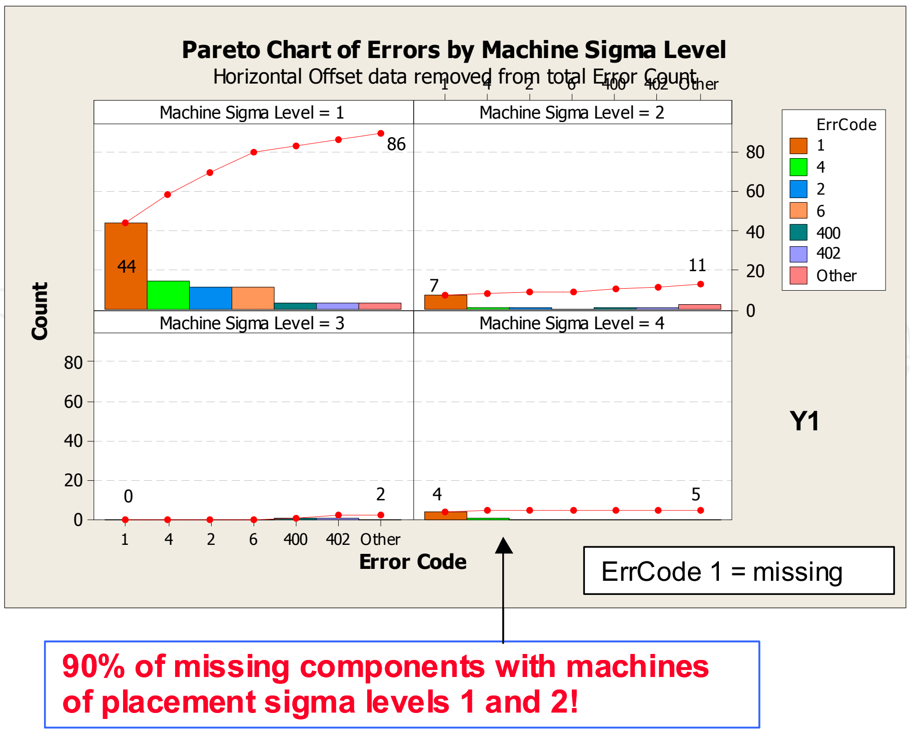


Fig. 12. Pareto chart of placement error counts (Y1) by machine sigma level (i.e. PSL).

The Pareto chart of error counts analysis in Fig. 12 shows that 90% of missing components come from machines having PSL 1 and 2. It can also be seen that PSL 4 board shows 5 errors and PSL 3 only 2 errors, both being however at a very low level.

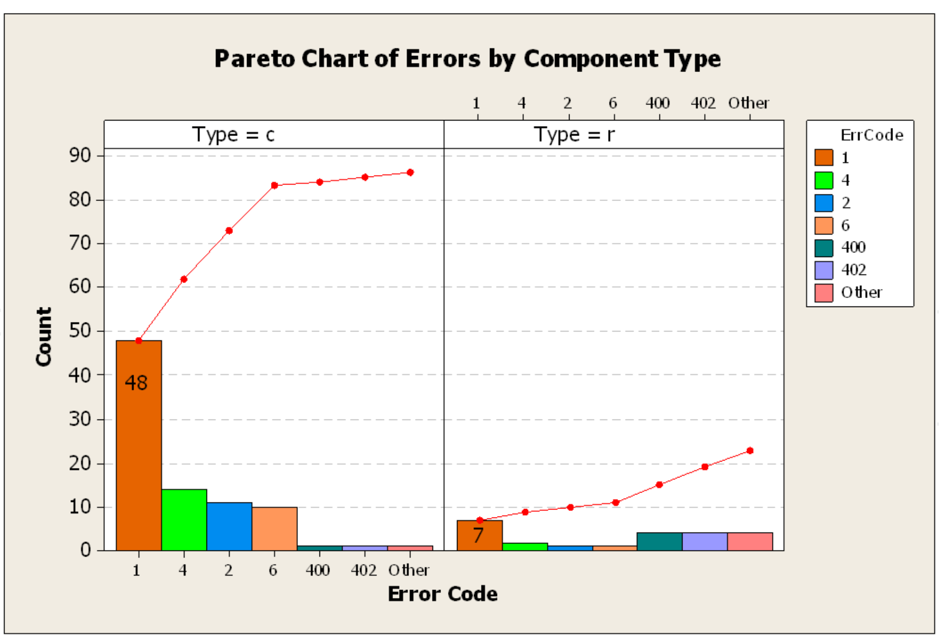


Fig. 13. Pareto chart of placement error counts (Y1) by type (i.e. resistors and capacitors).

Fig. 13 shows Pareto chart of error counts analysis separately for resistors and capacitors. We can see that missing components are clearly found with capacitors, where missing chip count is 48 against that of only seven with resistors.

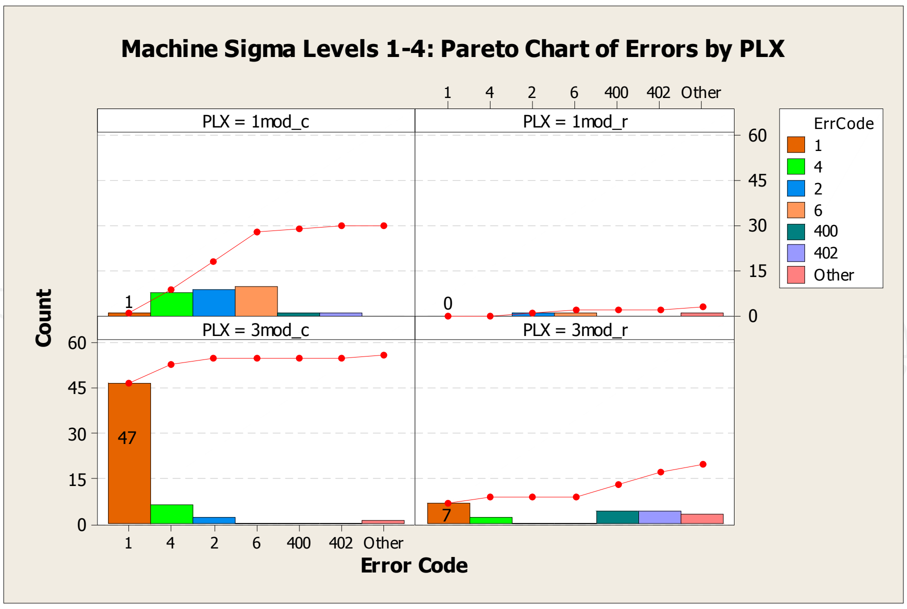


Fig. 14. Pareto chart of placement error counts (Y1) by placement sequence (1mod_c = capacitors on module 1, 1mod_r = resistors on module 1, 3mod_c = capacitors on module 3 and 3mod_r = resistors on module 3).

Further studies show that placement errors are found clearly on module 3 capacitors, which all were placed before any resistors on that module. On module 3 capacitor error count for missing (ErrCode=1) is 47 and resistor error count is 7. On module 1 all resistors were placed before any capacitors and the error levels are then much lower. On module 1 total error count for missing (ErrCode=1) is 1. These conclusions can be made from Pareto chart of error counts analysis by placement sequence in Fig. 14.

All three Paretos in Fig. 12, 13 and 14 show together that placement errors are found with machines of PSL 1 and 2, and in those machines especially with capacitors on module 3. On module 3 all capacitors are placed before any resistors.

Boxplot analysis (see chapter 4.2 for description on boxplot tool.) in Fig. 15 and 16 show that means from placement sigma levels 3 and 4 are approximately on the same level and around zero in X axis, and that mean is slightly on higher level with sigma level 4 in Y axis, which was already seen in basic capability distributions in Fig. 8 and 9. Generally, however, means are good. Standard deviations are good with placement sigma levels 3 and 4, especially in X-axis. Machines of placement sigma levels 1 and 2 show significantly bigger standard deviation. Also mean is off the center with PSL 2 in X-axis.

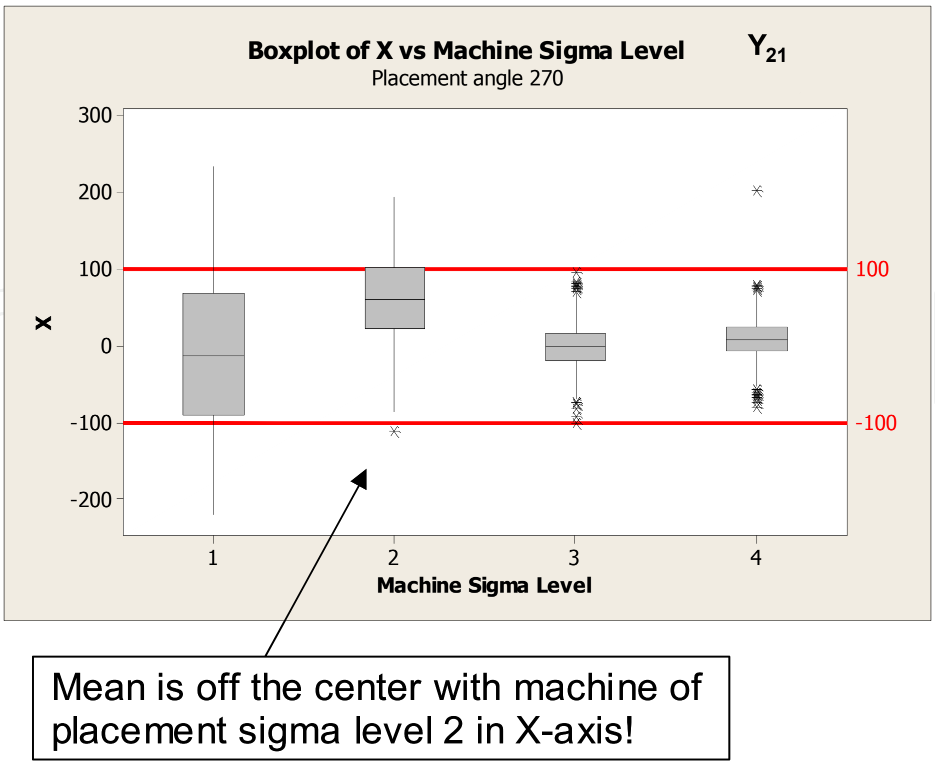


Fig. 15. Boxplot analysis of ΔX results by PSL. ΔX values presented in micrometers.

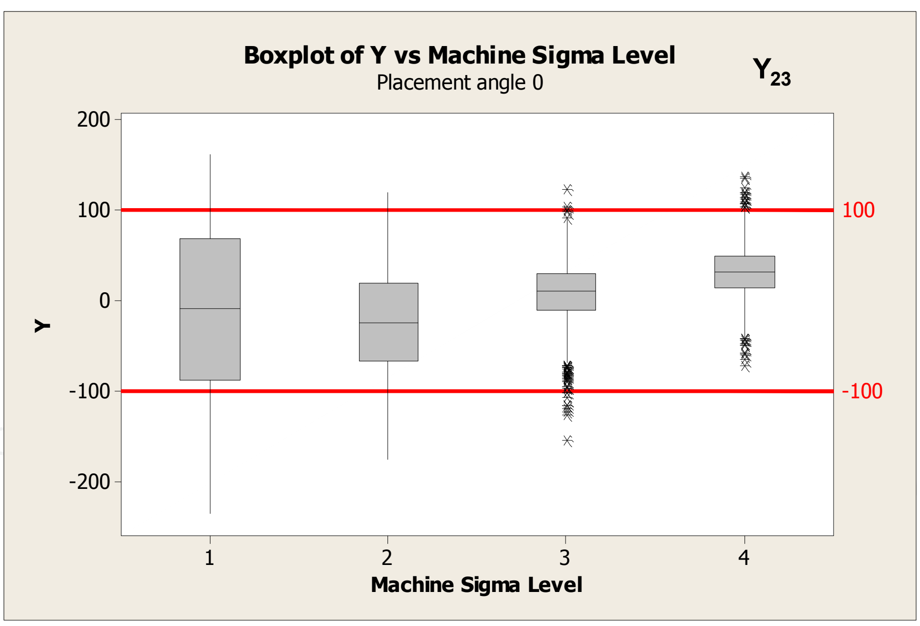


Fig. 16. Boxplot analysis of ΔY results by PSL. ΔY values presented in micrometers.

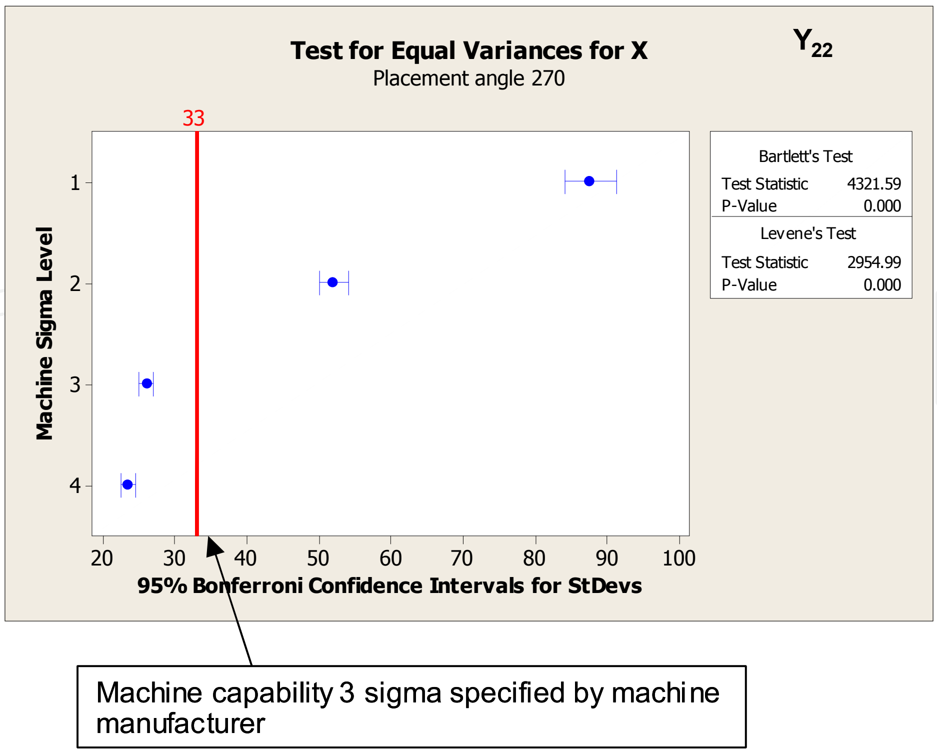


Fig. 17. Test for equal variances of ΔX results by different PSL levels. ΔX values presented in micrometers.

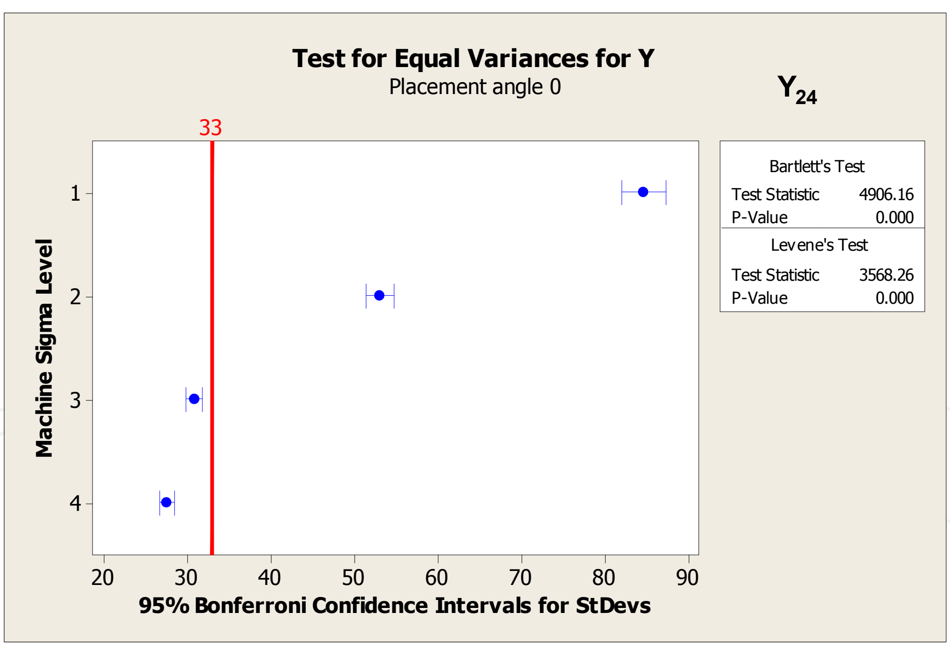


Fig. 18. Test for equal variances of ΔY results by different PSL levels. ΔY values presented in micrometers.

Two analysis of variances in Fig. 17 and 18 show that machines with placement sigma levels 3 and 4 are clearly inside minimum machine capability 3 sigma (Standard deviation 33 µm) specified by machine manufacturer. Standard deviation required to achieve six sigma process would be 17 µm. Analysis show also that machines with placement sigma levels 1 and 2 are clearly outside the 3-sigma limit on both axes.

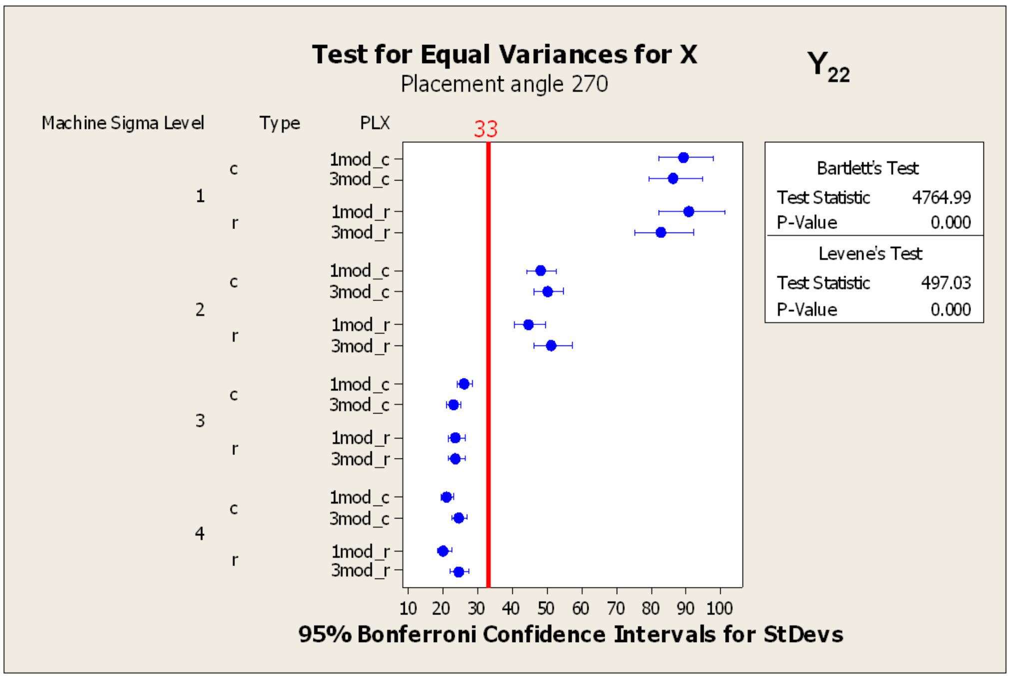


Fig. 19. Test for equal variances of ΔX by PSL, component type (R/C) and placement sequence for R/C. ΔX values presented in micrometers.

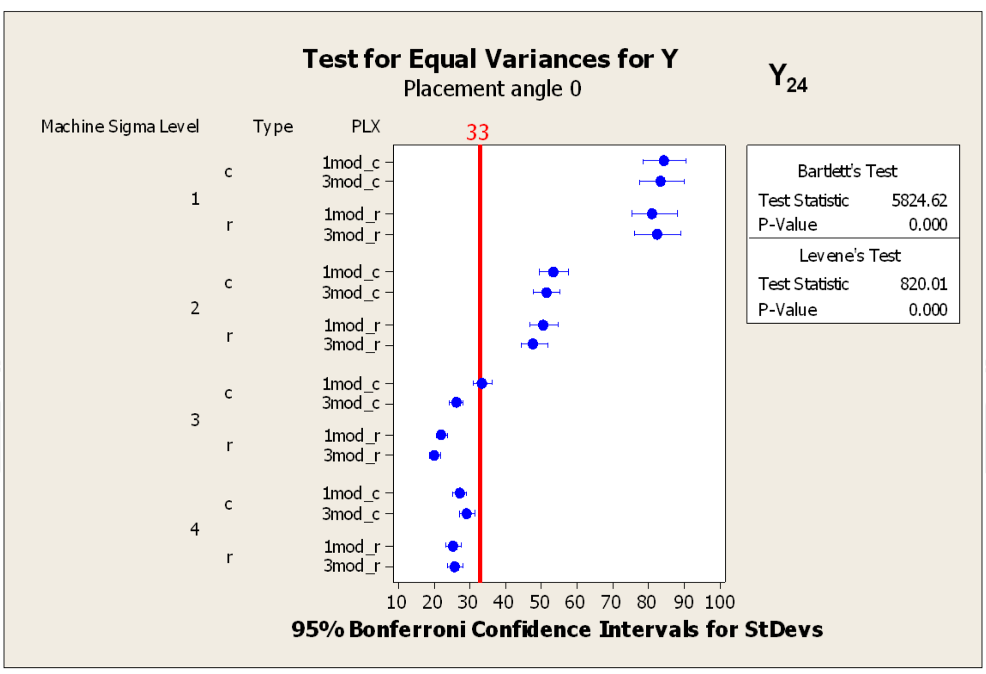


Fig. 20. Test for equal variances of ΔY by PSL, component type (R/C) and placement sequence for R/C. ΔY values presented in micrometers.

Analysis of variances in Fig. 19 and 20 show that no difference is found between module 1 and module 3 results when analyzed separately for resistors and capacitors (i.e. component type) and machine sigma levels. This means that no difference is found with placement sequence for resistors vs. capacitors based on variance test inside each PSL.

5.2 Test of Hypotheses

Test of hypotheses showed in this chapter are meant to make sure that our sample sizes have been large enough to give reliable results during the graphical analysis made.

5.2.1 Power and Sample Size

2-Sample t Test in Minitab® statistical software

Testing mean 1 = mean 2 (versus not =)
Calculating power for mean 1 = mean 2 + difference
Alpha = 0.05, assumed standard deviation = 33

Sample Size	Power	Difference
5050	0.9	2.12898

The sample size is for each group. With sample size 5050 and "target" standard deviation 33 μm (3 sigma process, specified by machine manufacturer) we are sensitive enough to reliably detect 2.12 μm shift in distribution mean (95% Confidence Interval). This shows that our analysis made are very reliable.

Test for Two Proportions in Minitab® statistical software

Testing proportion 1 = proportion 2 (versus not =)
Calculating power for proportion 2 = 0.5
Alpha = 0.05

Sample Size	Power	Proportion 1
5050	0.9	0.532231

The sample size is for each group. With sample size 5050 and error rate 50% (proportion 2 default in Minitab® statistical software is 0.5) we are sensitive enough to reliably detect 3.2% error rate change (95% Confidence Interval). This shows that our analysis made are very reliable.

5.2.2 Test and Confidence Intervals for Two Proportions

P-charts (proportion of defects) were created in Minitab® to analyze statistically that the sample sizes used have been statistically large enough and therefore the confidence intervals are acceptable (Breyfogle, 2003; Montgomery, 2008).

Fig. 21 shows error counts per PSL level in P-chart from Minitab® including confidence intervals. Fig. 21 is supporting the following statistical analysis A, B and C. It should be noted that "HorOff" (horizontal offset) placement errors were removed from the following analysis data because AOI showed poor repeatability (precision) with that inspection direction (see chapter 4.2).

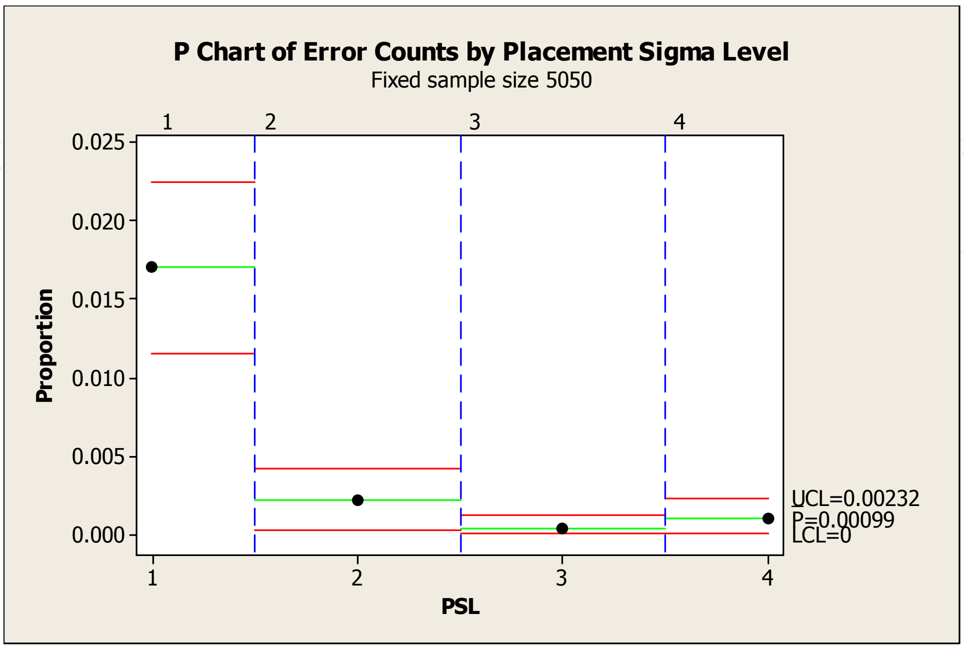


Fig. 21. Error counts per PSL level in P-chart from Minitab® including confidence intervals.

A) Test and CI for Two Proportions in Minitab® statistical software (Error Count between Machine Sigma Level 1 and 2, HorOff removed)

Sample	X	N	Sample p
1	86	5050	0.017030
2	11	5050	0.002178

Difference = p (1) - p (2)
Estimate for difference: 0.0148515
95% CI for difference: (0.0110585, 0.0186445)
Test for difference = 0 (vs not = 0): Z = 7.67 P-Value = 0.000
=> since P-value <0.05 there is statistically sicnificant difference between proportions of PSL level 1 and 2

B) Test and CI for Two Proportions in Minitab® statistical software (Error Count between Machine Sigma Level 2 and 3, HorOff removed)

Sample	X	N	Sample p
1	11	5050	0.002178
2	2	5050	0.000396

Difference = p (1) - p (2)
Estimate for difference: -0.00178218
95% CI for difference: (-0.00318020, -0.000384155)
Test for difference = 0 (vs not = 0): Z = -2.50 P-Value = 0.012
=> There is statistically sicnificant difference between proportions of PSL level 3 and 2

C) Test and CI for Two Proportions in Minitab® statistical software (Error Count between Machine Sigma Level 3 and 4, HorOff removed)

Sample	X	N	Sample p
1	2	5050	0.000396
2	5	5050	0.000990

Difference = p (1) - p (2)
Estimate for difference: -0.000594059
95% CI for difference: (-0.00162049, 0.000432366)
Test for difference = 0 (vs not = 0): Z = -1.13 P-Value = 0.257
=> There isn't statistically sicnificant difference between error counts of PSL level 3 and 4, which can also be seen from Fig. 21 where confidence intervals overlap between PSL3 and 4.

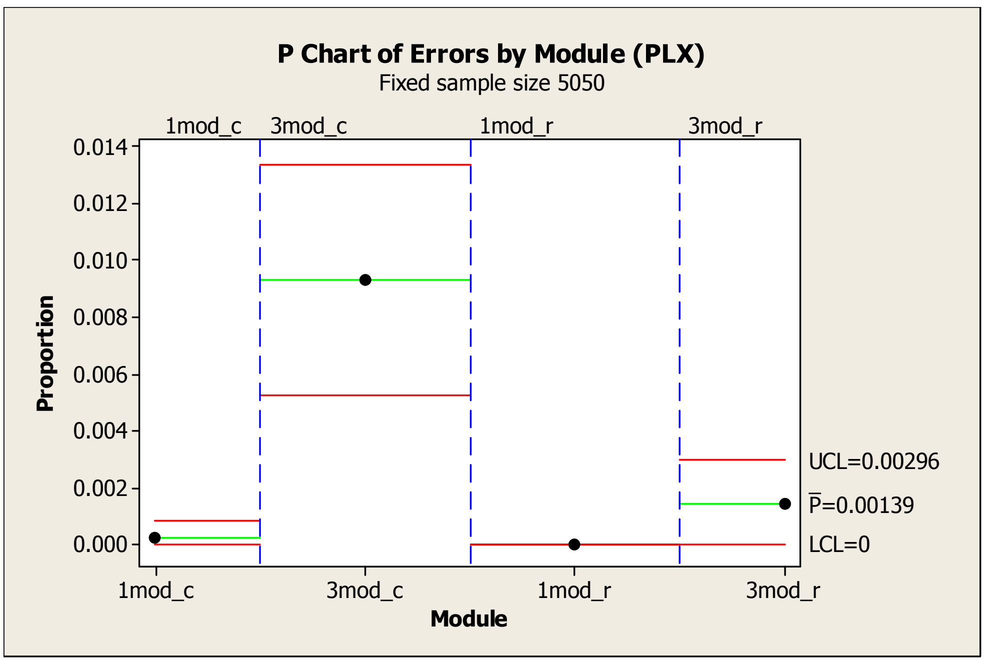


Fig. 22. Error counts per PWB module in P-chart from Minitab® including confidence intervals.

Fig. 22 shows Error counts per PWB module in P-chart from Minitab® including confidence intervals. PWB module represents different placement sequences for resistors and capacitors. Fig. 22 is supporting the following statistical analysis D and E.

D) Test and CI for Two Proportions in Minitab® statistical software (Error count for "Missing Chip" between 1mod_c and 3mod_c)

Sample	X	N	Sample p
1	1	5621	0.000178
2	47	5621	0.008362

Difference = p (1) - p (2)
Estimate for difference: -0.00818360
95% CI for difference: (-0.0105895, -0.00577774)

Test for difference = 0 (vs not = 0): Z = -6.67 P-Value = 0.000
=> There is statistically sicnificant difference between proportions 1mod_c and 3mod_c

E) Test and CI for Two Proportions in Minitab® statistical software (Error count for "Missing Chip" between 1mod_r and 3mod_r)

Sample	X	N	Sample p
1	0	4476	0.000000
2	7	476	0.014706

Difference = p (1) - p (2)
Estimate for difference: -0.0147059
95% CI for difference: (-0.0255196, -0.00389221)
Test for difference = 0 (vs not = 0): Z = -2.67 P-Value = 0.008
=> There is statistically sicnificant difference between proportions of 1mod_r and 3mod_r

5.3 X's from Analyze Phase

What placement sigma level is required to place high-density 0402s with good quality? Analyses showed that the problem is not the mean, e.g. even with placementy sigma level 1 the mean is in the center of the specification limits (±100um) but also a lot of data is outside the limits. The problem is concentrated generally on too large deviation. Because lower placement sigma levels (1,2,3) are "created" manually by manipulating the machine parameters of the very same machine and thus affecting the deviation of the placement heads, means are approximately the same and good in every case. If PSL procedure (PAM-board testing) shows that the means are not in the center (offset) they can be moved easily inside the specification limits by changing the parameter values and ensuring then the result by repeating PSL measurement. The X's from analyze phase can now be defined as follows:

1) Define required placement sigma level in order to keep standard deviation and error counts within desired range

2) Investigate the effect of forced placement sequence to error counts and standard deviations between machines of different placement sigma levels

6. The IMPROVE phase

6.1 DOE Plan

Because this six sigma project is quite short some phases like analyze and improve were combined partly together already in the beginning of planning the experiments. DOE has been mostly presented already in the previous analysis and only the interactions found there are presented in this improve phase.

6.2 DOE Results

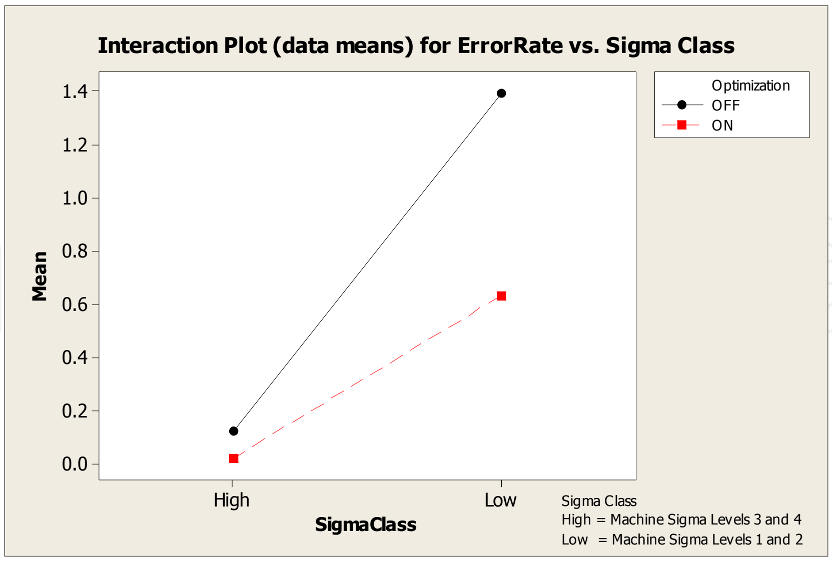


Fig. 23. Interaction plot of error rate versus Sigma class. Optimization ON means that all resistors have been placed before any capacitors. Sigma class HIGH includes PSL levels 3 and 4, LOW includes PSL 1 and 2.

Interaction plot of Minitab® in Fig. 23 shows that optimization of resistors' and capacitors' placement sequence is not needed when placement sigma level of the machine is at least 3 sigmas (i.e. belonging to high sigma class). However we can clearly see that with low sigma class machines placement sequence has a strong effect on placement Quality.

Improvement actions are based on analysis of error counts and variance analysis. Standard deviation can be measured using PSL procedure (PAM-board) and means/offsets can be corrected if those are found. The analysis made show that PSL result is critical when defining high-density capability of an individual placement machine.

7. The CONTROL phase

7.1 Control Plan

Placement machines having placement sigma level 3 or higher can be used for high-density placement. However this six sigma study strongly recommends ensuring the capability using PAM-board testing for individual machines before starting high-density production for the first time due to e.g. machine irregularities. Forced placement sequence of resistors and capacitors is not needed for machine sigma levels 3 or higher. Machines having placement sigma level lower than 3 may not be used for high-density placement, not even with forced placement sequence, which, however, gives better placement results with these machines; we can say clearly better but not good enough.

When machines are ranked according to PSL result the best ones can then be selected for high-density production. The project recommends that PSL level is measured on regular basis e.g. once per month to maintain the placement accuracy required by the new PWB technology.

8. Conclusions

Turret type placement machines having different placement sigma levels were investigated and "ranked" according to their capability to place high-density 0402s. This was managed using standard commercially available 0402 type components and simple FR4 type PWB material. Standard widely used in-line type AOI machine was used successfully for measurements. Project outcome was that placement machines having sigma level 3 or better can be used. Possible need for forced placement sequence was also investigated. Project found out that we don't have to place resistors before capacitors (with placement sigma level ≥ 3), which would have decreased quantitative placement capacity in the future. As an extra result the company can also delay globally some preliminary planned machine investments that were based on new technology requirements.

Future studies should concentrate on developing placement machine accuracy measurements for leaded and especially solder bumped integrated circuits (IC) type components, where the solderable bumbs to be used in component alignment by the placement machine are located beneath the component body and therefore are invisible after placement. Some basic and pioneering development in this area has already been published by some members of the project team (Hurtig & Liukkonen, 2007).

9. Acknowledgement

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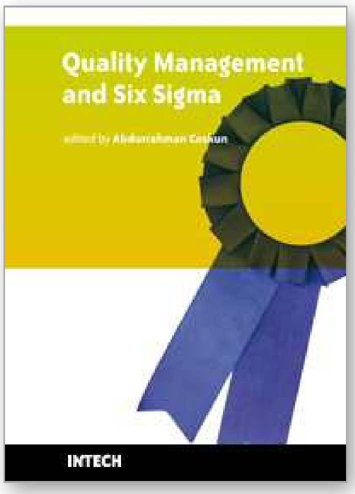

Quality Management and Six Sigma
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If you do not measure, you do not know, and if you do not know, you cannot manage. Modern Quality Management and Six Sigma shows us how to measure and, consequently, how to manage the companies in business and industries. Six Sigma provides principles and tools that can be applied to any process as a means used to measure defects and/or error rates. In the new millennium thousands of people work in various companies that use Modern Quality Management and Six Sigma to reduce the cost of products and eliminate the defects. This book provides the necessary guidance for selecting, performing and evaluating various procedures of Quality Management and particularly Six Sigma. In the book you will see how to use data, i.e. plot, interpret and validate it for Six Sigma projects in business, industry and even in medical laboratories.

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