Using Lean Six Sigma to Optimize Critical Inputs on Solder Paste Printing

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Abstract
Solder paste printing is the first step in the surface mount manufacturing process for PCBA assembly. When the solder paste printing process is uncontrolled, defects can be produced, which may not become apparent until the PCBA is downstream. Even though defects are present, the PCBAs may not be scrapped because rework can fix the defects. This can make the cost of poor quality appear low because the scrap rate is low. These rework loops are also called the hidden factory. The hidden factory means that these rework loops hide the cost of poor quality associated with fixing the defects because the PCBA was not produced right the first time. Rework also reduces efficiency because of the time required to fix the defect. From a lean perspective, rework is the waste of defect, which is one of the eight wastes.

The surface mount solder paste printing process has a solder paste inspection process immediately afterwards. This inspection process measures certain characteristics of the solder paste, such as volume, height, area and offset. The inspection process will alert the operator to a potential defect. When an alert happens, the operator will look at the PCBA to determine whether or not there is a true defect. If the operator determines that there is no defect, or the alert was a false failure, the operator will manually override the solder paste inspection machine and label the PCBA as a pass. The PCBA then proceeds to the parts placement machines. The risk present in the manual override is that it relies on operator judgement. There is also the risk that if too many false failures present themselves, the operator may be led to believe that every alert is a false failure and immediately override the alert even though a defect is present. This can be a very high risk scenario, especially with PCBAs that go into medical devices. Some manufacturers are looking into turning off the override function, which will stop the line if the automated inspection system sees a potential defect. This will prevent defective PCBAs from getting to the customer but will cause efficiency loss, and increased cost, when the line stops. There is also the risk of not getting the customer the product on time. This makes it real important to identify the critical inputs to the solder paste printing process and ensure they are controlled so that manufacturers are able to optimize the output of the process.

This paper will discuss how Lean Six Sigma techniques were used to optimize the solder paste printing process. It will highlight how a cross-functional team used the structured Define, Measure, Analyze, Improve and Control (DMAIC) methodology to identify and control the critical inputs. The advantage of the Lean Six Sigma methodology is that it guides the team through the rigorous structured process so that all possible inputs are considered and the critical ones can be identified. The cross-functional team is led by a Master Black Belt or Black Belt, who is skilled in both the technical aspects of the Lean Six Sigma methodology along with the soft skills needed for team management. The paper will demonstrate the use of tools such as the IPO (Input-Process-Output) diagram, Cause and Effect Diagram, Fractional Factorial Experiments and Full Factorial Experiments. It will then show how pilot runs were made in order to confirm the model, which was drawn from the designed experiments.

Introduction
Electronics manufacturing companies, that assemble PCBAs that go into medical devices, have to follow guidelines put forth by the FDA. The FDA requires process validation requirements such as installation qualification (IQ), operational qualification (OQ) and performance qualification (PQ). The goal is to ensure that manufacturers have control over their processes to that a constant and reliable product is produced. Installation qualification is establishing by objective evidence that all key aspects of the manufacturing equipment adhere to the manufacturer's approved specification. Operational Qualification is defined as the means establishing by objective evidence process control limits and action levels which results in product that meets all predetermined requirements. Performance qualification is defined as establishing by objective evidence that under anticipated conditions, the process consistently produces product which meets all predetermined requirements.

This paper will specifically talk about how the Lean Six Sigma tools were utilized in the operational qualification process. During the operational qualification process, the inputs should be challenged to ensure that they will result in a product that meets all defined requirements under worst case conditions. The reason for worst case testing is because even though we can control the inputs to the process under the short term, environmental conditions will change over the long term and we must make our process robust to these changes. Once the critical inputs are defined, the ranges where they can be varied must also

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be defined. Once the ranges are defined, the expectation is that you will not vary outside these settings. This is why Lean Six Sigma tools must be used to determine the critical inputs and the ranges in which they can vary.

Define Phase

Before you can begin, a specific product needs to be chosen. When you have a high mix, low volume environment with many different customer designs, you need to focus on one at a time. The critical inputs to the solder paste printing process may be the same but the target settings and ranges may be different depending on the pad design. The team working on this project chose the assembly and then proceeded to identify the measurable outputs for the solder paste printing process. The Manufacturing Engineering Subject Matter Expert over the surface mount process was the critical team member for determining the measurable outputs. Figure 1 below shows the measureable outputs and their specifications.

Volume of Solder
  a. Target: 100% of aperture L x W x H
  b. LSL: 65% of aperture L x W x H
  c. USL: 165% of aperture L x W x H

Location of Solder
  a. Target: Offset = 0
  b. USL: Offset =30% max

Figure 1

After the measureable outputs were determined, the next step was to select the pad locations which would initially be measured. Eight pad locations were chosen. The pad locations varied in size so we could see how the solder paste could be effectively optimized. In the end, the team would look at the performance for the whole board.

Measure Phase

The first step in the Measure Phase was to understand the process by using an Input-Process-Output (IPO) diagram. Figure 2 below shows the IPO diagram for the solder paste printing process.

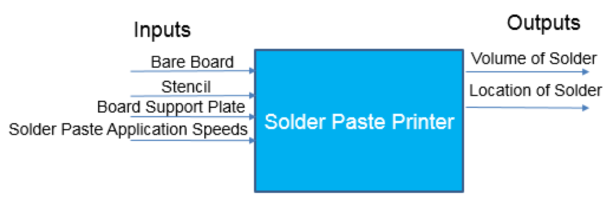

Figure 2

The IPO diagram helped the team to visualize how the solder paste printing process works and determine some of the inputs which could affect the volume of solder and offset (location of solder).

Before the team obtained baseline measurements on the outputs, they had to ensure a Gage R&R was completed on the solder paste inspection machine. The Six Sigma tools are used to reduce variation. Total variation is made up of measurement system variation and part to part variation. Since our goal is to be able to see and reduce part to part variation, we want variation in the measurement system to be very low. Since Gage R&R's were completed on all process measurement systems annually, the team reviewed the most recent Gage R&R on the solder paste inspection machine to ensure that it was within acceptable limits. Figure 3 below shows the details of the Gage R&R analysis.

1. Pad 410 [1206 Chip Pad]

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.06841	0.4105	1.03
Repeatability	0.05064	0.3039	0.76
Reproducibility	0.04599	0.2759	0.69
Operators	0.04599	0.2759	0.69
Part-To-Part	6.63384	39.8031	99.99
Total Variation	6.63420	39.8052	100.00

Figure 3

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2. Pad 808 [0402 Chip Pad]

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.13697	0.8218	2.20
Repeatability	0.08304	0.4982	1.34
Reproducibility	0.10893	0.6536	1.75
Operators	0.08268	0.4961	1.33
Operators*Parts	0.07093	0.4256	1.14
Part-To-Part	6.21792	37.3075	99.98
Total Variation	6.21943	37.3166	100.00

3. Pad 982 [0201 Chip Pad]

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.18287	1.0972	2.13
Repeatability	0.18072	1.0843	2.10
Reproducibility	0.02799	0.1680	0.33
Operators	0.02799	0.1680	0.33
Part-To-Part	8.58952	51.5371	99.98
Total Variation	8.59147	51.5488	100.00

4. Pad 2010 [0.4mm pitch QFP Pad]

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.3301	1.9806	2.72
Repeatability	0.3301	1.9806	2.72
Reproducibility	0.0000	0.0000	0.00
Operators	0.0000	0.0000	0.00
Part-To-Part	12.1207	72.7244	99.96
Total Variation	12.1252	72.7513	100.00

Figure 3

In the analysis, we are looking at %Study Variation under Total gage R&R. The analysis showed that measurements on 4 pads of different sizes had acceptable results with Gage R&R less than 10%.

The next step performed by the team was to pull 6 months of baseline data off the solder paste inspection machine for the reference designators the team was looking at. Table 1 shows the baseline data results.

Table 1

Pad	Mean	StDev	Max	Min
E18	106.63	2.63	112.73	94.61
U6	108.06	6.90	134.94	81.29
U3	102.63	6.36	126.24	75.69
E21	120.08	5.05	132.52	106.42
U17	107.56	4.31	119.27	94.02
CR5	102.77	4.68	115.72	88.60
U16	103.12	6.62	116.03	88.10
Y2	95.35	3.47	104.08	85.37

The analysis showed that the range of the average volume over the 8 pads varied by about 11%. Baseline date was also pulled for all pads across the board. Figure 4 shows the results of the baseline capability analysis.

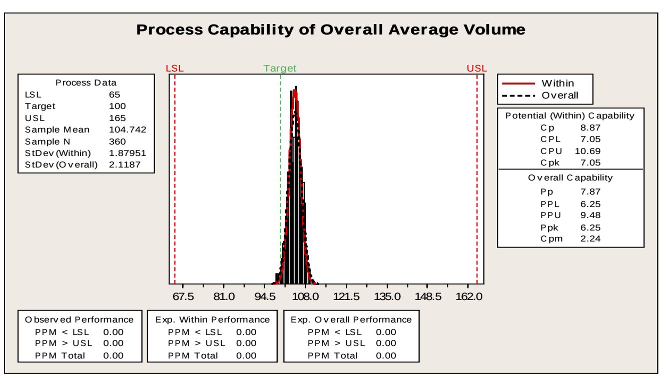


Figure 4

The baseline analysis shows that the short term process capability (Cpk) is 7.05 and long term performance (Ppk) at 6.25. The mean is shifted slightly to the right of the target at 104.742%.

Analysis Phase

Moving into the Analysis Phase, the team needed to brainstorm all the potential inputs that could affect the solder paste volume and offset. They decided to use a Cause and Effect Diagram, also known as a Fishbone Diagram, to help them brainstorm all the potential inputs. This tool is useful because it ensures that all process variables are considered before beginning any experiments. The team was able to identify key equipment parameters that might affect the measured output. Figure 5 shows the Cause and Effect Diagram that was developed by the team.

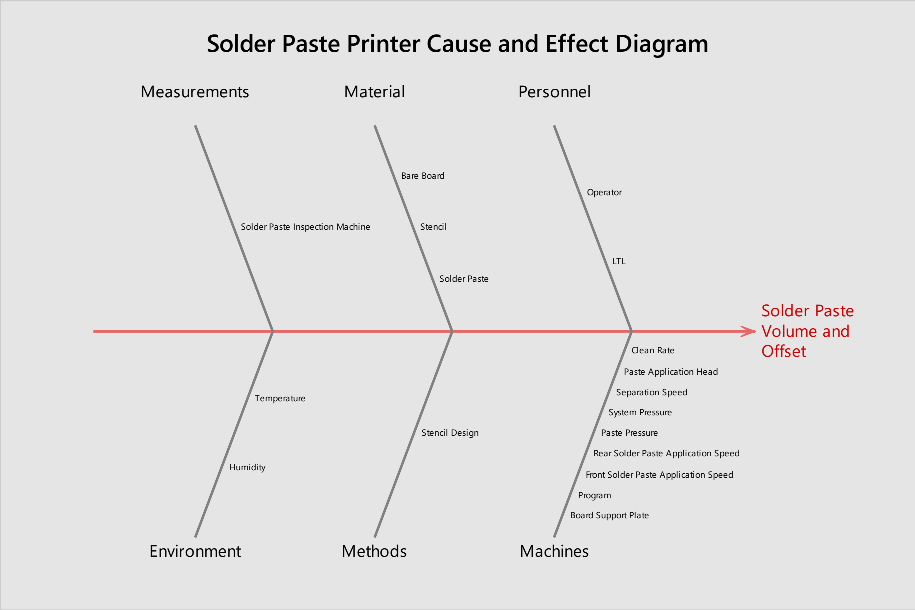


Figure 5

After developing the Cause and Effect Diagram, the team needed to determine which input factors they would look at for the designed experiments in the Improvement Phase. SOP are factors that would be held constant, N are noise factors which cannot be controlled or are very difficult/expensive to control, DF are design factors which would be varied during the experiments. They started with the Materials Branch. Bare board was going to be kept as an SOP because this would not affect the outputs. The board design and supplier was controlled by the customer and was set. Stencil was also kept as an SOP. This is not something which would be changed without an Engineering Change Order. Solder paste was kept as an SOP because once this is established for the design, it would take testing and customer approval to change. Under the measurements branch, the solder paste inspection machine is an SOP because it is a piece of capital equipment on the surface mount line and cannot be changed without significant cost. Under the Environment Branch, both temperature and humidity are noise factors which were currently not controlled. Under the Machines Branch, the board support plate and program were kept as SOP factors. The board support plate is a constant set-up. The overall program was kept as an SOP. The type of paste application head was also kept as an SOP. The team decided to look at six machine factors for the designed experiments. These factors were front solder paste application speed, rear solder paste application speed, paste pressure, system pressure, separation speed and clean rate.

Improve Phase

The Improve Phase is where the team looked into performing Design of Experiments. Design of Experiments usually starts with screening experiments followed by full factorial experiments. Screening experiments are used to screen out insignificant input variables when you have a large number of them. The advantage of screening experiments, also known as fraction factorials, is that you can run them with a few number of runs. Since you only have a few number of runs, the resolution of the design is less, which means interaction effects are limited. Since the team was looking at 6 factors, each at 2 levels, a full factorial would have meant 64 runs with only 1 replication. If the decision was made to replicate the experiment, this would equate to 128 runs. A more cost effective solution was to conduct a screening experiment followed by a full factorial experiment. Table 2 shows the factor level settings for the 6 factors in the screening experiment.

Table 2

Factor	Low Level Setting	High Level Setting
Front Solder Paste Application Speed	20 mm/sec	120 mm/sec
Rear Solder Paste Application Speed	20 mm/sec	120 mm/sec
Paste Pressure	1.0 kg of force	3.0 kg of force
System Pressure	1.0 bar	3.0 bar
Separation Speed	0.5 mm/sec	4.5 mm/sec
Clean Rate	1 print	5 prints

The team then created the screening design in the statistical software. Figure 6 shows how the inputs factors were varied during the first 6 runs. The experiment was fully randomized.

	Front Application Speed	Rear Application Speed	Paste Pressure	System Pressure	Separation Speed	Clean Rate
Entry Direction	120	20	1	1	4.5	1
2	120	120	3	1	4.5	1
3	120	20	1	3	4.5	5
4	120	20	1	3	4.5	5
5	20	120	1	3	4.5	1
6	120	20	3	3	0.5	1

Figure 6

The screening design chosen was a ¼ fractional factorial with 2 replicates. This equated to 32 runs. In order to get buy-in from the operations staff, the team put together a plan for running the experiment and presented it to them. A total of 20 panels were taken from stock and scrapped as engineering samples. After running through the solder paste application process and solder paste inspection machine, the solder paste would be washed off the panels so they could be reused. This would minimize the scrap cost. The cost per panel was $1.67, which equated to $33.40 for the 20 panels. The plan was to set up the solder paste application machine for each run according to the input settings for each of the 6 factors. Three panels would be run only through the solder paste application machine to ensure printing was stabilized. Then 5 panels would be run through the solder paste application machine and the solder paste inspection machine. The time for each run was estimated at 5 minutes. Setting up each run and cleaning the panels, panels would be cleaned by an operator in parallel with setting up the run, was estimated at 10 minutes. This equated to 15 minutes per run. For 32 runs this came out to a total of 8.5 hours per run. Three people at an estimated cost of $94 per hour would equate to a labor cost of $799. With this information, the team estimated the total cost of the experiment at $832.40.

In order to ensure that data was captured properly by the solder paste inspection machine, it was decided not to place label barcodes on the panels but manually enter the run and panel information. Run 1 panel 1 would be coded as 1-1, run 1 panel 2 coded as 1-2, run 3 panel 1 as 3-1, etc.

The experiment was run and the volume, x-offset and y-offset were measured for all pads. For the analysis, these three measurements were exported from the solder paste inspection machine for the 8 pads which the team were looking at. The main effects plot for volume on one of the pads is shown in Figure 6.

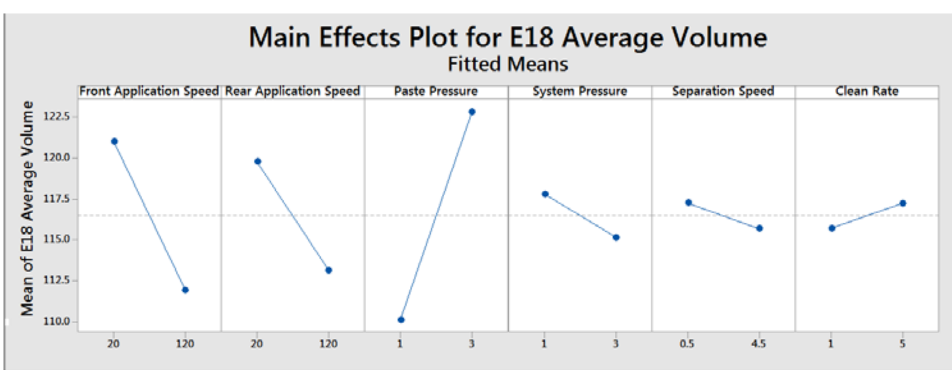


Figure 7

Looking at the main effects plot, main effects with the steeper sloped lines are the ones which have a stronger effect as the inputs change from low to high. For this pad, it appears that front application speed, rear application speed and paste pressure have more of an effect than system pressure, separation speed and clean rate. Main effects plots only provide a graphical analysis so you can see which inputs appear significant. Statistical analysis was performed and Figure 7 shows what was found to be statistically significant in this example. Any bar crossing the red line is statistically significant at a confidence level of 95%.

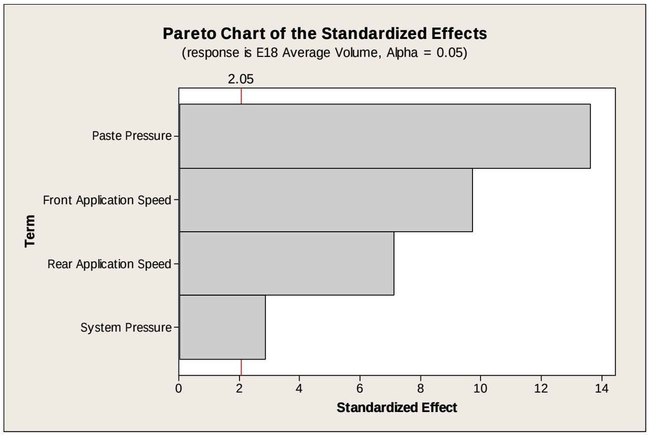


Figure 8

This same analysis was performed for all 8 pads on %volume, x-offset and y-offset. This meant the team had a total of 24 possible outputs to analyze. Since the inputs had varying statistical effects, the team put together a table to see how many outputs they were statistically significant in. Table 3 shows the inputs, how many outputs they were significant in and % of the total outputs they influence.

Table 3

Input	Total (24 Outputs)	% of Total
Paste Pressure	19	79%
Front Solder Paste Application Speed	17	71%
Rear Solder Paste Application Speed	23	96%
System Pressure	15	63%
Clean Rate	12	50%
Separation Speed	8	33%

In order to determine which input variables to carry over to a full factorial experiment, the team decided to look at the ones which were significant in 70% or more of the potential outputs. Based on the table above, the team decided to look at Paste Pressure, Front Application Speed and Rear Application Speed in the full factorial experiment.

For the full factorial experiment, the team decided to keep the level settings of each factor the same. Table 4 shows these settings.

Table 4

Factor	Low Level Setting	High Level Setting
Front Solder Paste Application Speed	20 mm/sec	120 mm/sec
Rear Solder Paste Application Speed	20 mm/sec	120 mm/sec
Paste Pressure	1.0 kg of force	3.0 kg of force

The other 3 factors, which were looked at during the screening design, became SOP factors for the full factorial design. Their settings are shown in Table 5.

Table 5

System Pressure	3 bars
Clean Rate	5 prints
Separation Speed	4.5 mm/sec

A full factorial with 2 replicates was run. Figure 8 shows how the experiment was set up.

Front Application Speed	Rear Application Speed	Paste Pressure
120	120	1
120	20	3
20	120	1
120	120	3
20	20	3
20	20	1
20	120	3
120	20	1
120	20	1
120	120	3
20	20	3
120	120	1
20	120	3
20	20	1
20	120	1
120	20	3

Figure 9

Just like the screening experiment, all runs were fully randomized. This time, the average volume across all the pads was analyzed in order to see which main effects and interactions were statistically significant. Statistical analysis was performed and Figure 9 shows what was found to be statistically significant in this example. Any bar crossing the red line is statistically significant at a confidence level of 95%.

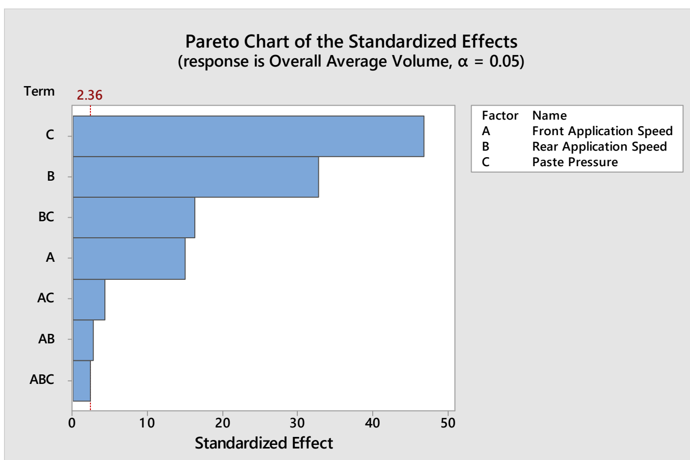


Figure 10

For the optimization model, the team focused on average volume across all the pads. They used the model for the statistically significant main effects, two way interactions and three way interaction in Figure 9. For the desired volume, the team input a target volume of 100%. The optimization plot showing the desired settings for the significant input factors is shown in Figure 10.

Front Speed Rear Speed Paste Pressure

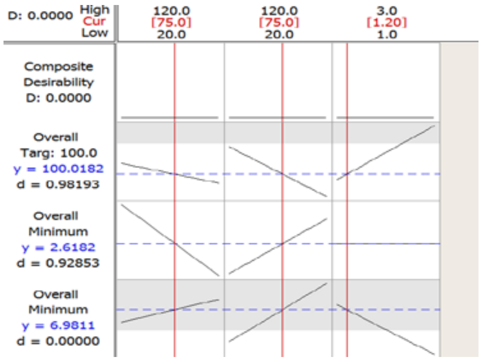


Figure 11

The Front Solder Paste Application Speed needs to be set at 75 mm/sec, the Rear Solder Paste Application Speed needs to be set at 75 mm/sec and the Paste Pressure needs to be set at 1.2 kg of force in order to obtain an average solder paste volume of 100.018% across all the pads. The team also ran the model looking at average x-offset and average y-offset. Using these input settings, the overall average x-offset was predicted to be 2.618% and the overall average y-offset was predicted to be 6.981%. The team also used the optimization model to set ranges for the inputs, which line technology leaders could vary between due to day to day environmental changes, in order to hold the 100% volume. Table 6 shows the ranges for the inputs.

Table 6

	Low	High
Front Solder Paste Application Speed	65 mm/sec	85 mm/sec
Rear Solder Paste Application Speed	65 mm/sec	85 mm/sec
Paste Pressure	1.0 kg of force	2.5 kg of force

The optimization plot is a great model but a confirmation run needed to be performed. The team used the statistical analysis software to determine the appropriate sample size needed for the confirmation run. They used a power value of 0.85, the baseline standard deviation of 5.05264 and a critical difference of 5% in volume in order to come up with a sample size of 20. Figure 11 shows the sample size graph.

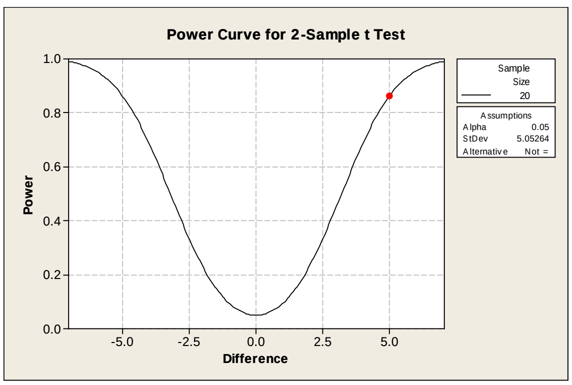


Figure 12

Table 7 shows the input settings for the factors during the confirmation run.

Table 7

Front Solder Paste Application Speed	75 mm/sec
Rear Solder Paste Application Speed	75 mm/sec
Paste Pressure	1.2 kg of Force
System Pressure	3 bars
Clean Rate	5 prints
Separation Speed	4.5 mm/sec

The confirmation run was completed and Figure 11 shows the capability analysis.

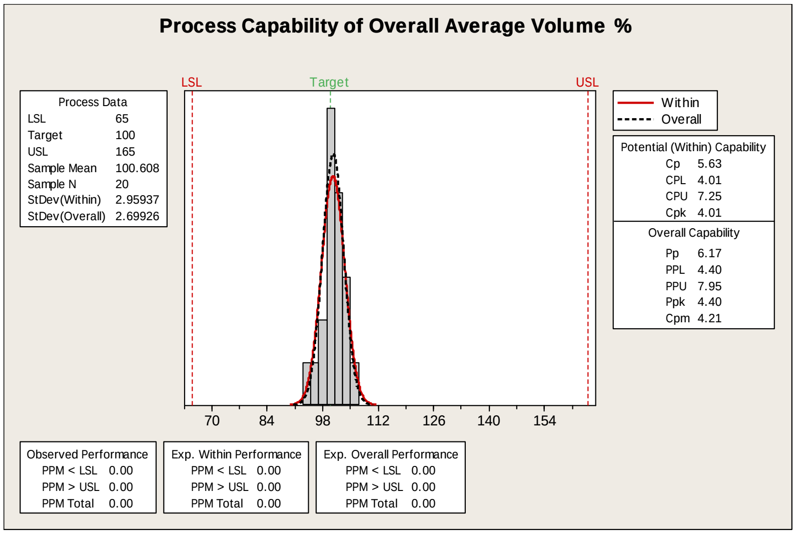


Figure 12

The confirmation run showed that the average volume across all the pads measured 100.608% compared to 100.0182%, which is what the optimization plot predicted. Compared to the baseline, the average volume shifted 4.134% towards the target. Looking at the histogram in Figure 11, the average volume is right on target.

The team then looked at whether or not the shift in the average was statistically significant. They performed a 2 Sample T-Test, which showed that the shift in the average volume was statistically significant with a p value of 0.000. Figure 12 shows the analysis.

Two-Sample T-Test and CI: Overall Average Volume B, Overall Average Volume I

```
Two-sample T for Overall Average Volume Baseline vs Overall Average Volume
     Improve

                             N    Mean  StDev  SE Mean
Overall Average Volume B   360  104.74   2.12     0.11
Overall Average Volume I    20  100.61   2.70     0.60


Difference = mu (Overall Average Volume Baseline) - mu (Overall Average Volume
     Improve)
Estimate for difference:  4.134
95% CI for difference:  (2.854, 5.415)
T-Test of difference = 0 (vs not =): T-Value = 6.74  P-Value = 0.000  DF = 20
```

Figure 13

The variation, standard deviation, increased from 2.12% to 2.74%. The team used a test of two variances to see whether or not this was statistically significant. The p value was 0.097, which meant there was no statistical difference. Figure 13 shows the details of this analysis.

Test and CI for Two Variances: Overall Average , Overall Average

```
Method

Null hypothesis          Sigma(Overall Average Volume Baseline) / Sigma(Overall Average Volume Improve) = 1
Alternative hypothesis   Sigma(Overall Average Volume Baseline) / Sigma(Overall Average Volume Improve) not = 1
Significance level       Alpha = 0.05


Statistics

Variable                           N  StDev  Variance
Overall Average Volume Baseline  360  2.119     4.489
Overall Average Volume Improve    20  2.699     7.286

Ratio of standard deviations = 0.785
Ratio of variances = 0.616


95% Confidence Intervals

                                 CI for
Distribution   CI for StDev     Variance
of Data           Ratio           Ratio
Normal        (0.534, 1.043)  (0.286, 1.089)
Continuous    (0.555, 1.105)  (0.308, 1.220)


Tests

                                               Test
Method                          DF1  DF2  Statistic  P-Value
F Test (normal)                 359   19       0.62    0.097
```

Figure 14

Control Phase

To ensure the solder paste application process remained optimized, the process instruction for the operators and line technology leaders was updated to reflect the target settings and ranges for the Front Solder Paste Application Speed, Rear Solder Paste Application Speed and the Paste Pressure. In addition, the target settings were set in the recipe for the solder paste application machine.

Conclusion

Using the Lean Six Sigma methodology, you can use a rigorous and standardized approach for optimizing solder paste printing performance in PCBA assembly. The methodology will allow you to brainstorm all potential input variables which could affect the solder paste printing parameters. As you go through the different phases of Define, Measure, Analyze, Improve and Control, the insignificant inputs will be filtered out so you are left with the critical few inputs. When these critical few inputs vary, the solder paste printing performance is affected. Design of Experiments helps you figure out the optimized settings in order to achieve the desired performance. Documenting these optimized settings in the process instructions will ensure standardization among shifts and reduce solder paste printing variability.

Using Lean Six Sigma to Optimize Critical Inputs on Solder Paste Printing

Tom Watson – Continuous Improvement Manager

(Kimball Electronics Jasper, Indiana)

Project Background

- The solder paste printing process is the first critical step in the surface mount process for PCBA assembly
- If solder paste printing is uncontrolled, defects can be produced which may not become apparent until the PCBA is downstream
- In order to fix the defects, rework loops are created which are otherwise known as the hidden factory
- Solder paste inspection process is an automated process which alerts the operator to potential defects but allows the operator to override the alerts, or false failures
- In order to eliminate the false failures, the solder paste printing process needs to be controlled

Project Purpose

The purpose of this project was to:

- Address the importance of using the Lean Six Sigma tools to optimize solder paste printing
- Explain how outputs to measure solder paste printing were defined and the specifications chosen
- Show the use of an Input-Process-Output Diagram to define the process
- Show the importance of Gage R&R with respect to the measurement system
- Discuss obtaining baseline data on the process
- Address the use of a Cause and Effect diagram and a cross-functional team to determine all possible inputs to the solder paste printing process

Project Purpose

- Discuss Fractional Factorial (Screening) Experiments
- Discuss Full Factorial Experiments
- Show how to create an optimization model based off the Full Factorial Experiments
- Show the importance of conducting a confirmation run
- Explain the importance of a control plan

Define Phase

- Y = f(x's) where the x's are the critical inputs
- Choose a specific product when working in a high mix low volume environment
- For the solder paste printing process, critical inputs may be the same but their optimized settings different depending on the design
- Measurable outputs need to be defined, which needs the help of Subject Matter Experts on a cross-functional team

Volume of Solder

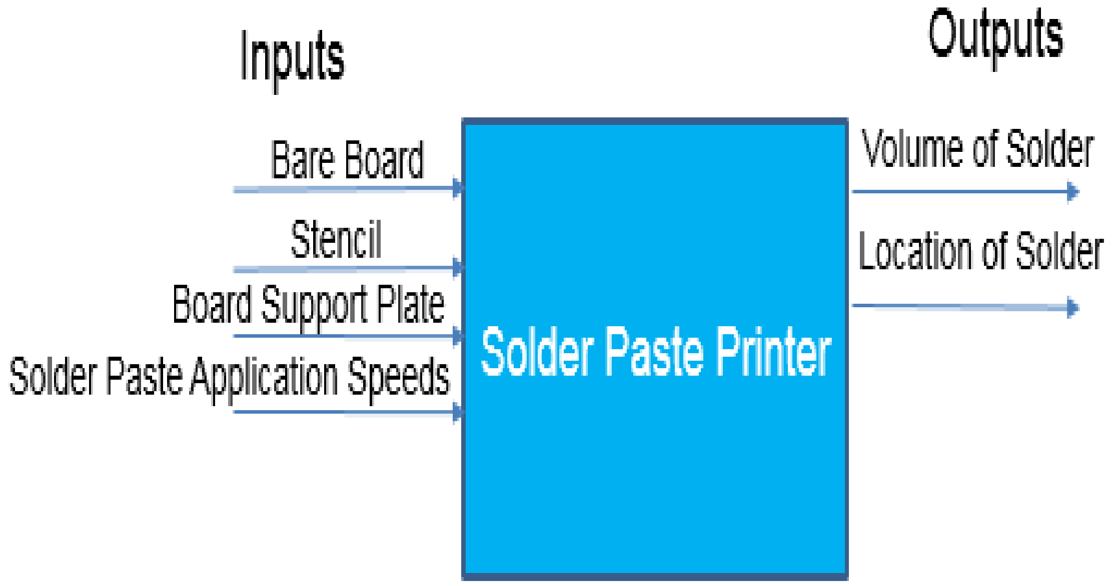
a. Target: 100% of aperture L x W x H
b. LSL: 65% of aperture L x W x H
c. USL: 165% of aperture L x W x H

Location of Solder

a. Target: Offset = 0
b. USL: Offset =30% max

Measure Phase

- First step in the Measure Phase is to understand your process by using an Input-Process-Output diagram



Measure Phase

- Total Variation = Measurement System Variation + Part to Part Variation
- We are trying to reduce Part to Part Variation so we want the Measurement System Variation on our solder paste inspection machine to be low, <10% best case, 10% to 30% OK, if we don't want our variation reduction efforts to be overshadowed with variation in the measurement system

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Operators*Parts	0.07093	0.4256	1.14
Part-To-Part	6.21792	37.3075	99.98
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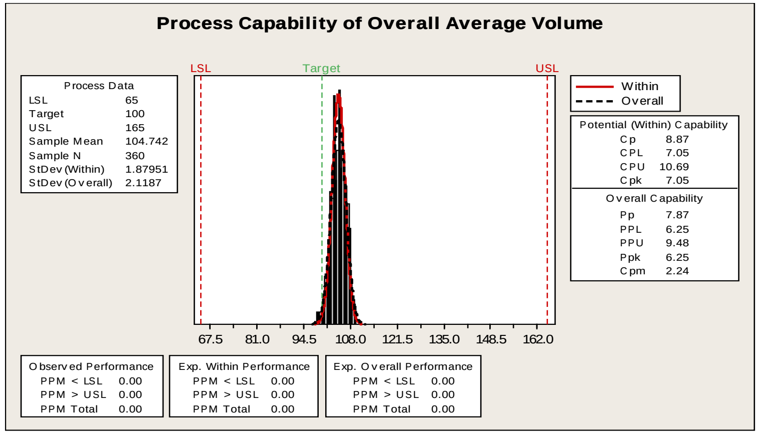
Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.18287	1.0972	2.13
Repeatability	0.18072	1.0843	2.10
Reproducibility	0.02799	0.1680	0.33
Operators	0.02799	0.1680	0.33
Part-To-Part	8.58952	51.5371	99.98
Total Variation	8.59147	51.5488	100.00

Measure Phase

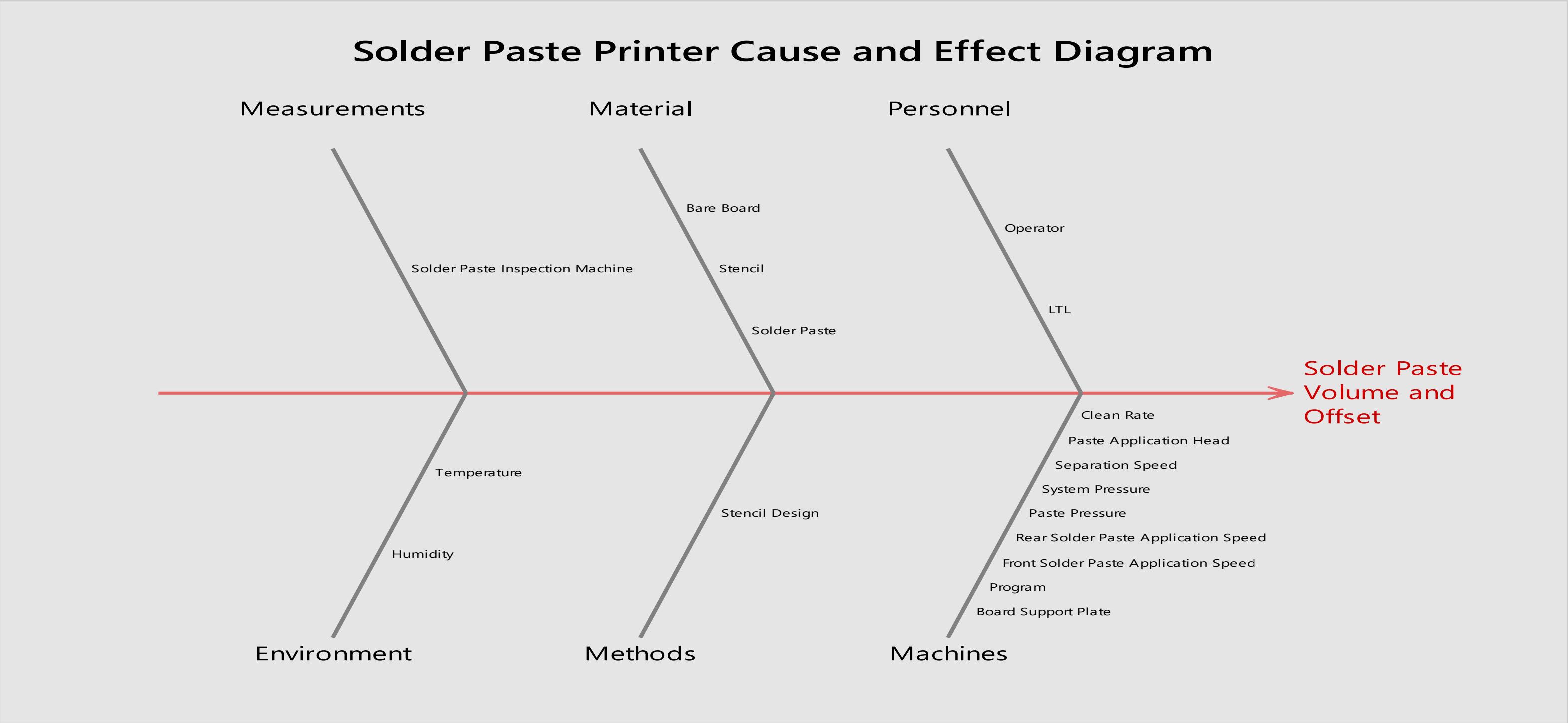
- The third step was to gather 6 months of baseline data stored on the solder paste inspection machine
- The team looked at baseline data on 8 pads they were going to look at during the screening experiment plus the overall volume for all pads on the board

Pad	Mean	StDev	Max	Min
E18	106.63	2.63	112.73	94.61
U6	108.06	6.90	134.94	81.29
U3	102.63	6.36	126.24	75.69
E21	120.08	5.05	132.52	106.42
U17	107.56	4.31	119.27	94.02
CR5	102.77	4.68	115.72	88.60
U16	103.12	6.62	116.03	88.10
Y2	95.35	3.47	104.08	85.37



Analyze Phase

- In the Analyze Phase, the team brainstormed all potential inputs which could affect the solder paste volume and offset
- The Cause and Effect diagram (Fishbone Diagram) was the tool used to brainstorm all these potential inputs



Analyze Phase

- After brainstorming all the factors, the team classified them as SOP factors, Noise factors and Design Factors
- SOP factors are inputs which can be adjusted for a designed experiment but are chosen to be held constant
- Noise factors are inputs which cannot be controlled, difficult to control or are expensive to control
- Design factors are inputs which are planned to be varied during a designed experiment

SOP Factors	Noise Factors	Design Factors
Bare board	Temperature	Front solder paste application speed
Stencil	Humidity	Rear solder paste application speed
Solder paste		Paste pressure
Solder paste inspection machine		System pressure
Board support plate		Separation speed
Program		Clean rate
Paste application head		

Improve Phase

- Designed experiments were performed in order to determine the critical inputs and their optimized settings
- Since there were 6 inputs initially identified as design factors, the team started off with a fraction factorial or screening experiment
- Advantage of screening experiments is that they allow you to screen a large number of factors with minimal runs
- Disadvantage is that resolution is lost and you may not be able to see higher order interactions
- The screening experiment chosen was a ¼ fractional factorial with 2 replications which came out to 32 runs

Improve Phase

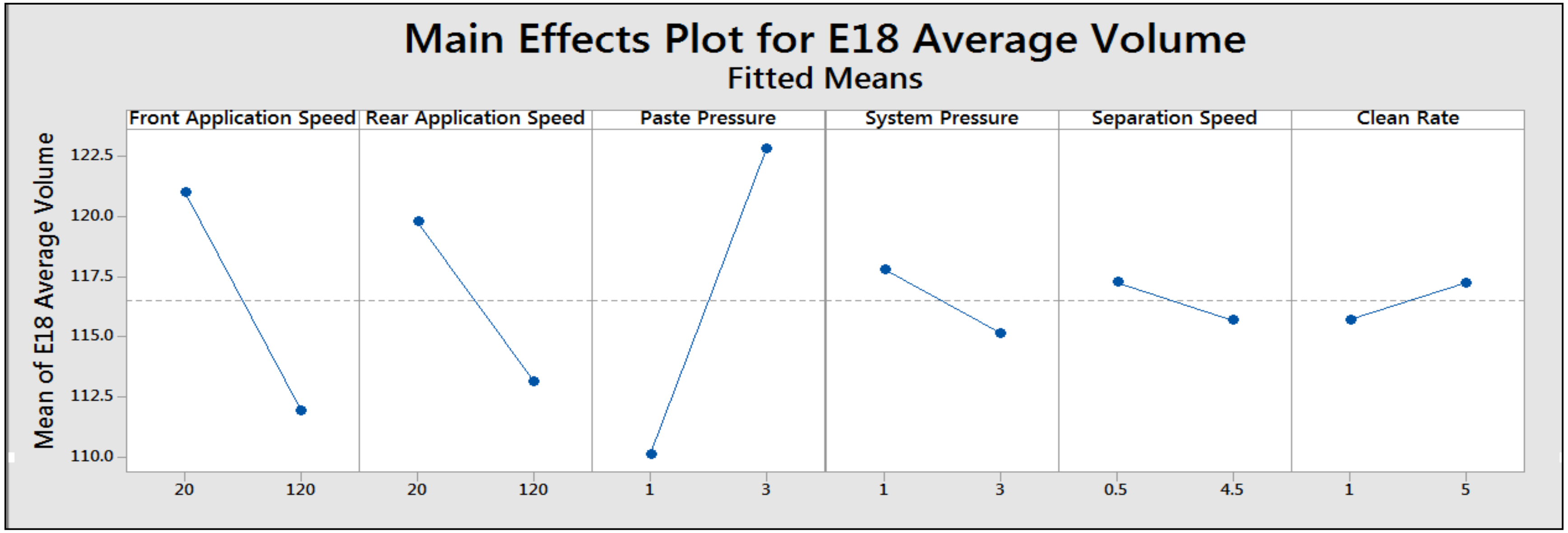
- For each run, the team started off running 3 panels through the solder paste application machine in order to ensure solder paste printing was stabilized
- The team then ran 5 panels through the solder paste application machine and solder paste inspection machine, for each run, in order to collect the data
- The experiment was fully randomized

Factor	Low Level Setting	High Level Setting
Front Solder Paste Application Speed	20 mm/sec	120 mm/sec
Rear Solder Paste Application Speed	20 mm/sec	120 mm/sec
Paste Pressure	1.0 kg of force	3.0 kg of force
System Pressure	1.0 bar	3.0 bar
Separation Speed	0.5 mm/sec	4.5 mm/sec
Clean Rate	1 print	5 prints

	Front Application Speed	Rear Application Speed	Paste Pressure	System Pressure	Separation Speed	Clean Rate
Entry Direction	120	20	1	1	4.5	1
2	120	120	3	1	4.5	1
3	120	20	1	3	4.5	5
4	120	20	1	3	4.5	5
5	20	120	1	3	4.5	1
6	120	20	3	3	0.5	1

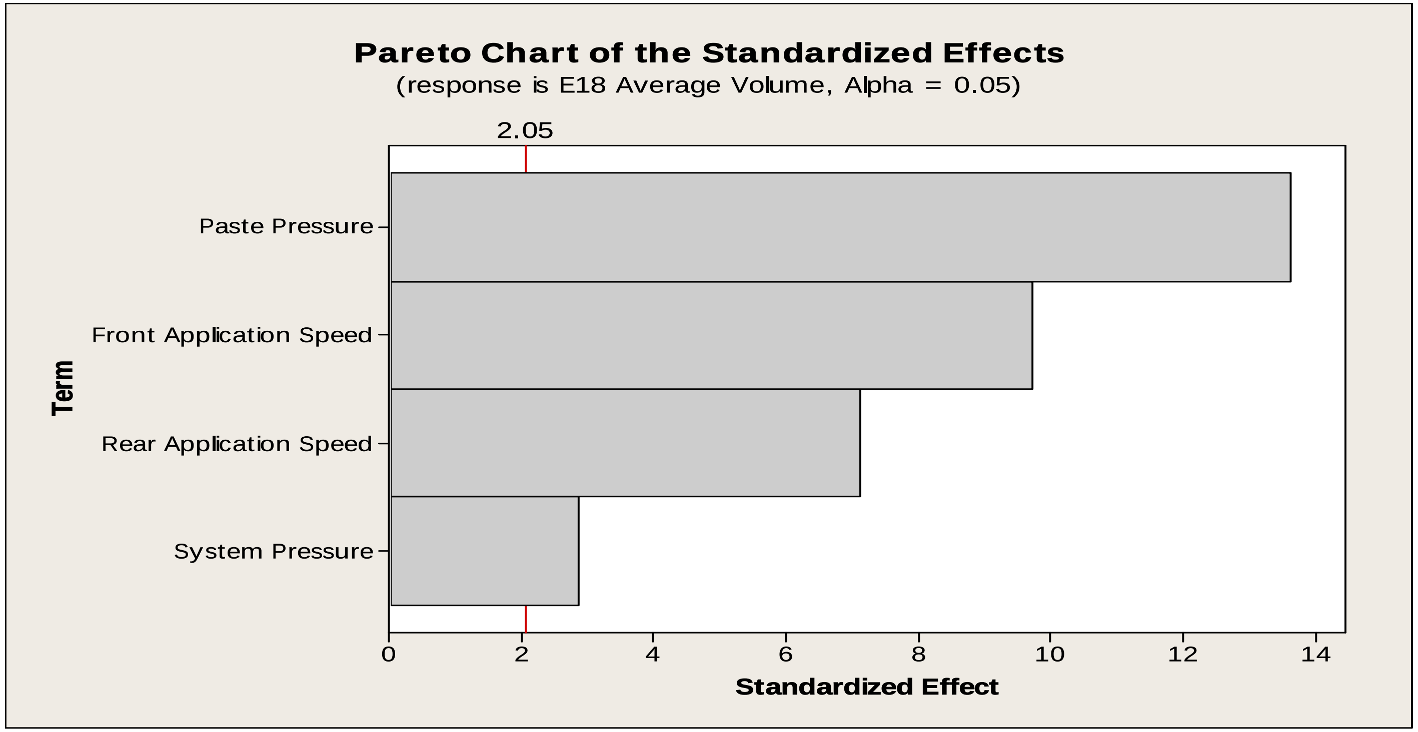
Improve Phase

- The experiment was run and volume, x-offset and y-offset were measured for all pads
- Main effects plot was used to visually see which variables could have a big effect



Improve Phase

- Statistical analysis was performed and the Pareto Chart of Standardized Effects was used to see which factors were statistically significant
- Volume on pad E18 is shown below with all factors crossing the red line being statistically significant



Improve Phase

- The team performed this analysis on all 8 pads for %volume, x-offset and y-offset
- Out of 24 possible outputs, team quantified how many outputs each input was statistically significant in and chose the ones which were significant in at least 70%

Input	Total (24 Outputs)	% of Total
Paste Pressure	19	79%
Front Solder Paste Application Speed	17	71%
Rear Solder Paste Application Speed	23	96%
System Pressure	15	63%
Clean Rate	12	50%
Separation Speed	8	33%

Improve Phase

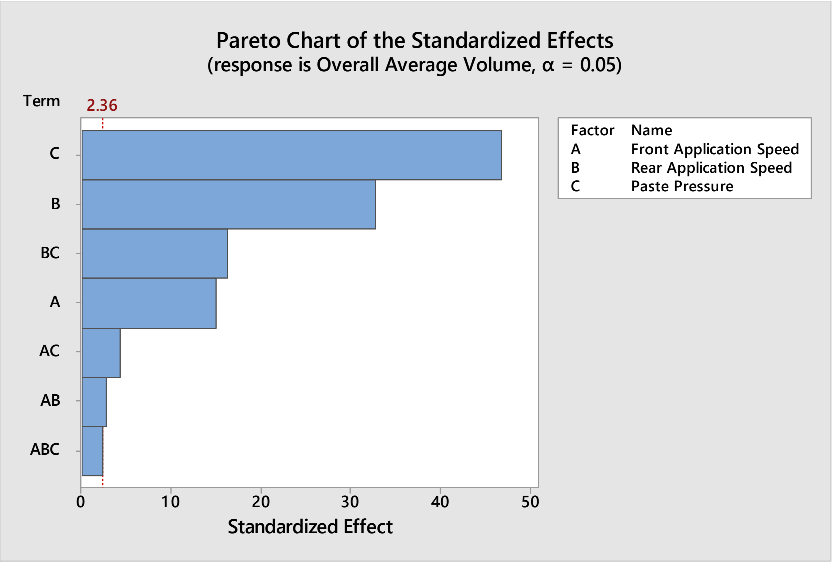
- A full factorial experiment was then conducted with front solder paste application speed, rear solder paste application speed and paste pressure being the design factors
- System pressure, clean rate and separation speed were kept as SOP factors
- A full factorial experiment with 2 replications was run

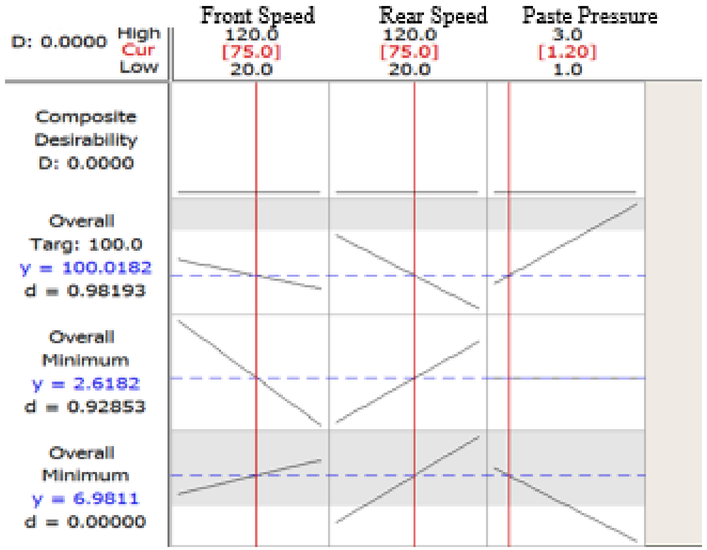
Factor	Low Level Setting	High Level Setting
Front Solder Paste Application Speed	20 mm/sec	120 mm/sec
Rear Solder Paste Application Speed	20 mm/sec	120 mm/sec
Paste Pressure	1.0 kg of force	3.0 kg of force

System Pressure	3 bars
Clean Rate	5 prints
Separation Speed	4.5 mm/sec

Improve Phase

- For the full factorial, average volume across all pads was analyzed in order to see which main effects and interactions were statistically significant
- Like in the screening design, the Pareto Chart of Standardized Effects was used to see which ones crossed the red line
- For the optimization model, the team used 100% as the target volume with all significant main effects and interactions included





Improve Phase

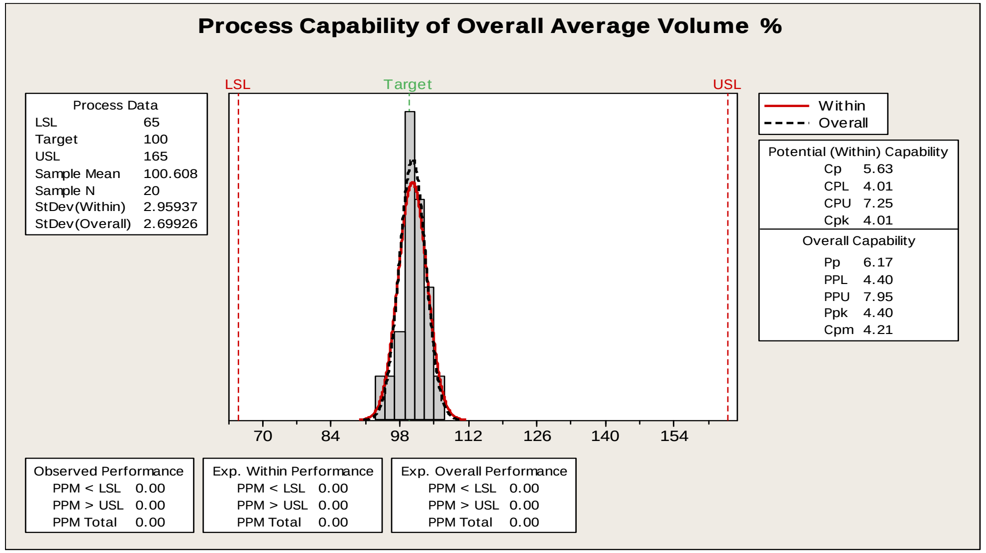
- Based on the optimization model, front solder paste application speed needs to be set at 75 mm/sec, rear solder paste application speed at 75 mm/sec and paste pressure at 1.2 kg of force
- Target was 100% volume and optimization model showed we could hit 100.0182% with these input settings
- The average x-offset was predicted to be 2.618% and average y-offset was predicted to be 6.981%
- Team used the optimization model to set ranges for the 3 critical inputs in order to account for day to day environmental changes

	Low	High
Front Solder Paste Application Speed	65 mm/sec	85 mm/sec
Rear Solder Paste Application Speed	65 mm/sec	85 mm/sec
Paste Pressure	1.0 kg of force	2.5 kg of force

Improve Phase

- In order to confirm the model, the team performed a confirmation run with the 3 critical inputs set at the optimized settings
- The system pressure, clean rate and separation speed were set at their SOP settings
- The confirmation run yielded an overall average volume of 100.608%, 0.5898% off the volume which the model predicted

Front Solder Paste Application Speed	75 mm/sec
Rear Solder Paste Application Speed	75 mm/sec
Paste Pressure	1.2 kg of Force
System Pressure	3 bars
Clean Rate	5 prints
Separation Speed	4.5 mm/sec



Control Phase

- To ensure the solder paste application process remained optimized, the process instruction for the operators on the line and line technology leaders was updated to reflect the target settings and ranges for the front solder paste application speed, rear solder paste application speed and paste pressure
- The target settings were also set in the recipe for the solder paste application machine

Conclusions

- The Lean Six Sigma methodology can help you identify the critical inputs and optimize the solder paste application process
- A cross-functional team made up of Subject Matter Experts is needed in order to identify all potential input variables
- Design of Experiments helps you figure out the optimized settings and provides you with a model
- Don't forget to run a confirmation run to verify the model

THANK YOU

ANY QUESTIONS?