The 1st IMT-GT Regional Conf. on Mathematics, Statistics and Their Applications
13-15 June 2005
Parapat, Lake Toba, Indonesia

APPLICATION OF DESIGN OF EXPERIMENT IN PRINTED CUIRCUIT BOARD ASSEMBLY INDUSTRY

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Abstract

Printed circuit board assembly (PCBA) is a process of mounting and inserting components to printed circuit board (PCB) by means of several principle processes such as Manual Insertion, Auto Insertion (Axial & Radial), Wave Soldering, Surface Mount Technology and Box Build. Manufacturers of PCBA are forced to produce better quality with less cost in order to stay in the business as globalization taking shape. To achieve such a goal, manufacturers are forced to strive to attain and maintain high first pass-yield. Hence, Design of Experiments (DOE) is one of the statistical tools that can be used by the manufacturers of PCBA to purposefully evaluate and optimize designs and processes; so that the manufacturers can achieve greater first pass yield and lower wastage which attributes to decrease the product cost. A project was implemented in a PCBA manufacturing company using the Full Factorial Design with two levels for the wave soldering process with the aid of MINITAB Software. And the objectives of the experiment are to determine the key factors of the process and optimize the process for higher yield. The results of the experiments were excellent, the yield at the wave soldering increased from 90.6 to 97.4. At the same time the key factors were identified and monitored closely to minimize variations.

Keywords: printed cuircuit board, full factorial design, wave soldering;

1. Introduction

Design of Experiments (DOE) is the statistical methodology of planning investigations and research, collecting data and data analysis. DOE identifies the key inputs or factors of a process and these factors are consciously changed to observe the consequences or outputs. A process is series of activities that convert inputs such as man, material, machine, method, etc. into the desired stage or outputs .

The main reasons for implementing DOE are to: understand and reduce variability, determine optimum operating conditions or setting, perform a comparative study, ascertain the most influential inputs on response or process, acquire knowledge of the system, reduce wastage and save costs, reduce product development cycle (see Tony et al., 2004).

A good yardstick to identify the process stability is the Statistical Process Control (SPC) technique. Since, before an experiment can be carried out the process variations got to be addressed. If the process is in control, the performance is predictable over time, then the consequence can be determined by varying the principle factors of the process.The common reasons for poor experimental results: too much noise, incapable or unstable metrology, undefined scope, perplexed effects, interference with uncontrolled effects, inadequate sample size, inappropriate factor setting (Harriet et al., 2003, Stephen et al ., 1999).

For full factorial design, the number of runs (n) for each combinations of the *k* factors is given by $n = 2^k$. The effect of a factor or interactions of factors is the average of all the data when the term is at the high level minus the average of all the data when the term is at the low level i.e,

$$\text{Effect} = \text{Min Value Response}_{high} - \text{Min Value Response}_{low}$$

2.0 DOE Application

The project presented in this dissertation was undertaken in Celestica (M) Sdn. Bhd. which is a Multinational company situated in the Kulim High Tech Park. The company is a PCBA contract manufacturer. Design of Experiment (DOE) was carried for the wave soldering process of a PCBA line and the objectives of the experiment were to: determine the key factors of the process, optimize the process for higher yield, reduce the conversion time. A team of people who have technical knowledge of the wave soldering machine and the processes carried out the project.

Std Order	Run Order	CenterPt	Blocks	Speed	Main Wave	Pre-heat	Yield
2	1	1	1	1	380	240	92.4
14	2	1	1	1	380	280	91.3
4	3	1	1	1	460	240	97.3
3	4	1	1	0.6	460	240	96.4
1	5	1	1	0.6	380	240	93.3
16	6	1	1	1	460	280	89.4
11	7	1	1	0.6	460	240	97.7
7	8	1	1	0.6	460	280	92.3
6	9	1	1	1	380	280	89.9
8	10	1	1	1	460	280	91.7
5	11	1	1	0.6	380	280	90.2
9	12	1	1	0.6	380	240	93.9
12	13	1	1	1	460	240	97.5
10	14	1	1	1	380	240	95.2
15	15	1	1	0.6	460	280	90.5
13	16	1	1	0.6	380	280	91.4

Table 2.1 : Results of the Experiments

The team identified 3 key factors that may effect process i.e. machine conveyor speed, main wave pump and pre-heater. The experiment was carried out based on the combinations given in table 2.1. For each run, 100 units of Printed Circuit boards were evaluated and the corresponding yield (results) were recorded

In respect to the results of analysis in figure 2.1, the P values for Main Effects in the Analysis of Variance (ANOVA) table for Yield is 0.000 which is less than $\alpha = 0.05$, where α (alpha) is the significance level used for this experiment. From the ANOVA table the interaction effects are not significant. However, from the Effects and Coefficients for Yield table suggest that Main Wave, Pre-heat and Main Wave * Pre- heat (interaction) are significant using $\alpha = 0.05$.

Factorial Fit: Yield versus Speed, Main Wave, Pre-heat

Estimated Effects and Coefficients for Yield (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		93.150	0.2922	318.77	0.000
Speed	-0.125	-0.062	0.2922	-0.21	0.836
Main Wav	1.900	0.950	0.2922	3.25	0.012
Pre-heat	-4.625	-2.312	0.2922	-7.91	0.000
Speed*Main Wav	-0.125	-0.063	0.2922	-0.21	0.836
Speed*Pre-heat	-0.400	-0.200	0.2922	-0.68	0.513
Main Wav*Pre-heat	-1.625	-0.812	0.2922	-2.78	0.024
Speed*Main Wav* Pre-heat	-0.200	-0.100	0.2922	-0.34	0.741

Analysis of Variance for Yield (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	100.065	100.065	33.3550	24.41	0.000
2-Way Interactions	3	11.265	11.265	3.7550	2.75	0.112
3-Way Interactions	1	0.160	0.160	0.1600	0.12	0.741
Residual Error	8	10.930	10.930	1.3662		
Pure Error	8	10.930	10.930	1.3662		
Total	15	122.420				

Estimated Coefficients for Yield using data in uncoded units

Term	Coef
Constant	44.156
Speed	-52.281
Main Wav	0.164062
Pre-heat	0.140937
Speed*Main Wav	0.154688
Speed*Pre-heat	0.212500
Main Wav*Pre-heat	-0.00051562
Speed*Main Wav*Pre-heat	-0.00062500

Figure 2.1 : *Minitab window output for Data Analysis*

Hence, the combination of those results, the following notion being interpreted:

- **Main Wave** has an effect of 1.900 which means that high factor setting i.e. 460 rpm results in a better yield as compared to the low factor setting i.e. 380 rpm. The intensity of this effect is lower than Pre-heat but higher than of the interaction of Main Wave * Pre- heat.
- **Pre-heat** has the greatest effect i.e. – 4.625 as compared to the Main Wave and interaction of Main Wave * Pre- heat. Its effect is significant at low factor setting i.e. 240 °C.
- **Main Wave * Pre- heat**, the value of this interaction is –1.625, which means it has impact during the low factor settings.

The Pareto in figure 2.2 (a) was used to compare the relative magnitude and statistical significance for both main and interaction effects. Based on the Pareto chart, the 3 effects identified earlier (i.e. Main Wave, Pre-heat and Main Wave * Pre- heat) passes the reference line. Besides the Pareto, the normal effects plot in figure 2.2 (b) also reinforces the notion that Main Wave, Pre-heat and Main Wave * Pre- heat are significant.

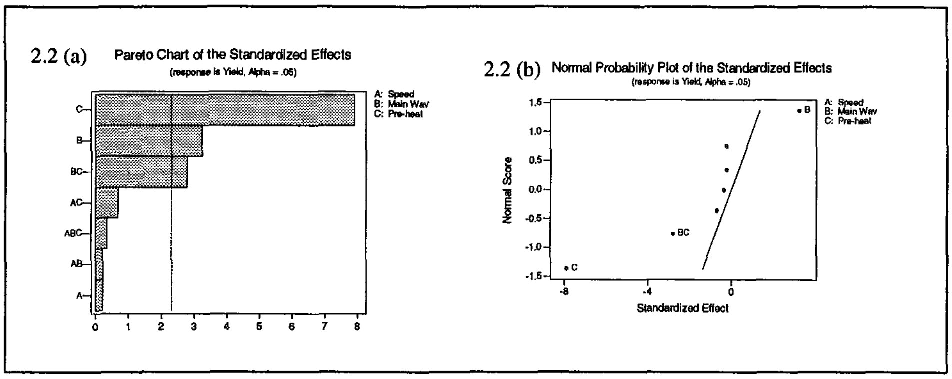


Figure 2.2: Pareto Chart & Normal Probability Plot of the Standardized Effects

2.1 Fitting a Reduced Model

Next, we fitted a reduced model; for the terms which were identified significant in earlier analysis. The results for the reduced model are shown in figure 2.3. In the ANOVA table for yield, the P values for both Main Effects and Two-Way interactions are both lower than the α value of 0.05. Therefore, the ANOVA suggests that both Main Effects and Two-Way interactions are significant.

Again in the "Estimated Effects and Coefficients for Yield (coded units)" table Main Wave, Pre-heat and Main Wave * Pre-heat read P value which is inferior to the α value of 0.05. This means that these factors are significant. The reduced model is further checked by using Residual Histogram for Yield – Figure 2.4 (a), Normal plot of Residuals for Yield – Figure 2.4 (b), Residuals vs. Fits for Yield – Figure 2.4 (c), and Residuals vs. Order for Yield – Figure 2.4 (d)

Factorial Fit: Yield versus Main Wave, Pre-heat

Estimated Effects and Coefficients for Yield (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		93.150	0.2485	374.87	0.000
Main Wav	1.900	0.950	0.2485	3.82	0.002
Pre-heat	-4.625	-2.312	0.2485	-9.31	0.000
Main Wav*Pre-heat	-1.625	-0.812	0.2485	-3.27	0.007

Analysis of Variance for Yield (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	100.002	100.002	50.0012	50.61	0.000
2-Way Interactions	1	10.562	10.562	10.5625	10.69	0.007
Residual Error	12	11.855	11.855	0.9879		
Pure Error	12	11.855	11.855	0.9879		
Total	15	122.420				

Estimated Coefficients for Yield using data in uncoded units

Term	Coef
Constant	2.3312
Main Wav	0.287813
Pre-heat	0.310938
Main Wav*Pre-heat	-0.00101563

Figure 2.3 : *Minitab window output for Reduced Model*

The Histogram in figure 2.4 (a) is approximately normally distributed, therefore it is basically can be interpreted as that the data do not contain any major unusual observations. The normal plot in figure 2.4 (b) was used to determine the distribution of the residuals. The points are very close to in forming a straight line, which means that the residuals are normally distributed.

Residuals versus fits in figure 2.4 (c) illustrates there is no fixed pattern and scatted randomly in the plot, therefore it can be assumed that there is no unusual factor and it has non-constant variance. The residual versus order plot in figure 2.4 (d) is randomly scatted closed to the zero line and no specific pattern detected. This pattern indicates that there are no systematic effects of time or data collection order.

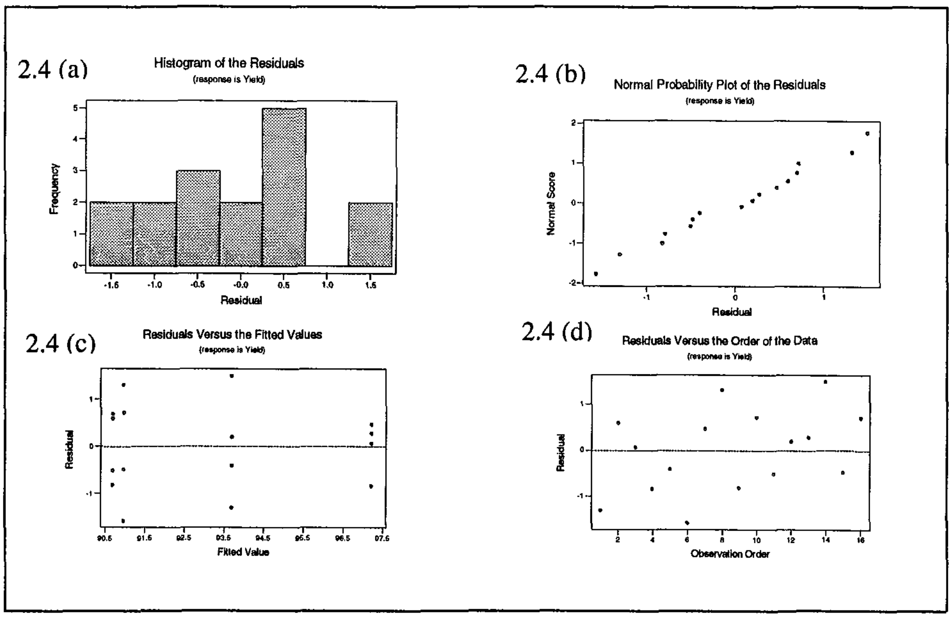
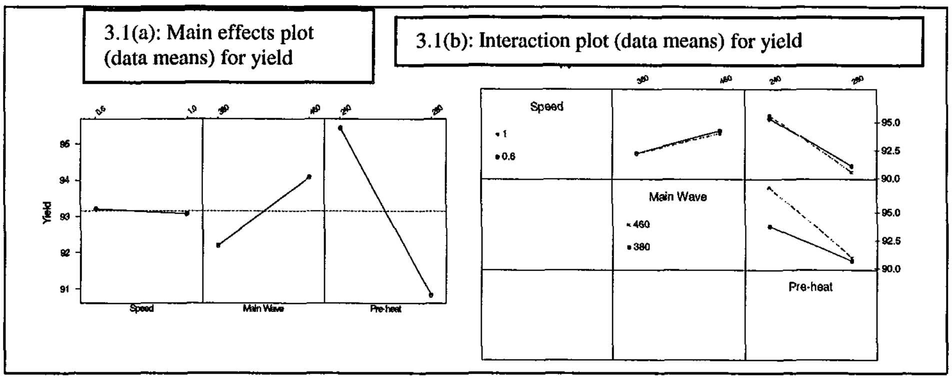


Figure 2.4

3.0 Drawing Conclusion

Factorial plots for main effects (figure 3.1(a)) and interaction effects (figure 3.1(b)) were generated to compare the relative strength of the effects. From figure 3.1 it can be interpreted that Pre-heat has the highest impact since the line connecting the mean responses for Pre-heat 240 °C to 280 °C has a steeper slope. Followed by the Main Wave since there is a slope between Main Wave 380 and 460. As for the Speed, the line connecting the mean responses from 0.6 to 1.0 relatively parallel to X-axis, which interpreted as no main effect present.



Figures *3.1(a) & 3.1 (b)*

On the other hand, from figure 3.1(b) the interaction plot, only the interaction between Main Wave and Pre-heat has some degree of divergence, which suggests there is some effects due to the interactions of these factors. Other plots are relatively parallel which means there is no interaction present. Besides that, cube plot in figure 4.8 was drawn to illustrate the relationship between factors and the response. The interpretation derived from the cube plot is that Main Wave set at 460 rpm and Pre-heat set at 240 °C produce the best yield. Nevertheless, varying speed between 0.6 and 1.0 shows a very small improvement; however, in practice Speed may not exhibit any difference.

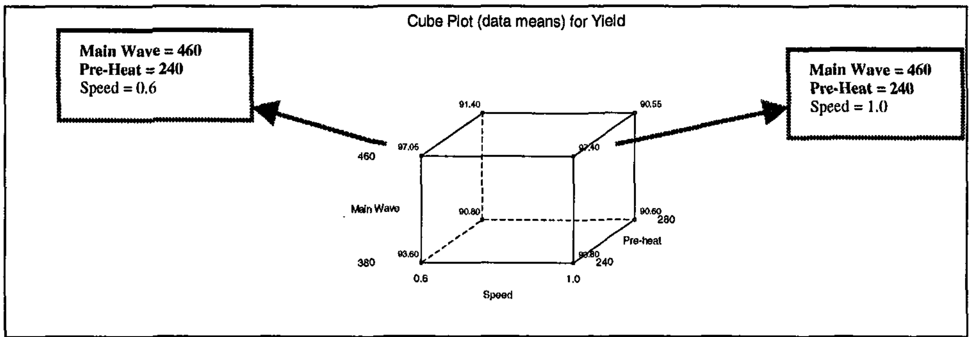


Figure 3.2: *Cube Plot*

Based upon the above analysis and confirmation carried out (through out the experiment), the following mathematical model derived to identify the critical factors by using the coefficients:

Yield = 93.150 + 0.950 (main wave) - 2.312 (Pre-heat) - 0.812 (Wave * Pre-heat)

Further to the above mathematical expression of the Yield, the epsilon squared (ε^2) values (illustrated in figure 3.3) were calculated to assess the significance in terms of practical. Based on the epsilon squared values, pre-heat has the most impact, which controls 69.89 %; followed by main wave (11.80 %) and the interaction of pre-heat and main wave 8.63%. However, there is an error of 9.68 % which is contributed by other factors that were not covered in the experiment; but for practical application this value is within the acceptable level.

Analysis of Variance for Yield

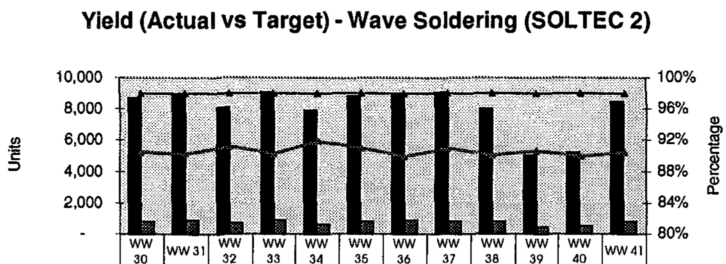
Source	DF	SS	MS	F	P	ε^2
Pre-heat	1	85.563	85.563	86.61	0.000	69.89%
Main Wav	1	14.440	14.440	14.62	0.002	11.80%
Pre-heat*Main Wav	1	10.563	10.563	10.69	0.007	8.63%
Error	12	11.855	0.988			9.68%
Total	15	122.420				

Figure 3.3: *Epsilon Squared values for the Reduced Model*

4.0 Project Conclusion

The Project described in section 2 was carried out in a Canadian company operating in Kulim High Tech Park. The aim of the project was to carry out Design of Experiment (DOE) to the wave soldering process of a PCBA line. With the objectives to determine the key factors of the process and optimizes the process for higher yield.

Wave soldering process was selected because it was performing below the established target of 98 percent for the Yield. The average yield from work week (ww) 30 to 41 is 90.6 percent; which is very far below the established target. The high rejection rate translated into high rework & repair cost and sometimes delays in delivery to customer.

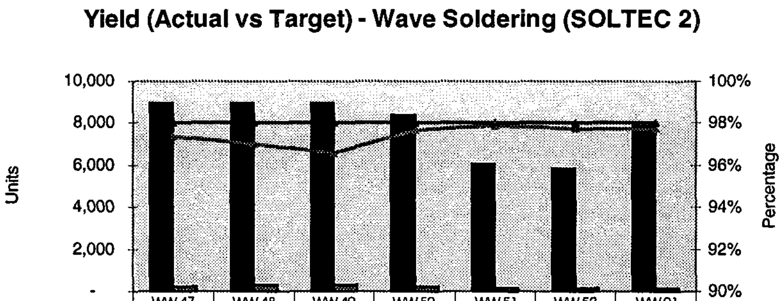


	WW 30	WW 31	WW 32	WW 33	WW 34	WW 35	WW 36	WW 37	WW 38	WW 39	WW 40	WW 41
Series2	8,750	8,970	8,107	9,055	7,934	8,805	8,926	9,101	8,021	5,034	5,201	8,506
Series1	839	873	714	873	646	801	904	827	799	471	529	817
Series3	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%
Series4	90.41%	90.27%	91.19%	90.36%	91.87%	90.90%	89.87%	90.91%	90.04%	90.64%	89.83%	90.40%

Figure 4.1: *Wave Solder Performance before DOE*

Figure 4.1 illustrates the performance of the wave soldering machine after design of experiments being carried out (data collected from work week 47 to 51). The average yield had improved from 90.6 percent to 97.4 percent; which is an improvement of 6.8 percent. The most crucial improvement was the reduction in number of PCBAs for rework; previously on the average 749 PCBAs due for rework every month and with improvement the average monthly quantity dropped to 119 PCBAs (which is approximately 84 percent reduction).

This proves the potential of Design of Experiments in the PCBA industry. Although, the target of 98 percent yet to be achieved, but it has come to close to the target line. Besides that, the DOE enabled to identify the key factors that influence the wave soldering process. This knowledge is the crucial to the next path of continuous improvements.



	WW 47	WW 48	WW 49	WW 50	WW 51	WW 52	WW 01
Series 2	9,003	9,011	8,994	8,408	6,032	5,865	7,859
Series 1	237	268	310	197	128	132	175
Series 3	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%
Series 4	97.37%	97.03%	96.55%	97.66%	97.88%	97.75%	97.77%

Series 2: Total Output
Series 1: Total Reject
Series 3: Target Yield
Series 4: Actual Yield

Figure 4.2: *Wave Solder Performance after implementation of DOE*

5.0 Scope for Further Work

While DOE proved to be effective in the PCBA industry but there are also other advanced tools like Response Surface Method. Which can used to examine the relationship between a response and a set of quantitative experimental variables or factors.

Response surface method can be engaged to:

- find factor settings (operating conditions) that produce the "best" response,
- find factor settings that satisfy operating or process specifications,
- identify new operating conditions that produce demonstrated improvement in product quality over the quality achieved by current conditions, and
- model a relationship between the quantitative factors and the response

Acknowledgements

This paper is part of the first author's MSc dissertation. The second author would like to thank Universiti Sains Malaysia for the support and financial assistance. Such contributions are gratefully acknowledged.

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