Optimization of Thermal Profile Process in Assembly Line of Printed Circuit Boards (PCB) Using Design of Experiments

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Abstract

The aim of this paper is to study the thermal profile process of manufacturing Printed Circuit Boards (PCB). The thermal profile process controls the cycle time and temperature level of the oven, in other words, the solder joints have to reach the correct cycle time of the soldering temperature. Therefore, it is challenging to simultaneously control the temperatures in different zones with specific cycle time in each zone. The solder paste and components should be well-matched in the heating slope for each zone; the solder paste has different types and different manufacturers. Also, these variables (temperature and time in each zone) are interconnected and thus, result in good quality in solder joint; as well as to determine which variables are more significant to get good solder quality by using design of experiment (DOE). Minitab software will be used for DOE. The data of the research will be collected from real assembly line of PCB. Obtaining a better yield via improving the time of the PCB assembly process is another objective of this research. Hence, the outcome to all of these attempts of optimizing the assembly line of PCB for continuous improvement is to deliver good quality products, reduce cost, and minimize the time of delivery and meet the customer expectations.

Keywords: Printed circuit board, Oven, PCB, thermal profile, DOE

1. INTRODUCTION

The thermal profile process controls time period and the temperature, in other words, the solder joints has to reach the time of the soldering temperature. Therefore, it is challenging to control the temperatures in different zones with specific time in each zone. The solder paste and components should be well-matched in the heating slope for each zone; the solder paste has different types and different manufacturer. Also, these variables (temperature in each zone and time in each zone) are interconnected and thus, results in good quality in solder joint. Usually, the oven profile recommendations are considered for the setting profile process. In the past, five oven zones or less were used and this is hard to control the temperature, the more zones in the oven the better control of the temperature. The sizes of the oven zones (length) studied will be performed on 13 zones. Typical zones of the oven temperatures are preheat, pre-flow (or soak/ dry out), reflow, and cooling zone as shown in the figure below. So, thermal profile is a significant element of the oven process in order to continue improvement to the PCB assembly line. Figure 1 shows the typical oven temperature zones (profile):

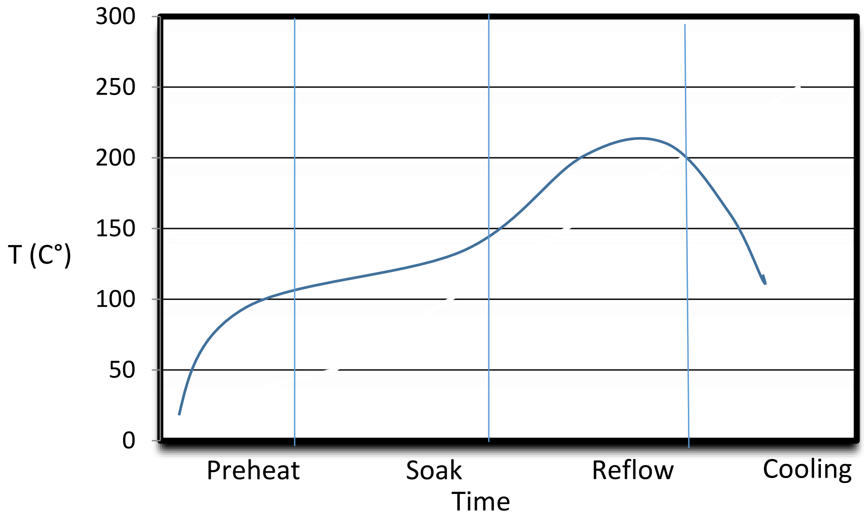

Figure 1. Typical Oven temperature zones

2. PURPOSE OF THE STUDY

The purpose of the profile study and the optimization are to avoid presumptions or the engineering estimate on the initial temperature zone set, time and speed setting, reduce changeover times, reduce production downtime energy saved for the oven. As a result, obtaining high quality with low defect of the solder joint. Verdi [6] indicated some problems that occur because of the profile setting, figure 2 describes them.

Problem	Possible Thermal Profile Root Cause
Cracked Chip Capacitors	Excessive rise rate in the preheat zone
Solder Balls	Incomplete drying before reflow *Dry-out section too cool and too short a duration* Excessive drying temperature Improper gas atmosphere: Air versus Nitrogen
Cold Solder Joints	Insufficient time over reflow temperature
Solder Not Wetting To Leads	Excessive drying time causing flux to deteriorate Excessive reflow temperature/time causing oxidation
Solder Not Wet On Pad	Lead is heating faster than board (too much airflow)
Component / Board Burning	Excessive reflow temperature

Figure 2. Thermal profile issues [6]

The purpose of the design of experiment is to minimize the iterations of the experiments, and then define the significant factors that affect the outcome and quality of the circuit board. After significant factors are defined, analysis for variables is performed to come up with good optimization for these variables. Three level designs have been selected to have a more occurred curvature temperature response. The three level designs are usually used if the variables are quantitative (nonlinear) while the two levels are used when there is a linear relationship. Figure 3 describes the actual profile that runs for the oven on local PCB local company, which is not very close to the recommendation profile setting.

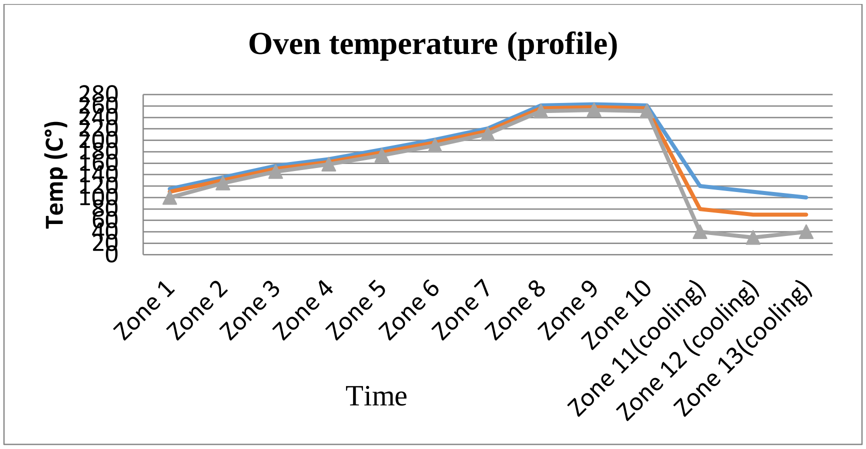

Figure 3. Oven temperature zones

3. THERMAL PROFILE OPTIMIZATION LITERATURE SURVEY

Tsai, Mapa and Vancha [1, 2] approached similar methods using Design of Experiment (DOE) to solve for reflow soldering problems. Tsai studied the optimization of the thermal parameters of reflow soldering process using various three alternative approaches (traditional response surface methodology (RS), nonlinear programming (NLP), and a hybrid AI technique). The three alternative methods were used to model and solve the thermal parameters optimization problems for the reflow soldering process in PCB. The reflow soldering process is usually nonlinear and includes various performance characteristics. Thus, the thermal reflow profile was the method used to regulate the process parameters and control the effects of heating on the board assembly. Tsai used an experimental design using eight factor levels (input) for the reflow thermal profiling and is presented by eleven responses (output). As a result, all three methods provided a decent soldering performance. However, among the three alternative methods used, the hybrid AI technique was better at formulating nonlinear mapping and solving optimization problems, and also provided better optimization performance.

Similarly, Mapa and Vancha created a Design of Experiment (DOE) model to examine the factors that affect heat losses at high and low levels. Their goal is to expose the factors that have a major role in heat loss while making design developments to increase the productivity of the ovens. While Tsai used eight factors for his experiment, Mapa and Vancha used four process variables that contribute to heat losses which are flap design, speed of the conveyor belt, blower speed and insulation. The DOE methodology helped designers find major factors and connections between the factors at the levels tested in the experiment. Using the Statistical Analysis software (SAS) statistical software, the flap design and the blower speed were the most important factors contributing to heat loss in ovens. While Tsai, Mapa and Vancha focused on the thermal profile, Flaig [3] introduced a new classification of variables in design of experiments. Controllable or uncontrollable are the two classification of factors used in experiment design, but these classification of input variables may not always be successful in displaying the “observed structure” of some experiments. Since some factors that are classified as controllable are really semi-controllable, Flaig adds semi-controllable input variables into the overall process model structure. He used the three process input variables to model for the production environment. The semi-controllable input variable helps with better process performance and also helps a practitioner to make an adequate model for estimating the mean response and response variance through designed experiments.

Despite that fact Tsai, Mapa, and Flaig [1, 2, 3] used Design of Experiment in their study, Gong [4] used a different method. He used the FEM simulation model to optimize reflow soldering temperature profile. Decreasing the maximum thermal stress shows an important development on the reliability of solder joints; therefore, the temperature distribution along with stress distribution of a particular BGA contained electronic assembly during reflow was simulated. In order to decrease the maximum thermal stress in the whole assembly, Gong studied some basic reflow parameters including the highest reflow temperature, dwell time above liquids, soak times, ramp rate, and conveyor speed. As a result of the simulation model used, the maximum thermal stress can be reduced via the optimization of the above mentioned reflow profile parameters.

Similar to Tsai, Mapa, and Flaig, Ming-Hung [5] studied optimization temperature profile of reflow oven to obtain robust soldering quality. He used 4 factors for this purpose (peak temperature, reflow time, cooling slope and soak time). All factors included three levels. Ming used Tahuch's $L_9(3^4)$ orthogonal array.

Jin, and Hong Wan [7, 8] performed a study for optimization of reflow soldering process and determine heat factors. They determined the significant problem of how to adjust the heating zone in the profile to ensure reflow for all solder joints. The main purpose of their research is to achieve high quality and reliability of solder joints. They determined the following variables that effect the process and product quality of the solder joints and described on Figure 4.

1- PCB
   A- PCP thickness
   B- PCB number
   C- PCB type
   D- PCB size
   E- PCB Materials and structure
2- Oven
   A- Cooling capacity
   B- Heat transfer capacity
   C- Total heating length
   D- Total heating zone number
3- Target profile
   A- Upper limit of heating rate
   B- Upper limit of cooling rate
   C- Upper heat factor
   D- Lower heat factor
   E- Conveyor speed

Jin define the heating factor as:

$$Q_\eta = \int_{t_1}^{t_2} (T(t) - T_m) dt \qquad (1)$$

Where:
T_m = melting point of solder alloy
t_1, t_2 = Time of reaching T_m, and of falling back below T_m respectively,

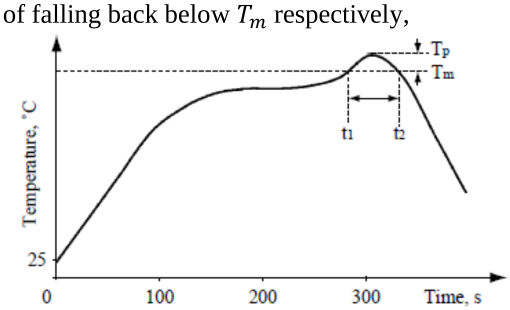

Figure 4: heating factor on reflow profile [7]

4. METHODOLOGY

Figure 5 shows the overall methodology steps for optimization of assembly line of printed circuit board process for design of experiment using Minitab software. Box-Behnken designs will be used with 3 levels per factor, which also let the model curvature in the response. It is useful for understanding the region of the response surface and how changes in the variables will affect the response. Also, it will help to fine the variables that need for optimize response. Box-Behnken is useful if the operating zone of the process is known (specification). Therefore, the design will be in safe operating zone and also the Box-Behnken ensures that not all the factors will be set to the high level at the same time. With seven factors, Box-Behnken could run in one or two blocks. This method used is due to the limit access to the oven at the company to verify the result that come from DOE and confirm that the selections of the most significate variables are correct.

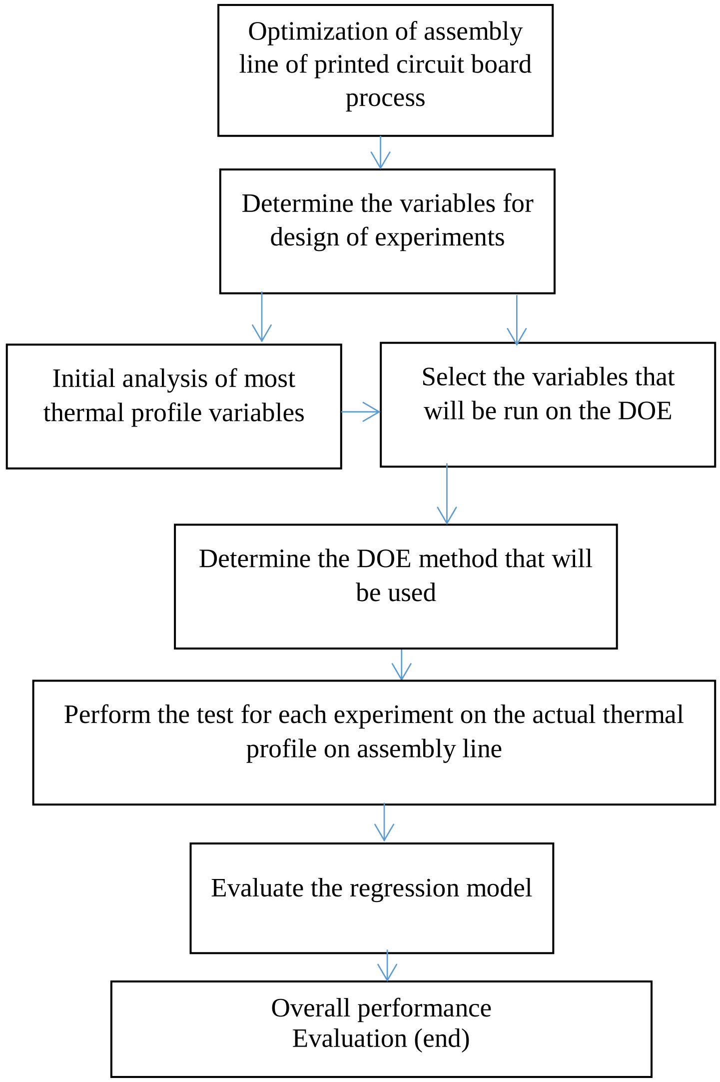

Figure 5. Overall methodology steps for optimization

4.1 VARIABLE OF THERMAL PROFILE

Variables selected for this study are based on the literature review and discussion with technical matter expert in the PCB companies. Conveyor speed and time are related to each other and that's why one of them has been selected, if the speed increases then the time should be shorter and contrariwise; the slope of each zone should be considered as well. Length conveyor 20ft- in cm (609.6). Time = length/speed of conveyor, 609.6cm/104.5 cm/min= 5.83min (0.448 Sec in each zone of the 13 zones). 13 zones on the oven (length) divided into zones of oven temperature, for example the first 3 zones could be considered one zone of the oven temperatures (preheat zone) and same thing for the remaining zones will be part of the (pre-flow, reflow, and cooling zones). Four temperature zones will be set individually, so consider these four different variables. Also, Copper Thickness is considered as one of the other independent variable. Last, PCB mass differential is one of the variables (itself) that depend on many factors. Mass differential calculation could be used CAD Gerber file and the BOM as Tsung [1] used in his research, or different method could be used and that will be determined during collecting the info for this variable. Mass differential and heat transfer into the PCB depend on several variables as Baehr [9] explain it in this book.

Where:

$$Q = mC_p\Delta T \quad (2)$$

Where Q = heat transfer
m = Mass
C_p = Specific heat
ΔT = Time interval
$m * C_p$ = Thermal mass

The PCB's manufacturing company use serval types of printed circuit board size obtained by taking the average of each of the three types of component density per panel where 332.5, 457 and 890 representative by 1, 2 and 3 accordingly as shown on table 1 on the comp size. The copper thickness of the three types used as well as ½ oz, 1 oz and 2 oz; representative by three different levels consequently as shown on table 2. Also, the remaining heat zone temperatures and speed of conveyor described in Table 2.

Table 1. Factors level

Variable level	**Comp size**	**Conveyor speed cm/min**	**Preheat Temp C°**	**Soak Temp C°**	**Reflow Temp C°**	**Cooling Temp C°**	**Copper Thickness mm**
	X1	X2	X3	X4	X5	X6	X7
1	1	80	155	145	215	70	0.018
2	2	85	165	215	245	75	0.036
3	3	90	175	180	275	80	0.071

List of the variables

1- PCB Size - (PCBS)
2- Conveyor Speed (cm/min)- CS
3- Preheat Zone Temp C° (PZT)
4- Soak Zone Temp C° (SZT)
5- Reflow Zone Temp C° (RZT)
6- Cooling Zone Temp C° (CZT)
7- PCB Copper Thickness mm (PCBCT)

Table 2 is the matrix possible combination of the seven variables that will be verified.

Table 2. DOE variables combination

PCBS	CS	PZT	SZT	RZT	CZT	PCBCT
0	0	0	-1	-1	-1	0
0	0	0	1	-1	-1	0
0	0	0	-1	1	-1	0
0	0	0	1	1	-1	0
0	0	0	-1	-1	1	0
0	0	0	1	-1	1	0
0	0	0	-1	1	1	0
0	0	0	1	1	1	0
-1	0	0	0	0	-1	-1
1	0	0	0	0	-1	-1
-1	0	0	0	0	1	-1
1	0	0	0	0	1	-1
-1	0	0	0	0	-1	1

1	0	0	0	0	-1	1
-1	0	0	0	0	1	1
1	0	0	0	0	1	1
0	-1	0	0	-1	0	-1
0	1	0	0	-1	0	-1
0	-1	0	0	1	0	-1
0	1	0	0	1	0	-1
0	-1	0	0	-1	0	1
0	1	0	0	-1	0	1
0	-1	0	0	1	0	1
0	1	0	0	1	0	1
-1	-1	0	-1	0	0	0
1	-1	0	-1	0	0	0
-1	1	0	-1	0	0	0
1	1	0	-1	0	0	0
-1	-1	0	1	0	0	0
1	-1	0	1	0	0	0
-1	1	0	1	0	0	0

PCBS	CS	PZT	SZT	RZT	CZT	PCBCT
1	1	0	1	0	0	0
0	0	-1	-1	0	0	-1
0	0	1	-1	0	0	-1
0	0	-1	1	0	0	-1
0	0	1	1	0	0	-1
0	0	-1	-1	0	0	1
0	0	1	-1	0	0	1
0	0	-1	1	0	0	1
0	0	1	1	0	0	1
-1	0	-1	0	-1	0	0
1	0	-1	0	-1	0	0
-1	0	1	0	-1	0	0
1	0	1	0	-1	0	0
-1	0	-1	0	1	0	0
1	0	-1	0	1	0	0
-1	0	1	0	1	0	0
1	0	1	0	1	0	0
0	-1	-1	0	0	-1	0
0	1	-1	0	0	-1	0
0	-1	1	0	0	-1	0
0	1	1	0	0	-1	0
0	-1	-1	0	0	1	0

0	1	-1	0	0	1	0
0	-1	1	0	0	1	0
0	1	1	0	0	1	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

4.2 RESULT AND ANALYSIS

DOE results of the thermocouple compared to the recommended profile and Regression model are used to understand the behavior of the variables and the relationship among the variables. Table 3 shows the average test results of the all combination that gets run for thermocouple, and comparing it to the recommended specifications. Based on that test temperature of the oven zone, it can be adjusted considering the quality of the solder joint.

Table 3. Profile test result

	Response			
	Preheat slope (C/min)	Soak slope (C/min)	Ramp-up slope (C/min)	Cooling slope (-C / min)
Result of the thermocouple Ave	0.60	1.58	0.59	-1.66
Specifications	0.72	1.44	0.67	-2.82

In addition, table 4 shows current temperature values based on the copper thickness and board size (density of the components) and recommended adjusted values based on recommended specification and technical specialist. Figure 6 shows the current run compared to the recommended values; where series 1is the recommended graph and series 2-4 are three experiments. From the graph, there is obvious observation on the soak zone area where the temperature slightly goes down before it rises to the next temperature zone (reflow zone). Figure 7 shows the graph after the adjustment and how close to the suggested specifications.

Table 4. Recommended adjusted temperature

Copper thickness	0.071	Board size		
Time (s)	Temp (C)	3	1	2
0	28	25	25	25
100	110	85	85	80
180	225	155	175	155
225	255	180	180	180
280	100	275	275	245
360	50	75	75	70
Recommended Adjusted Temperature				
0	28	25	25	25
100	110	90	95	100
180	225	200	205	210
225	255	250	250	250
280	100	100	95	95
360	50	60	65	60

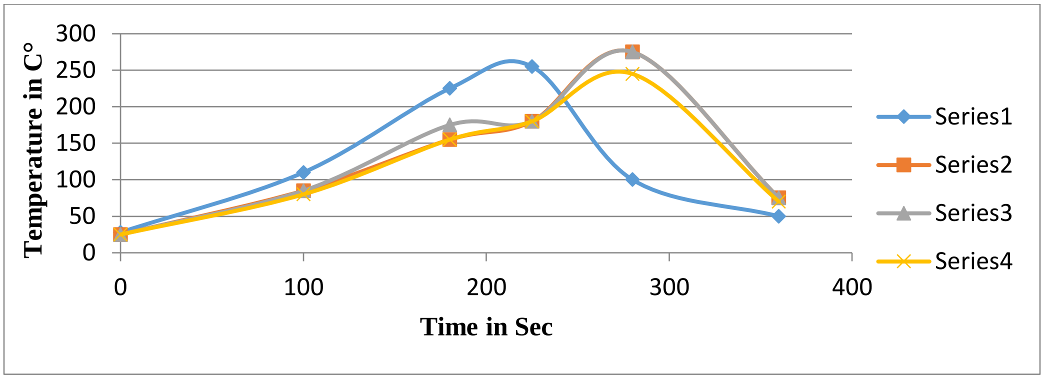

Figure 6. Temperature values before adjustment

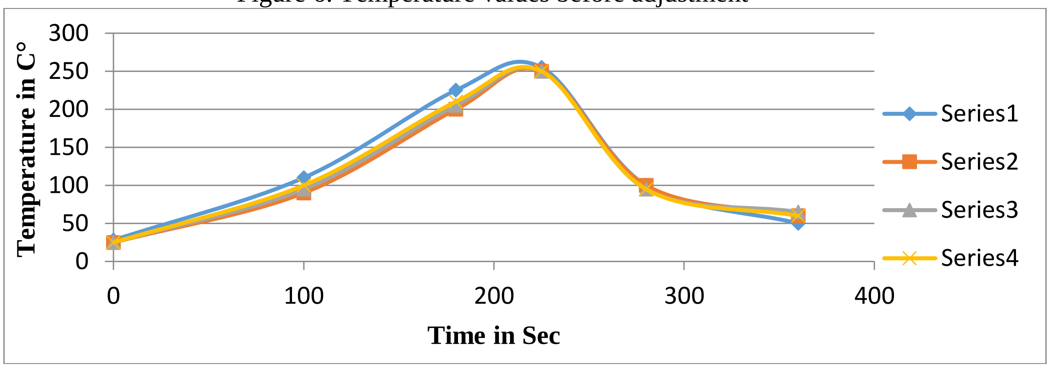

Figure 7. Temperature values after adjustment

4.2.1 REGRESSION MODEL

Due to the complexity of models, only two models were selected based on the most effected variables which are response soak slope and response reflow slope as shown in the below two equations where variables (x_1 ... x_7) defined on table 1 respectively.

Response Soak Slope = 127.022+ 0.43 x_1 -0.82 x_2 +0.003x_3 + 0.003x_4 -2.45(E-04)x_5 +0.013 x_6 -11 x_7 - 0.0001 x_1 x_2 +2.5 (E-05) x_1 x_3 + 4.05 (E-05) x_1 x_4 + 2.8 (E-06) x_1 x_5 + 5.0 (E-05) x_1 x_6 – 18.5 x_1 x_7 - 4.0(E-06) x_2 x_3 + 1.53 (E-06) x_2 x_4 + 3.33 (E-07) x_2 x_5 + 1.6 (E-04) x_2 x_6 -0.11 x_2 x_7 -6.12 (E-08) x_3 x_4 - 2.78 (E-08) x_3 x_5 – 4.0 (E-06) x_3 x_6 -1.43957 (E-15) x_3 x_7 -1.003 (E-08) x_4 x_5 - 0.083 x_4 x_7 + 0.001 x_5 x_7 -0.008 x_6 x_7 - 0.002 x_1^2+ 7.6(E-05) x_2^2+ 4.4 (E-07) x_3^2 + 6.14 (E-09) x_5^2+ 1.3 (E-05) x_6^2 + 55761.4 x_7^2

Response Reflow slope = 183 + 1.09 x_1 -0.064 x_2 +0.003x_3 + 0.001x_4 +0.0003 x_5 +0.035 x_6- 2159.8 x_7 - 0.0001 x_1 x_2 -1.25 (E-05) x_1 x_3 -7.33270(E-06) x_1 x_4 + 2.8 (E-06) x_1 x_5 + 5.0 (E-05) x_1 x_6 – 28.78 x_1 x_7 – 1.0(E-06) x_2 x_3 + 1.43 (E-06) x_2 x_4 – 5.56 (E-07) x_2 x_5 + 4.0 (E-04) x_2 x_6 -0.21 x_2 x_7 +1.02 (E-08) x_3 x_4 +1.39 (E-08) x_3 x_5 – 1.0 (E-06) x_3 x_6 – 9.3 (E-16) x_3 x_7 -3.37 (E-08) x_4 x_5 - 0.036 x_4 x_7 -9.05013(E-04) x_5 x_7 -0.1 x_6 x_7 - 0.0013 x_1^2 – 5.5(E-05) x_2^2- 6.5 (E-07) x_3^2 + 1.3 (E-09) x_5^2- 3.43 (E-05) x_6^2 + 27711.9 x_7^2

4.2.2 MAIN EFFECTS VARIABLES

The main effect variables for each response will be independent for each output and as shown on figure 8, the most effective variables on the soak zone temperatures are the component size, conveyor of speed as well as the copper thickness, noted that other variables are not neglected. Similarly, with reflow zone temperatures, none of the seven variables can be neglected but there are some variables that have the most effect on the reflow temperature response. These variables are the component size (or density components) where more density of components require more period of time into the reflow zone, likewise soak and reflow zone are also effective variables as shown on figure 8:

5. CONCLUSION

Studying the thermal profile process of manufacturing Printed Circuit Boards (PCB) is to control the cycle time and temperature level of the oven using Box-Behnken designs. The quality of the solder joints is very critical to the lifetime of the PCB and the performance of the PCB. In this study of the local company of assembly line determined which variables are more significant to get good solder quality. In this study case, all the variables are impotent and none of them are neglected, but understanding the behavior of each variables regression model and the relationship between the variables help on the adjustment and optimization temperatures in each zone as shown on table 4. The study helps to minimize the iteration of prototype by having to try until getting the desired zones temperature. In addition, getting a better yield via improving the time of the PCB assembly process where time included oven programming, iteration retry, automated optical inspection, and visual inspection. Moreover, fewer prototypes printed circuit board. In terms of cost save, there are about 6 minutes for each iteration of the thermal profile and if the retry happened only 4 times, this means 24 minutes; assume the programing for the oven occur only once a week, so there are 21 hours. It is well-known that if the oven stops for programing then the assembly line will stop as well. The cost for assembly line estimated to be $10k per hour (included SMT, oven, printer, AOI, wash machine). As a result, the cost save will be $105K minimum. Thus, the conclusion to all of these efforts of optimizing the assembly line of PCB for continuous improvement is to provide good quality products, decrease cost, and reduce the time of delivery and meet the customer expectations. This research helps to understand and recommend the next step that could help the improvement of the printed circuit board assembly line. Since the entire seven variables are affective variables, therefore the recommendation for the oven temperature self-control will be very helpful for the thermal profile optimization.

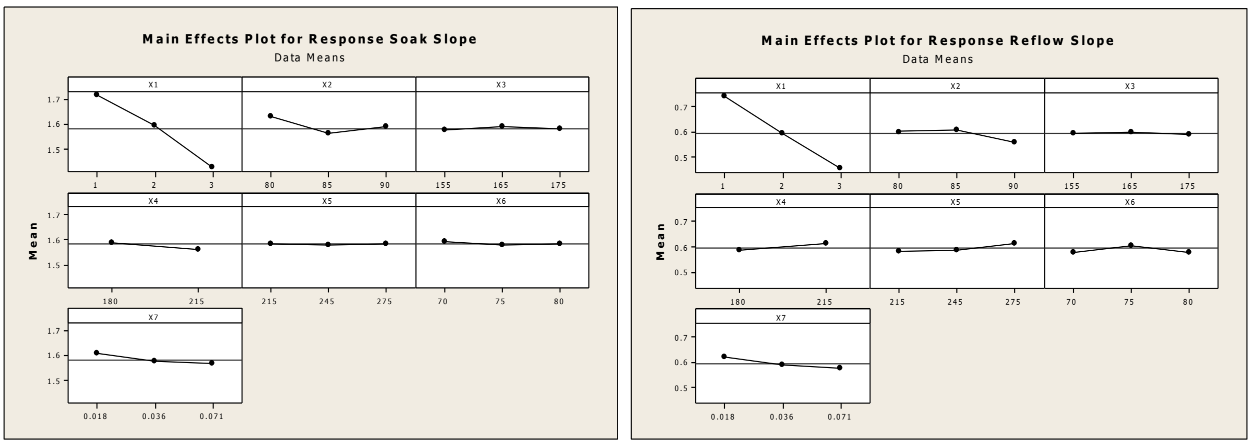

Figure 8. Main affects variables

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