USING ANOVA FOR OPTIMIZING THERMAL PROFILE PROCESS IN ASSEMBLY LINE OF PRINTED CIRCUIT BOARDS (PCB)

Dr. Kamal Alzameli, Design Multimedia System Engineer
Doctor of Engineering in Manufacturing Systems
Research and Vehicle Technology, Ford Motor Company

Dr. Daw Alwerfalli, Professor, Director
Master of Engineering Management
A. Leon Linton Department of Mechanical Engineering
College of Engineering
Lawrence Technological University

Dr. Ahmed Alsamarai, Senior Electrical Engineer
Product Devolvement Center, Ford Motor Company

ABSTRACT

The aim of this paper is to provide ANOVA study for 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; they also 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 are collected from real assembly line of PCB. Obtaining a better yield via improving the time of the PCB assembly process is another aim of the 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.

Key words: 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).
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, reducing changeover times, and reducing production downtime energy saved for the oven. As a result, obtaining high quality with low defect of the solder joint.

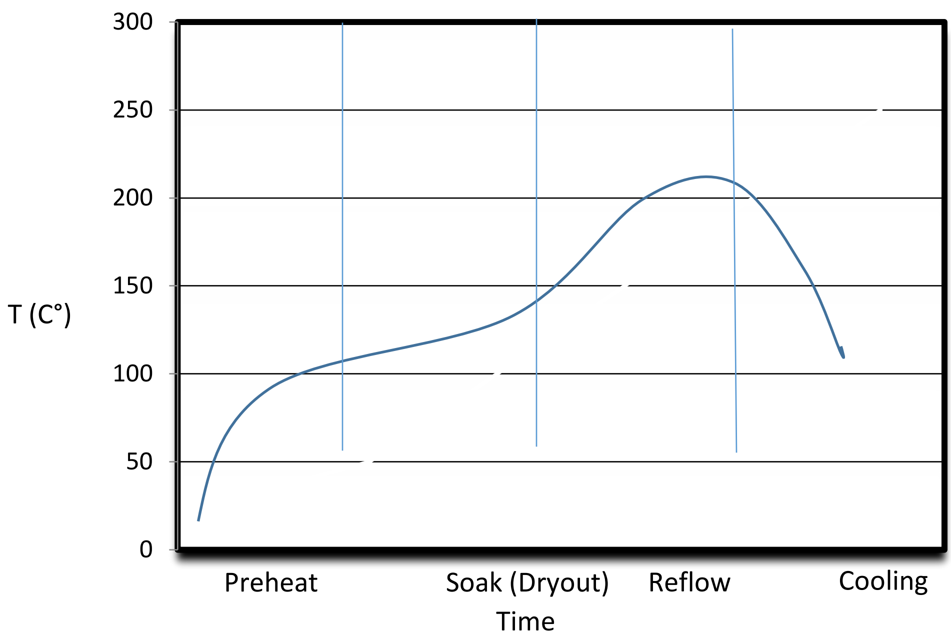

Figure 1. Typical Oven temperature zones

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.

2. 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 the 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 affect the process and product quality of the solder joints and described in figure 2.

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:

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

(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,

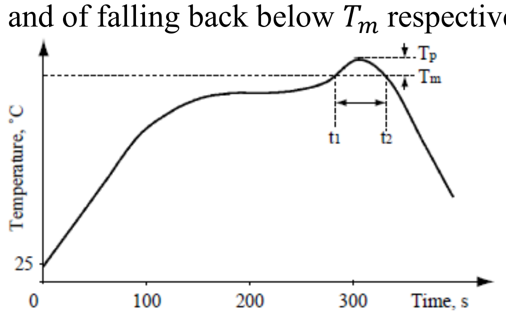

Figure 2: heating factor on reflow profile [7]

3. METHODOLOGY

Figure 3 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 will be needed for optimized response. Box-Behnken is useful if the operating zone of the process is known (specification). Therefore, the design will be in safe operating zone, the Box-Behnken ensures that not all factors will be set to at a high level at the same time. With seven factors, Box-Behnken could run in one or two blocks. This method is used due to the limited 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. Analysis of variance (ANOVA) is used to provide understanding of the behavior of the variables and error of the variables in order to adjust and improve the thermal profile.

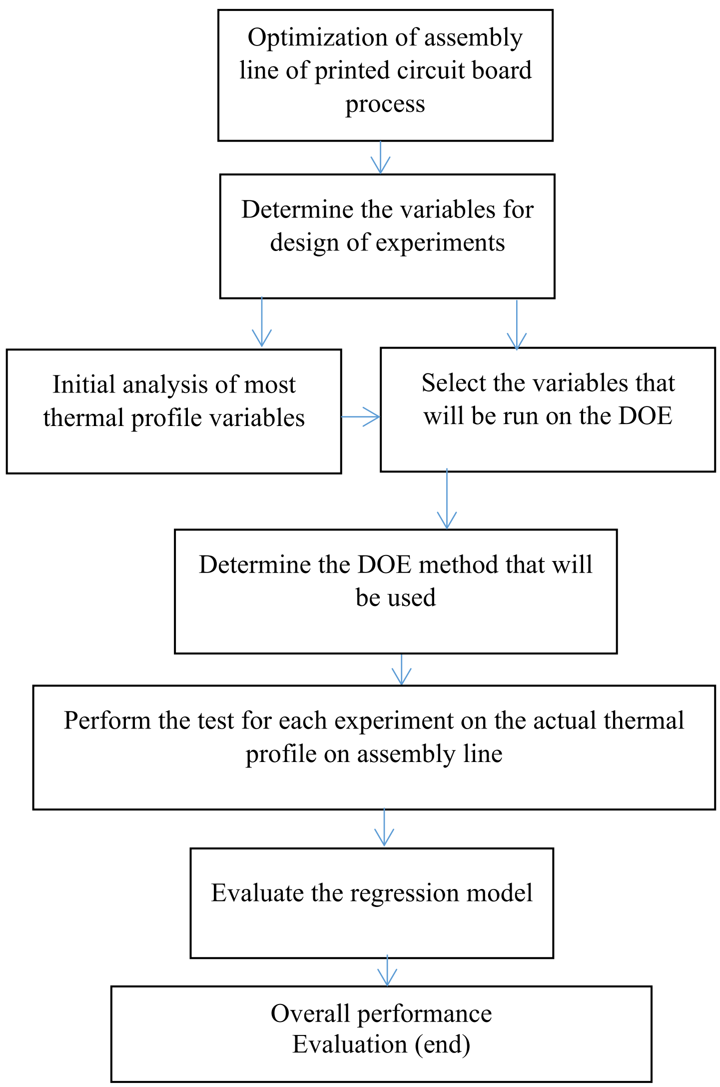

Figure 3. Overall methodology steps for optimization

3.1 VARIABLE OF THERMAL PROFILE

Variables selected for this study are based on the literature review and discussion with technical matter expert in 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 the same for the remaining zones which 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 methods could be used depending on the information collected for this variable. Mass differential and heat transfer into the PCB depends on several variables as Baehr [9] explain it in this book. Where:

$$Q = mC_p\Delta T \tag{2}$$

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; represented by three different levels consequently as shown on table 1. Also, the remaining heat zone temperatures and speed of conveyor are described in table 1.

Table1. 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)

3.2 ANOVA ANALYSIS AND HYPOTHESES

Similar to Regression model analysis performed in different research, ANVOA is the statistical analysis used to understand the significant effect variables. Similarly, hypotheses is used to find the significant factors and how it will be revealed to the ANOVA analysis.
Analyzing ANOVA to check the accepted and rejected hypotheses via P-value, results shown on table 2 from Minitab where 95% of the test result is confident. P-values range 0 -1 where a small value (<0.05) is used for significant level designated the effect of the result (preheat in the condition below) where variable x2 is <0.05; therefore, the Null hypothesis (H_0) will be rejected in this case and (H_a) Alternative hypothesis will be accepted. Other variables, the Null hypothesis (H_0) will be accepted and (H_a) Alternative hypothesis will be rejected.
Likewise, with other output result of Soak slope, Ramp up slope and cooling slope; hypotheses test and of ANOVA could be done.

- H_0: Null hypothesis: thermal profile variable does not affect Response Preheat Slope
- H_a: Alternative hypothesis: thermal profile variable does affect Response Preheat Slope.

Table 2. ANOVA Result

Response Surface Regression: Response Preheat versus X1, X2, X3, X4, X5, X6, X7 **The analysis was done using coded units.** **Estimated Regression Coefficients for Response Preheat Slope**				
Term	Coef	SE Coef	T	P
Constant	11.9762	5.7499	2.083	0.061
X1	-0.1508	0.2440	-0.618	0.549
X2	-0.1920	0.0611	-3.141	**0.009**
X3	0.0126	0.0302	0.419	0.684
X4	-0.0171	0.0085	-2.020	0.068
X5	-0.0065	0.0075	-0.862	0.407
X6	-0.0397	0.0576	-0.688	0.506
X7	-1.7141	9.0127	-0.190	0.853
X1*X1	0.0084	0.0073	1.149	0.275
X2*X2	0.0011	0.0003	3.790	**0.003**
X3*X3	0.0000	0.0001	0.341	0.740
X5*X5	0.0000	0.0000	0.833	0.423
X6*X6	0.0003	0.0003	0.912	0.381
X7*X7	17.7823	11.8438	1.501	0.161
X1*X2	0.0015	0.0020	0.764	0.461
X1*X3	-0.0000	0.0007	-0.000	1.000
X1*X4	0.0001	0.0003	0.195	0.849
X1*X5	0.0000	0.0002	0.000	1.000
X1*X6	-0.0015	0.0014	-1.081	0.303
X1*X7	-0.3767	0.2553	-1.475	0.168
X2*X3	-0.0002	0.0001	-1.802	0.099
X2*X4	0.0002	0.0001	2.974	**0.013**
X2*X5	0.0000	0.0000	0.180	0.860
X2*X6	0.0000	0.0003	0.000	1.000
X2*X7	-0.0162	0.0511	-0.317	0.757
X3*X4	-0.0000	0.0000	-0.110	0.915
X3*X5	0.0000	0.0000	0.360	0.725
X3*X6	0.0000	0.0001	0.000	1.000
X3*X7	-0.0000	0.0370	-0.000	1.000
X4*X5	0.0000	0.0000	0.279	0.785
X4*X7	0.0061	0.0118	0.513	0.618
X5*X7	0.0013	0.0085	0.148	0.885
X6*X7	0.0086	0.0511	0.169	0.869
S = 0.0196218 R-Sq = 98.36% R-Sq(adj) = 93.57%				

3.2.1 MAIN EFFECTS VARIABLES

The main effect variables for each response will be independent for each output 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 4:

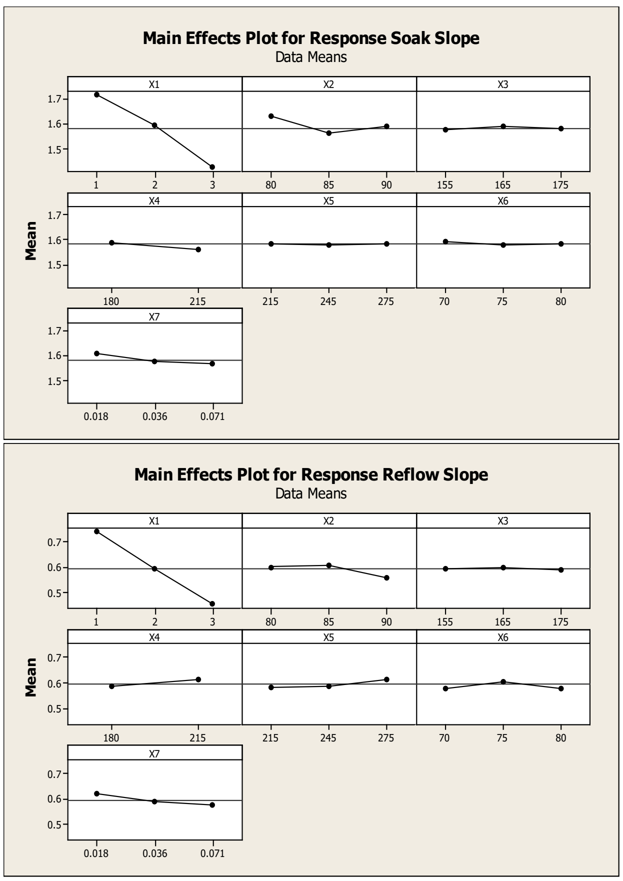

Figure 4. Main affects variables

3.2.2 Optimization

Table 3 shows the average test results of all the combinations that runs 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.

Table3. 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, board size (density of the components), and recommended adjusted values based on recommended specification and technical specialist. Figure 5 shows the current run compared to the recommended values, series 1 is 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 6 shows the graph after the adjustment and how close to the suggested specifications.

Table4. 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

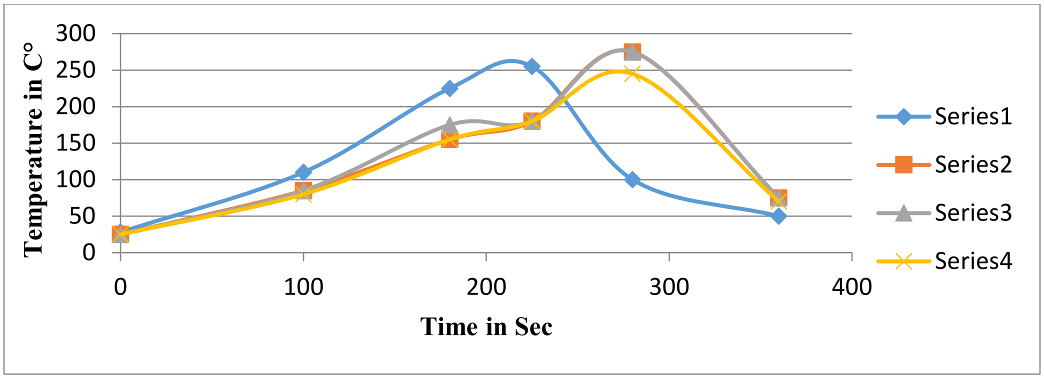

Figure 5. Temperature values before adjustment

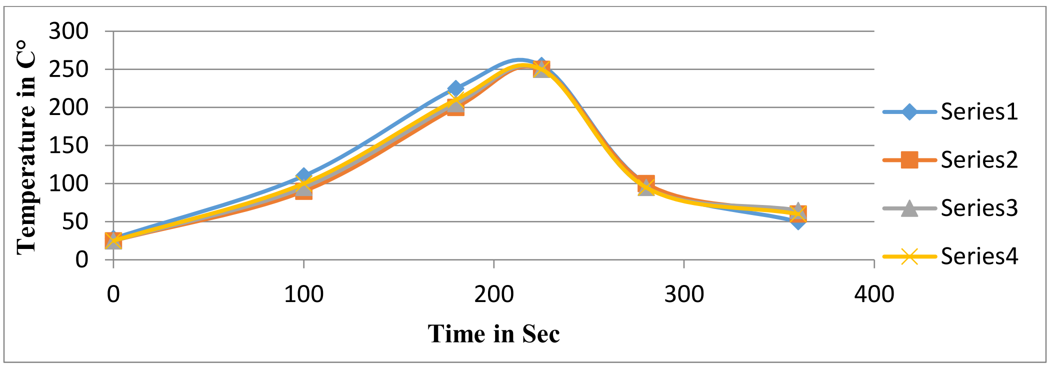

Figure 6. Temperature values after adjustment

4. CONCLUSION

Analysis of variance (ANOVA) is analyzing the behavior of the variables and error of the variables, which help to adjust and improve the thermal profile. 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, ANOVA helps 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.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my academic advisor Dr. Daw R. Alwerfalli on his valuable encouragement, timely guidance and patience. In addition, I would like to express my sincere gratitude to Dr. Ahmed Alsamarai who helped a lot during the investigation of the topic.

REFERENCES

[1] Tsai, T. N. (2012). Thermal parameters optimization of a reflow soldering profile in printed circuit board assembly: A comparative study. Applied Soft Computing, 12(8), 2601-2613.
[2] Mapa, L. B., & Vancha, M. A. R. (2012). AC 2012-5108: DESIGN OF EXPERIMENTS MODELING OF A HEAT TUNNEL. In American Society for Engineering Education. American Society for Engineering Education.
[3] Flaig, J. J. (2006). A New Classification of Variables in Design of Experiments.
[4] Gong, Y., Li, Q., & Yang, D. G. (2006, August). The optimization of reflow soldering temperature profile based on simulation. In Electronic Packaging Technology, 2006. ICEPT'06. 7th International Conference on (pp. 1-4). IEEE.
[5] Shu, M. H., Hsu, B. M., & Hu, M. C. (2012) made an optimal combination of soldering conditions of BGA for halogen-free and lead-free SMT-green processes. Microelectronics Reliability, 52(11), 2690-2700.
[6] Verdi, F. W. Lead Free Manufacturing: Reflow Soldering.
[7] Gao, J., Wu, Y., & Ding, H. (2007). Optimization of a reflow soldering process based on the heating factor. Soldering & surface mount technology, 19(1), 28-33.
[8] Gang Gao, J., Ping Wu, Y., Ding, H., & Hong Wan, N. (2008). Thermal profiling: a reflow process based on the heating factor. Soldering & Surface Mount Technology, 20(4), 20-27.
[9] Baehr, H. D., & Stephan, K. (2011). Heat and mass transfer.