TELKOMNIKA, Vol.17, No.5, October 2019, pp.2268~2275
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v17i5.12796

Electronics system thermal management optimization using finite element and Nelder-Mead method

Nurul Kausar Ab Majid*[1], Fatimah Sham Ismail[2]
[1,2]School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Johor Bahru, Johor, Malaysia
[1]Fakulti Teknologi Kejuruteraan Elektrik & Elektronik, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
*Corresponding author, e-mail: nurulkausar@utem.edu.my[1], fatimahs@utm.my[2]

Abstract

The demand for high-performance, smaller-sized, and multi-functional electronics component poses a great challenge to the thermal management issues in a printed circuit board (PCB) design. Moreover, this thermal problem can affect the lifespan, performance, and the reliability of the electronic system. This project presents the simulation of an optimal thermal distribution for various samples of electronics components arrangement on PCB. The objectives are to find the optimum components arrangement with minimal heat dissipation and cover small PCB area. Nelder-Mead Optimization (NMO) with Finite Element method has been used to solve these multi-objective problems. The results show that with the proper arrangement of electronics components, the area of PCB has been reduced by 26% while the temperature of components is able to reduce up to 40%. Therefore, this study significantly benefits for the case of thermal management and performance improvement onto the electronic product and system.

Keywords*: finite element method, Nelder-Mead method, optimization, thermal distribution*

1. Introduction

Current trends of electronics system technology trying to increase the packaging power density by reducing the size of components and the system itself. The increase of this power density has led to the study of thermal management issue. Moreover, the electronics system design become more complex and compact with increasing the numbers of chips on a small Printed Circuit Board (PCB) with reduction of packaging size. If this issue is not taken care of, the performance and life span of electronic components will drop drastically. Therefore, thermal management is one of the important factors at the early stage of the PCB design. With computational technologies, by using the finite element analysis, the thermal behaviour of the system can be observed by simulation before the product is fabricated.

Various optimization methods have been proposed to optimally place electronic components on a PCB during the manufacturing and fabrication process [1, 2]. Currently, Finite Element Method (FEM) is widely used as a tools to obtains the thermal distribution on PCB and MCM and to optimize the components arrangement [3-6]. However, in these papers, the optimization and evaluation are conducted with several limitations of the proposed optimal solutions. After that, FEM and optimization algorithm [7] had been incorporated with the used of Force-Directed Algorithm (FDA), chip overlapping in [2] had been solved. They had introduced a novel algorithm with the thermal force-directed algorithm. However, this research did not increase the thermal performance. Sequential Metamodeling based incorporated response surface methodology has been used to find an optimal arrangement of the components on Multi Component Module (MCM) [8, 9]. Artificial intelligence (AI) techniques conducted by [10-13] had improved the thermal problem. However, there are a few parameters were ignored such as the material of PCB and the thermal conductivity of the material [14-18]. The objective of this study is to develop an optimization model using Nelder-Mead Optimization (NMO) tools from Comsol Multiphysics software package. For comparative study, sample from [2] and [10] are

Received October 17, 2018; Revised April 19, 2019; Accepted May 13, 2019

selected for multi-objective optimization, which are average temperature of components and area of PCB.

2. Model Development

Nelder-Mead algorithm is a simplex search algorithm, where it is also known as one of the best-known algorithms for multidimension unconstrained optimization without derivatives [19]. The basic algorithm is simple to understand and easy to use. That is the reason, why it is very popular in many fields of science and technology. This method does not require any derivative information, which makes it suitable for non-smooth function problem. It is used to solve parameters estimation where the function values are subjected to noise [20]. Finate Element Method (FEM) and Nelder-Mead optimization (NMO) solver from COMSOL Multiphysics was use to solve single objective function for the temperature and multi-objective functions for temperature of the components and area of PCB.

Model of component on PCB has been developed following a few steps as shown in Figure 1. The initial arrangement of the component is created. Next, the other parameters such as thermal conductivity, material, initial temperature, and boundary temperature are set. Afterwards, the process of generating the finite element mesh has been conducted for optimization process. Figure 2 shows the Nelder Mead Optimization (NMO) solver process that has been selected to solve for single objective and multi-objective problem. This method has an ability to solve for the worse point on the control variable for proposing the optimal solution [13, 20-24].

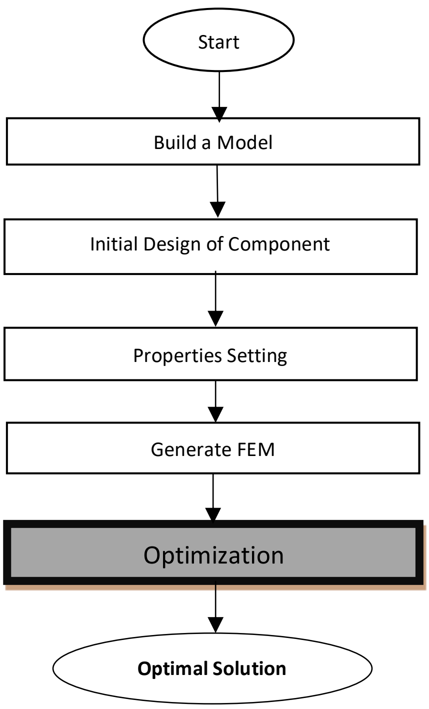


Figure 1. Flow chart COMSOL optimization process

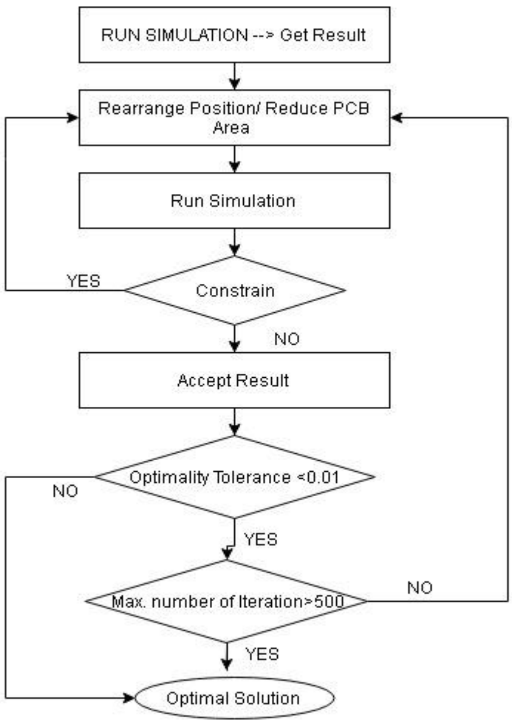


Figure 2. Nelder-Mead optimization solver

Model of celectronics component on PCB from optimization solver for a single objective function has been developed using Test sample, which consist of 3 components as listed in Table 1. Based on this result, a multi-objectives optimization model is designed and tested. Finally, comparative analysis from published samples by [2] and [10] is conducted and the optimal design of those samples is proposed.

Firstly, single objective function has been tested, where the temperature (*T*) of each component is optimized, hence the fitness function is given in (1).

$$f(T) = \sum_{i=1}^{n} T_i \tag{1}$$

where *i* is the current number of components and *n* is total number of components.

Secondly, multi-objective functions, which minimize the temperature of each components and area of PCB have been developed. The total fitness function is given by (2):

$$f(T, A) = \sum [\, f(T) + f(A)] \tag{2}$$

where;
$f(T)$: average Temperature of Components
$f(A)$: area of PCB
fitness function for area of PCB is given in (3)

$$f(A) = \frac{A}{A_{initial}} \text{A/A\_(Allow\_max)} \tag{3}$$

where:

$$A = (PCB\_L \times PCB\_W)$$
$$A_{allow\_max} = (PCB\_L_{max} - PCB\_L_{min}) \times (PCB\_W_{max} - PCB\_W_{min}) \tag{4}$$

Table 1. Parameter Setting for Test Sample

Components		PCB	C1	C2	C3
Size (cm)	x	5	2.5	1.5	1
	y	5	1.5	1	1
	z	0.16	0.1	0.1	0.1
Thermal Conductivity, (W/m.°k)	*k*	8		8.37	
Power, W		-	0.8	0.7	0.4
Location (cm)	x	-	-2	-1	-2
	y		-2	-1	1.3
	z		0.08	0.08	0.08
Material		Copper		Silicon	

In order to achieve an optimal fitness function $f(T)$, the solver will rearrange the position of each component on the PCB until the minimum average temperature is achieved. These control variables, which are the position of all components are evaluated. Fitness function for area of PCB, $f(A)$ is calculated from the length (*PCB_L*) and width (*PCB_W*) of PCB. By adjusting and reducing these parameters, it will able to minimise the size of PCB. Table 2 shows all the control parameters for sample Model. During evaluation process, the fitness function must satisfy all the constraint parameters such as maximum temperature allowed, maximum area of PCB, components overlapping, and all the components must be within set range [25]. All the constraints are listed in Table 3. Optimizer setting has been selected based on several trials and analysis such as maximum number of iterations is 500 and maximum number of populations is 100. While the number of optimality tolerance is 0.01. These set up are applicable for all simulation work in this paper.

Table 2. Parameter Setting for Test Sample Model

Parameters	Initial Value	Lower Bound	Upper Bound
C1_X	-1.5	-(PCB_W / 2)	(PCB_W / 2) - 1.5
C1_Y	-1.5	-(PCB_L / 2)	(PCB_L / 2) – 2.5
C2_X	1	-(PCB_W / 2)	(PCB_W / 2) - 1
C2_Y	1	-(PCB_L / 2)	(PCB_L / 2) - 1.5
C3_X	1	-(PCB_W / 2)	(PCB_W / 2) - 1
C4_Y	1.5	-(PCB_L / 2)	(PCB_L / 2) - 1
PCB_L	5	3.5	5
PCB_W	5	3.5	5

Table 3. Constraints Setting for Evaluation Process

Expression	Lower Bound	Upper Bound
(x1== x2) &&(y1==y2)	0	2.5
(x2== x3) &&(y2==y3)	0	2.5
(x1== x3) &&(y1==y3)	0	1.5

3. Results and Analysis

3.1. Single Objective Temperature Optimization

Average temperature of components from Test sample has been simulated and optimized based on the given initial design. The variation of an average temperature versus the number of iterations are plotted in Figure 3. The details average optimal temperature for each component are shown in Figures 4 (a) and 4 (b), which comparing thermal profile of initial design and proposed optimal design.

Table 4 shows the results of the temperature for all components have reduced as compared to the initial setting. While the location of all components relocates to the edge of the PCB and non-overlap occurred. This new arrangement has more space for a heat to dissipate by conduction within components and PCB or via convection to surrounding. This process has minimized the temperature of each components.

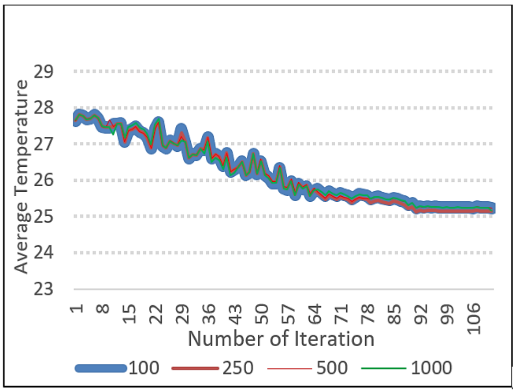
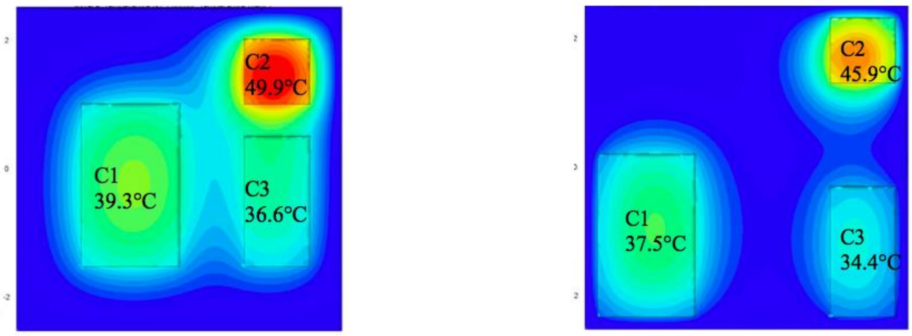


Figure 3. Graph of average temperature vs number of Iteration



(a) (b)

Figure 4. (a) Thermal profile of initial design and (b) thermal profile of optimal design

Table 4. Single Objective Data of Test Sample

Parameters measure	Initial Temperature (°C)	Final Temperature (°C)	Temperature Reduction (%)
C1	39.3	37.5	4.58
C2	49.9	45.9	8.02
C3	36.6	34.4	6.01

3.2. Multi-objective Temperature and Area Optimization

The same Test sample is used for multi-objective optimization algorithm, which is to minimize the average temperature of components and area of PCB. Figure 5 presents the result of multi-objective optimization process where the area of PCB is minimized to 16 cm^2 and the average of temperature on the PCB reduces up to 2°C. In this case, the process stops after the 80^{th} iteration since the stationary point is reached.

The thermal profile for the proposed optimal design is presented in Figure 6, while the initial design as in Figure 4. All results are recorded in Table 5. It can be seen that, even the area of the components is reduced about 34% to 16.4 cm^2. The temperature of components is reduced up to 16%. The components are moving towards the edge of PCB and located away from each other. It will help all the components to have better heat dissipation to the PCB and surrounding.

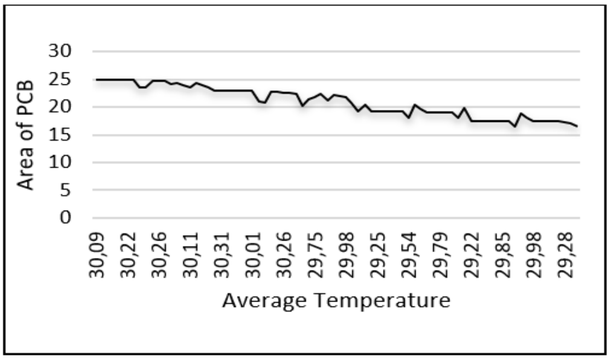


Figure 5. Graph for area of PCB vs average temperature

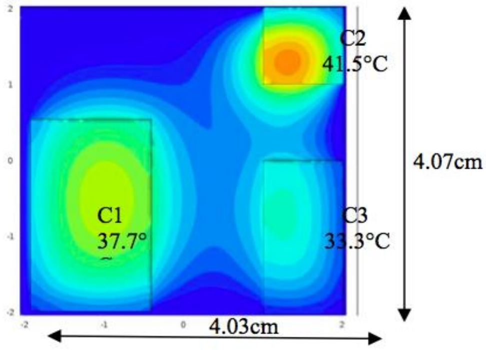


Figure 6. Thermal profile of optimal design test sample

Table 5. Multi-objective Data of Test Sample

Parameters measure	Initial T emperature (°C)	Final T emperature (°C)	Temperature/Area Reduction (%)
C1	39.30	37.70	4.11
C2	49.90	41.50	16.83
C3	36.60	33.30	9.35
Area PCB	25.00 cm^2	16.42 cm^2	34.29

3.3. Comparative Analysis using Sample [2]

The dimension of Sample [2] is a 5x5 cm PCB and consist of 8 same size components with various power dissipation. By using the same optimization parameters from Test sample, the result of optimal solution is plotted in Figure 7. Thermal profile for initial design and final design are presented in Figures 8 (a) and 8 (b) respectively.

By using NMO, the optimization algorithm is able to solve for worse point. The optimal design shows the temperature of the components has been minimized up to 22.8%. While the area of PCB reduced from 25cm^2 to 18.5cm^2, which is about 26.2%. All the results are recorded in Table 6.

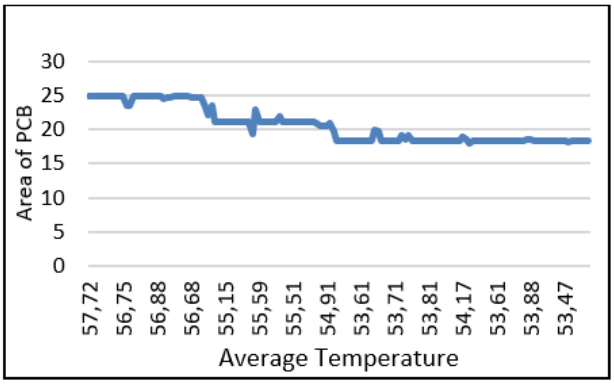
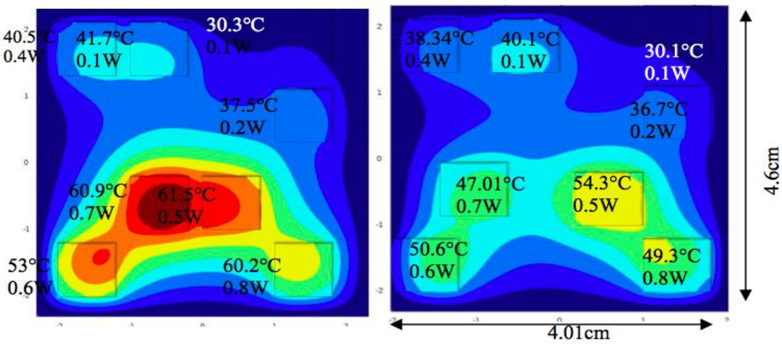


Figure 7. Graph for area of PCB vs average temperature of sample [2]



(a) (b)

Figure 8. (a) Thermal profile of initial design and
(b) thermal profile of optimal design of sample [2]

Table 6. Multi-objective Data of Sample [2]

Parameters measure	Initial Temperature (°C)	Final Temperature (°C)	Temperature/ Area Reduction (%)
C1	60.00	49.31	17.81
C2	60.90	47.01	22.80
C3	40.50	38.34	4.15
C4	41.70	40.10	4.10
C5	61.70	54.32	11.96
C6	53.00	50.59	3.96
C7	37.50	36.70	2.13
C8	30.30	30.14	0.53
Area PCB	25.00 cm^2	18.45 cm^2	26.20

3.4. Comparative Analysis using Sample [10]

Sample [10], Multi-voltage regulator (MVR) is a multipurpose signal conditioning circuits for laboratory equipment, especially for data acquisition and measurement system. This sample consists of 9 components with unequal power dissipation and the PCB area is 198 cm^2. There are also others non-heated components that was grouped together. The result of optimization is presented in Figure 9 and thermal profile for initial and optimal design can be seen in Figures 10 (a) and 10 (b) respectively.

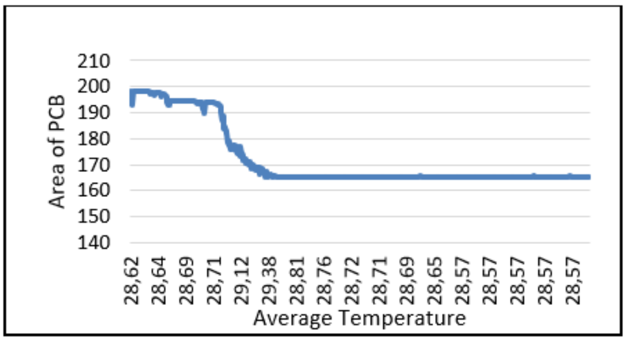
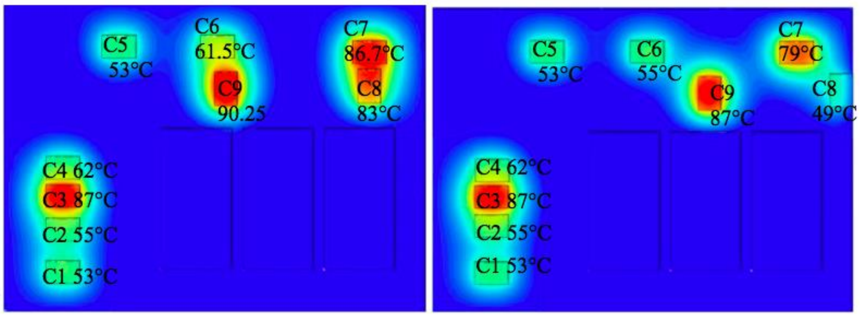


Figure 9. Graph for area of PCB vs average temperature of sample [10]

From the initial design as shown by Figure 10 (a), there are two high power components located near to each other. However, after optimization arrangement, the result shows that it is able to reduce the temperature up to 40%. Although this is the high-power dissipation components, when it placed at the edge of PCB, it will have more space for convection process, hence the reducing in temperature. At the same time, 16.67% area of PCB has been reduced. All the results of temperature and percentage of area reduction are presented in Table 7. The results show that the proposed approch in this work are better than using evaluationary Genetic Algorithm obtanied by [10].



(a) (b)

Figure 10. (a) Thermal profile of initial design and
(b) thermal profile of optimal design of sample [10]

Table 7. Multi-objective Data of Sample [10]

Parameters measure	Initial Temperature (°C)	Final Temperature (°C)	Temperature/ Area Reduction (%)	Genetic Algorithm [10]
C1	53.00	53.00	0	(-) 1.57
C2	55.00	55.00	0	(-)7.26
C3	87.00	87.00	0	18.03
C4	62.00	62.00	0	(-)4.49
C5	53.00	53.00	0	(-)0.54
C6	61.50	55.00	10.49	(-)0.5
C7	86.70	79.00	8.82	0.83
C8	83.00	49.20	40.70	0.01
C9	90.25	86.93	3.67	(-)0.01
Area PCB	198.00 cm^2	165.00 cm^2	16.67	19.84%

*(-) Temperature of component increases

4. Conclusion

This paper has presented optimization thermal management based on electronics components arrangement using Finite Element Method and Nelder-Mead optimization (NMO) solver. In general, when the size of packaging is reduced, it will contribute to the increment of power density. However, from the result of the sample showed that when the area of PCB is reduced by 26.2%, the highest temperature of component also has reduced by 22%. For sample the area of PCB is reduced by 16.67% and the temperature of components are able to reduce up to 40%. These results have confirmed that, with the proper arrangement of the components, the temperature of distribution can be maintained or reduce although the area of PCB is decreased. This optimization algorithm will help the designer to predict the temperature of components on PCB before the fabrication process. It will help to reduce the cost of development by enabling the optimization to be performed at the design stage to meet the customer satisfactions.

Acknowledgements

The authors would like to thank for the support given to this research by Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia (UTM), under Vot: GUP: 06H04 and 13H57.

References

[1] Mizuno Y, Soga I, Hirose S, Tsuboi O. *Si Microchannel Cooler Integrated with High Power Amplifiers for Base Station of Mobile Communication Systems.* 61th IEEE Electronic Components and Technology Conference (ECTC). 2011; 1541-1546.

[2] Ye N, Yang Y, Yuan Z, Shen H, Zhao N. *An Optimization Algorithm Based on TFPA for Multiple Components Modules.* 11th Conference on Industrial Electronics and Applications (ICIEA). 2016; 12–15.

[3] Cheng T, Luo X, Huang S, Liu S. Thermal Analysis and Optimization of Multiple LED Packaging Based on a General Analytical Solution, *Int. J. Therm. Sci.* 2010; 49(1): 196–201.
[4] Cheng HC, Chung IC, Chen WH. Thermal chip placement in MCMs using a novel hybrid optimization algorithm, *IEEE Trans. Components, Packag. Manuf. Technol.* 2012; 2(5): 764–774.
[5] Dogruoz M. B, Abarhama M. *Transient Thermal Behavior of SOIC Packages-An Optimization Study.* 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm). 2016; 1083-1092.
[6] Srinivasulu NV. Thermal Analysis of Printed Circuit Board (PCB) of Avionics Equipment. *in Int. J. Adv. reaserch Comput. Eng. Technol.* 2012; 1(6): 216–224.
[7] Huang YJ, Fu SL. Thermal Placement Design for MCM Applications. *Trans. Soc. Mech. Eng. J. Electron. Packag.* 2000; 122(2): 115–120.
[8] Cheng HC, Tsai YH, Chen KN, Fang J. Thermal Placement Optimization of Multichip Modules using a Sequential Metamodeling-Based Optimization Approach. *Appl. Therm. Eng.* 2010; 30(17): 2632-2642.
[9] Lee J. Thermal Placement Algorithm Based on Heat Conduction Analogy. *IEEE Trans. Comp Packag. Technology.* 2003; 26(2): 473-476.
[10] Ismail FS, Yusof R. *Multi-objective Optimization Problems : Method and Application.* 4th International Conference on Modelling, Simulation and Applied Optimization(ICMSAO). IEEE Massaschucetts. 2011: 1-6.
[11] Abubakar AK, Ismail FS. Optimal Thermal Distribution by using Inverse Genetic Algorithm Optimization Technique. *Journal of Telecomunication, Electronics & Computer Engineering*. 2016; 8(11): 15–21.
[12] Suwa T, Hadim H, Optimal Placement of Heat Generating Components at Various Levels of Electronics Packaging. *Microelectronics J.* 2010; 41(2-3): 129–134.
[13] Ismail FS, Yusof R, Khalid. Optimization of Electronics Component Placement Design on PCB Using Self Organizing Genetic Algorithm (SOGA). *J Intell Manuf.* 2012; 23(3): 883-895.
[14] Gao F, Han L. Implementing the Nelder-Mead Simplex Algorithm with Adaptive Parameters. *Computational Optimization and Applications*. 2012; 51(1): 259-277.
[15] Ismail FS, Yusof R, Khalid M, Selamat H, Ibrahim Z. Performance Evaluation of Self Organizing Genetic Algorithm for Multi-objective Optimization Problems. *International Journal of Research and Surveys ICIC Express Letters*. 2012; 6(1): 1-7.
[16] Hisham NWB, Ismail FS. Nawawi MAA. Thermal Performance Analysis for Optimal Passive Cooling Heat Sink Design. *TELKOMNIKA Telecommunication Computing Electronics and Control*. 2017; 2(15): 883-887.
[17] Hanafi MZM, Ismail FS. Multi-objective Optimal Thermal Heat Sink Design Using Evolutionary Method. *Jurnal Teknologi (Sciences & Engineering).* 2015; 72(2): 1–6.
[18] Hanafi MZM, Ismail FS. *Heat Sink Model and Design Analysis Based on Particle Swarm Optimization*. IEEE Innovative Smart Grid Technologies Conference- Asia (ISGT ASIA 2014). 2014.
[19] Rios L. M, Sahinidis NV. Derivative-free optimization : a review of algorithms and comparison of software implementations. *Journal of Global Optimization.* 2013; 56(3): 1247–1293,
[20] Bűrmen Á, Puhan J, Tuma. Grid Restrained Nelder-Mead Algorithm. *Computational Optimization and Applications*. 2006; 34(3): 359-375.
[21] Coope ID, Price CJ. Frame Based Methods for Unconstrained Optimization. *Journal of Optimization Theory and Applications*. 2000; 107: 261–274.
[22] Coope ID, Price CJ. On the Convergence of Grid-based Methods for Unconstrained Optimization. *SIAM J. Optim*. 2001; 11: 859–869.
[23] Lewis RM, Torczon VJ. Trosset MW. Direct Search Methods: Then and Now. *Journal of Computational and Applied Mathematics*. 2000; 124: 191–207.
[24] Price CJ, Coope ID, Byatt D. A Convergent Variant of the Nelder-Mead Algorithm. *Journal of Optimization Theory and Applications*. 2002; 113: 5–19.
[25] Wang D, Lu H, Xiao Z, Yang MH, Inverse Sparse Tracker With a Locally Weighted Distance Metric. *IEEE Trans. Image Process.* 2015; 24(9): 2646–2657.