Full Factorial Design Exploration Approach for Multi-Objective Optimization on the (FDM) 3D Printed Part

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Abstract. In the manufacturing industry, especially in automotive, quality, precision and productivity on the part that produces is crucial. 3D Printing technology offers a significant advantage to the manufacturer because its ability to produce complex geometry and low-cost investment risk compared with injection moulding. However, there are several issues of using this technology in mass scale and of the issue is dimensional accuracy. In this study, the application of optimisation approach which is Full Factorial Design (FFD) approach which has employed on 3D Printed bottom housing part made from Polylactic Acid (PLA) which were printed using Fused Deposition Modelling (FDM) 3D printer in order to minimise shrinkage on 3D printed parts. Based on the optimisation work, the results showed the performance of FFD approach provides a good dimensional accuracy compared to the drawing specification for the printed part. Therefore, this research provides beneficial scientific knowledge and alternative solution for the additive manufacturing process in industries application to enhance the quality of the 3D printed parts produced using FDM 3D printer machine.

1. Introduction

Industrial Revolution 4.0 has changed the landscape of the manufacturing sector, especially in the automotive industry. According to H. Blum [1], the automotive sector will become the highest global market value in industrial additive manufacturing market by 2025. Desktop 3D Printer is one of the additive manufacturing technologies and has become a key technology for the automotive industry. Ability to produce a complex part with significantly low-cost investment make this technology, highly regards as a future of the manufacturing industry and slowly replacing conventional techniques such as injection moulding. There three main types of additive manufacturing technologies which are Fused Deposition Modelling (FDM), Stereolithography Apparatus (SLA) and Selective Laser Sintering (SLS). FDM is a common technology that uses in desktop 3D Printer. The process involved molten thermoplastic filament move through the heated extruder and construct the 3-Dimensional geometrical part layer by layer. Figure 1 shows the schematic diagram of FDM 3D Printer.
Many automakers starting adopting FDM 3D Printing technologies in the product, especially the desktop version of 3D Printer compared with industrial version. Desktop 3D Printer is widely popular because of their competitive price, flexibility and easy to maintain compared with industrial version. However, Industrial 3D Printer offers bigger printing volume, higher accuracy, and durability.

Several issues regarding 3D Printing that causes these technologies yet to be used in mass scale. Warping, dimensional accuracy and surface quality are the issues that need to be resolved to make these technologies feasible for mass application. Dimensional accuracy is a crucial aspect of the automotive part. In this study, researchers will evaluate several parameters and their influence on part dimensional accuracy. Few factors can influence dimensional accuracy of the 3D printed part such as extruded temperature, platform temperature, printing speed and infill percentage. N. A. Sukindar et al [2] has listed the factors that consider influential to the dimensional accuracy of 3D printed part which are layer height, wall thickness, printing speed, extrusion rate, print fill density, size of the print, cooling fan interaction with print and shell thickness. J. Wu [3] stated nozzle temperature, material, fill rate, and print layer thickness are the primary factors. While M.A.Nazan et al [4] used Design of Experiment (DOE) technique to screen several factors and come out with four parameters which are layer temperature, infill density, and first layer height.

Therefore, this study will present the application of various research works to optimise multi-objective problem which are shrinkage in x, y and z directions on the 3D printed part. Based on the input of processing parameters, the design of experiment (DOE) will be generated by using Full Factorial Design (FFD) optimisation approach. Then, several samples will be printed by following each DOE run and regression analysis will be performed to obtain the Analysis of Variance (ANOVA) and the multi-objective optimised result.

2. Full Factorial Design
Full Factorial Design (FFD) is one of classical optimisation approach which using statistical manners. It used to demonstrate the relationship between variable parameters which influence the response by using the linear regression model [5]. The necessary information to construct the response model was accumulated by the experimental or simulation work [6, 7]. Figure 2 shows the flowchart of FFD used in this study.

In this study, extruder temperature, platform temperature, printing speed and infill percentage were selected as variable parameters because these parameters always been adjusted by the machine operator. The maximum and minimum limits for each parameter are shown in Table 1 based on material specification. Then, Full Factorial Design (FFD) with four centre points was performed to generate a set of DOE by using Design Expert 7.0 software. Therefore, 20 runs of the specified condition have been generated and each run will be set in a 3D printing machine to print the specimen. Then, each specimen shrinkage will be evaluated in x, y and z directions.
3D printed part with 2.5 mm of average thickness as shown in Figure 3 has taken as a specimen in this study. Continental Automotive Component, Malaysia has donated this part. This specimen has printed by using Fused Deposition Modeling (FDM) printer and Polylactic Acid (PLA) was used as a material.

### Table 1. Variable parameters range.

| Factors                        | Level         |
|--------------------------------|---------------|
| Extruder temperature, A (°C)   | 190 220       |
| Platform temperature, B (°C)   | 23 60         |
| Printing speed, C (mm/s)       | 40 100        |
| Infill percentage, D (%)       | 20 100        |

3. **FFD Regression Analysis**

The shrinkage results in all specified directions will be obtained for each DOE run by measuring process using coordinate measuring machine (CMM). Then, by utilising Design Expert 7.0 software the regression analysis was performed to obtain the recommended processing parameter setting which will optimise the shrinkage 3D printed part in all directions. The regression analysis will determine the
relationship between variable parameters and responses by using linear regression model in statistical manner and the results will be verified with analysis of variance (ANOVA).

4. Result and Discussion
Results from measuring process using CMM for bottom housing was shown in Table 2. The results tabulated the shrinkage values for each run of experiment with a specified variable parameters condition which obtained from the DOE. The dimensions that have been measured on this 3D printed part as shown in Figure 4 which representing shrinkage in x, y and z directions.

| DOE run | Extruder temperature (°C) | Platform temperature (°C) | Printing speed (mm/s) | Infill percentage (%) | Shrinkage x (mm) | Shrinkage y (mm) | Shrinkage z (mm) |
|---------|---------------------------|----------------------------|-----------------------|------------------------|------------------|------------------|------------------|
| 1       | 190                       | 23                         | 40                    | 20                     | 78.88            | 72.73            | 11.83            |
| 2       | 220                       | 23                         | 40                    | 20                     | 78.86            | 72.80            | 11.59            |
| 3       | 190                       | 60                         | 40                    | 20                     | 78.70            | 72.68            | 11.62            |
| 4       | 220                       | 60                         | 40                    | 20                     | 78.73            | 72.84            | 11.39            |
| 5       | 190                       | 23                         | 100                   | 20                     | 78.95            | 72.95            | 11.90            |
| 6       | 220                       | 23                         | 100                   | 20                     | 78.87            | 72.81            | 11.89            |
| 7       | 190                       | 60                         | 100                   | 20                     | 78.96            | 72.83            | 11.79            |
| 8       | 220                       | 60                         | 100                   | 20                     | 78.98            | 72.86            | 11.81            |
| 9       | 190                       | 23                         | 40                    | 100                    | 79.07            | 72.97            | 11.77            |
| 10      | 220                       | 23                         | 40                    | 100                    | 78.86            | 72.86            | 11.91            |
| 11      | 190                       | 60                         | 40                    | 100                    | 78.92            | 72.39            | 11.85            |
| 12      | 220                       | 60                         | 40                    | 100                    | 78.76            | 72.77            | 11.87            |
| 13      | 190                       | 23                         | 100                   | 100                    | 79.04            | 72.90            | 11.84            |
| 14      | 220                       | 23                         | 100                   | 100                    | 78.75            | 72.74            | 11.81            |
| 15      | 190                       | 60                         | 100                   | 100                    | 79.02            | 72.88            | 11.84            |
| 16      | 220                       | 60                         | 100                   | 100                    |                 |                  |                  |
| 17      | 205                       | 41.5                       | 70                    | 60                     | 79.11            | 72.87            | 12.13            |
| 18      | 205                       | 41.5                       | 70                    | 60                     | 79.11            | 72.87            | 12.13            |
| 19      | 205                       | 41.5                       | 70                    | 60                     | 79.11            | 72.87            | 12.13            |
| 20      | 205                       | 41.5                       | 70                    | 60                     | 79.11            | 72.87            | 12.13            |

Figure 4. Dimensions measured on 3D printing bottom housing.
The results of Analysis of Variance (ANOVA) were shown in Tables 3, 4 and 5 for shrinkage in x, y and z directions respectively. Based on the ANOVA results for bottom housing, DOE model was significant for x and z directions responses. However, in the y-direction, the DOE model was insignificant. This situation might be due to an insignificant variable parameter towards shrinkage in the y-direction. Then, the FFD optimisation approach will be utilised to obtain a multi-objective optimisation result.

Table 3. ANOVA results for shrinkage in x-direction.

| Source          | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|-----------------|----------------|----|-------------|---------|-----------------|
| Model           | 0.118          | 2  | 0.059       | 7.426   | 0.0052          |
| A-Extruder Temp | 0.077          | 1  | 0.077       | 9.767   | 0.0065          |
| D-Infill        | 0.040          | 1  | 0.040       | 5.084   | 0.0385          |
| Curvature       | 0.169          | 1  | 0.169       | 21.298  | 0.0003          |
| Residual        | 0.127          | 16 | 0.008       |         |                 |
| Lack of Fit     | 0.127          | 13 | 0.010       |         |                 |
| Pure Error      | 0              | 3  | 0           |         |                 |
| Cor Total       | 0.413          | 19 |             |         |                 |

Table 4. ANOVA results for shrinkage in y-direction

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|--------|----------------|----|-------------|---------|-----------------|
| Model  | 0.000          | 0  |             |         |                 |
| Curvature | 0.016      | 1  | 0.016       | 1.085   | 0.3113          |
| Residual | 0.270        | 18 | 0.015       |         |                 |
| Lack of Fit | 0.270       | 15 | 0.018       |         |                 |
| Pure Error | 0.000        | 3  | 0.000       |         |                 |
| Cor Total | 0.286        | 19 |             |         |                 |

Table 5. ANOVA results for shrinkage in z-direction

| Source          | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|-----------------|----------------|----|-------------|---------|-----------------|
| Model           | 0.144          | 3  | 0.048       | 5.042   | 0.0130          |
| A-Extruder Temp | 0.035          | 1  | 0.035       | 3.668   | 0.0747          |
| C-Print Speed   | 0.061          | 1  | 0.061       | 6.396   | 0.0231          |
| D-Infill        | 0.048          | 1  | 0.048       | 5.061   | 0.0399          |
| Curvature       | 0.378          | 1  | 0.378       | 39.753  | < 0.0001        |
| Residual        | 0.143          | 15 | 0.010       |         |                 |
| Lack of Fit     | 0.143          | 12 | 0.012       |         |                 |
| Pure Error      | 0              | 3  | 0           |         |                 |
| Cor Total       | 0.664          | 19 |             |         |                 |

To obtain the minimum condition of shrinkage on the 3D printed part, the processing parameters of the 3D printer setting should be in the optimal setting. By utilising the FFD optimisation approach to solve the multi-objective problem, the lowest value of shrinkages was defined based on the linear model where the best combination of parameters setting resulted in the better value of shrinkages in all
x, y and z directions. The multi-objective optimised results using FFD approach have been summarised as shown in Tables 6.

| Factors                        | Recommended simulation results | Predicted of dimension x (mm) | Predicted of dimension y (mm) | Predicted of dimension z (mm) |
|--------------------------------|--------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Extruder temperature (°C)     | 220                            |                               |                               |                               |
| Platform temperature (°C)     | 41.73                          | 78.99                         | 72.80                         | 11.72                         |
| Printing speed (mm/s)         | 40                             |                               |                               |                               |
| Infill percentage, (%)        | 95.84                          |                               |                               |                               |

5. Conclusion
This study is definitely helpful in improving the quality of 3D printed part where the objective to optimise shrinkage 3D printed bottom housing part have been achieved. Based on the results, the 3D printer optimised setting has been obtained by using Full Factorial Design (FFD) multi-objective optimisation approach where the dimensions in x, y and z directions were close with the dimension that is needed by the manufacturer (x: 78.99/78.99, y: 72.88/72.90, z: 11.70/11.72).

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References
[1] H Blum. 2015. The Future of 3D Printing. http://www.smitherspira.com/news/2015/june/3d-print-market-expected-to-reach-$49b-by-2025 (accessed September 4, 2016)
[2] N A Sukindar, M K A M Ariffin, B T H . Baharudin, C N A Jaafar and M I S Ismail, 2017. Optimization of the parameters for surface quality of the open-source 3D printing, J. Mech. Eng.
[3] J Wu, 2018. Study on optimization of 3D printing parameters Study on optimization of 3D printing parameters, IOP Conf. Series: Materials Science and Engineering 392.
[4] M A Nazan, F R Ramli and M N Sudin, 2017. Process parameter optimization of 3D printer using Response Surface Method. ARPN Journal of Engineering and Applied Sciences, 12(27), 2291-2295.
[5] Montgomery D, 2005. Design and Analysis of Experiments (6th Edition), John Wiley and Sons’ (New York, NY).
[6] Öktem H, Erzurumlu T, and Kurtaran H.2005. Application of response surface methodology in the optimization of cutting conditions for surface roughness, Journal of Materials Processing Technology. 170(1) 11-16.
[7] Ozcelik B, and Erzurumlu T, 2005. Determination of effecting dimensional parameters on warpage of thin shell plastic parts using integrated response surface method and genetic algorithm, International Communications in Heat and Mass Transfer. 32(8) 1085-1094.