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Application of Response Surface Method (RSM) to Optimize 3D Printer Process Parameter by using Polylactic Acid (PLA) Material

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Abstract

In this modern era, the process of Fused Deposition Modelling (FDM) developed well in the manufacturing industry. However, there were still some different types of defects found in the 3D printing process. This study performed the optimization of 3D printer process parameters by using the optimization method, Response Surface Method and the Design of Experiment (DoE) was Central Composite Design (CCD). The material used in this study is polylactic acid (PLA). The aim of the study was to decrease the defects in the 3D printed products and obtain the optimal process parameter. The 3D printer used in this study was Anycubic Chiron and the filament applied was PolyLiteTM PLA. The model applied in this study was an All in One 3D Printer Test specimen which obtained from Thingiverse. The inputs included were printing temperature, printing speed, first layer height, and the ability of retraction. 16 sets of data had been prepared to find the most optimal process parameter set. Based on the result from Response Surface Method (RSM), the optimal process parameters are 40mm/s (printing speed), 190°C (printing temperature), 0.3mm (first layer height), and disable the retraction function. The experiment is assumed conducted successfully since the defects had been reduced from the optimized model.

1. Introduction

In this modern century, technology has been developed to more advanced and effective. One of the advanced technology is the invention in additive manufacturing, 3D printing. Additive manufacturing (AM) or layer manufacturing (LM) technology or rapid prototyping (RP), also known as 3D printing, has progressed rapidly with a wide range of materials and forms that can be used to construct a 3D object. [1] Additive manufacturing has a number of advantages, including unambiguous data management and limitation, the ability to create complex shapes and interlocking plans, the elimination of contraption/work piece garbage, the elimination of moulds, the elimination of establishments and models, and mass customization. [2] In general, the technology used in the most of 3D printer is Fused Deposition Modelling (FDM) since this technique is low cost compared to the other techniques. Another name of FDM is Fused Filament

Fabrication (FFF). The method uses a plastic filament which is pushed the material through a heated extrusion nozzle melting. The approach starts with software that reads an STL or CAD (computer-aided design) file and mathematically slices and orients the model for fabrication. [3] Many studies have been dedicated to enhancing the performance of the FDM process by determining the ideal combination of process parameters since the FDM process may be utilized for a number of applications, including the creation of biomedical, aeronautical, and mechanical models. [4]

Lots of materials able to be utilized as the printing material for the 3D printing process. Thermoplastic polymers are still the most well-known type of additive manufacturing material. In various applications, polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polycarbonate (PC) each offer clear advantages. Polyvinyl alcohol (PVA), a water-soluble resin, is commonly utilized to create temporary support structures. Many metals and their compounds, as well as valuable metals including silver, gold, treated steel, and titanium, are used in additive manufacturing. In addition to zirconia, alumina, and tricalcium phosphate, a variety of ceramic materials have been used in additive manufacturing. [2] The material chosen for printing process in this study is PLA filament. Due to its mechanical property profile, thermoplastic process ability, and biological features such as biocompatibility and biodegradability, PLA is one of the most promising biodegradable polymers. [5]

Optimization method is a tool to minimize or maximize the parameter of the study that been applied in many field. For example, a company want to maximize the profit of the business, then they will apply a most suitable optimization method to find the best solution to achieve the objective. Response Surface Method (RSM) is applied in this study as optimization method of the process parameter of 3D printer. It is a method which under the Design of Experiment (DoE). Because of RSM capacity to deal with larger degrees of fitting models and multi-objectivity, thus this approach can provide a better solution for 3D printer optimization that has more than one response. [6]

From the past research, it was recorded the FDM technology bring defects on the 3D printed products. One of the disadvantages of open source FDM 3D printers is that the plastic filament that comes out of the nozzle shrinks, warps, and peels away from the bed platform. [7] Because FDM has a low surface quality, it cannot ensure the good quality of the printed part's surface finish and the function of rapid prototyping parts will be harmed by the poor surface finish. [8] To produce a good quality of product, the process parameter is a main characteristic to achieve this goal. In order to achieve the greatest quality of printed part, accurate input process parameter selection is critical. [6]

In this study, optimization method, Response Surface Method (RSM) was applied to find the optimal process parameter. The four process parameters utilized were printing speed (40-60mm/s), printing temperature (190-230℃), first layer height (0.1-0.3mm), and retraction (disable/enable). The Design of Experiment (DoE) selected was Central Composite Design (CCD) and two-level full factorial design was applied. Minitab was used to analyse the data.

2. Materials and Methods

In this chapter, it described the experiment process of optimization the process parameters of 3D printers by using Response Surface Method (RSM). This chapter is vital to give the overview of the approach applied in this experiment.

2.1 Flow Chart

The flow chart of this study was to optimize the process parameters of 3D printing process by using the Polylactic Acid (PLA) filament material. It started with the problem identification and ended with the validation of results. Before preparing the equipment and materials, it was required to determine the fixed and controlled variables of the experiment. Next, the identification of Design of Experiment (DoE) by determine the proper design used, levels, and the number of factors applied. The printing process of various sets of data was then conducted and the data was collected by observing the outlook of the printed specimens. Optimization process was done by using RSM and the optimal process parameters were obtained. Validation was then conducted to compare the difference of outlook of printed specimens before and after optimization process. Figure 1 showed the flow chart of the experiment.

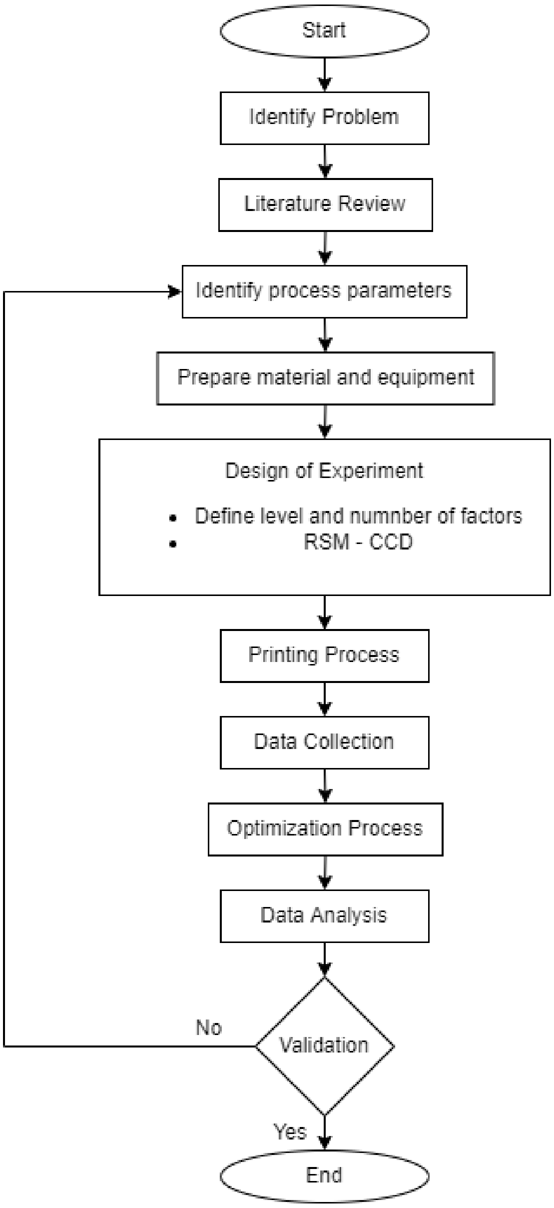


Figure 1 Experiment process flow chart.

2.2 Equipment and Materials

A Fused Deposition Modelling, FDM-based model, Anycubic Chiron 3D printer was used in this experiment. It was a 3D printer which manufactured by Shenzhen Anycubic Technology Co., Ltd. This model had a huge build volume which is 400mm x 400mm x 450mm and it consisted of a double Z limit switch that provides a more stable print bed levelling. The material of filament applied in this experiment was PolyLiteTM PLA which manufactured by Polymaker which located at Shanghai, China. This material was named as PolyPlusTM PLA formerly. The diameter of this filament was 1.75mm. A standard specimen, All in One 3D Printer Test was model that selected as printing specimen in this experiment. It was a model that downloaded from website, Thingiverse. The tests included in this specimen are overhanging test, stringing test, support test, hole test, diameter test, scale test, and bridging test. Figure 2 showed the specimen All in One 3D Printer Test.

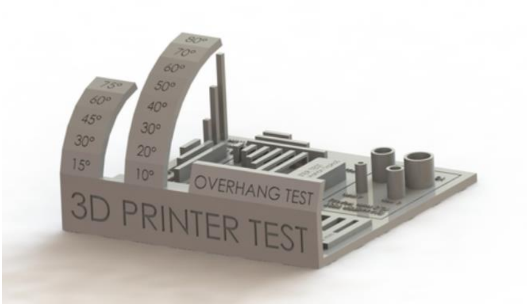


Figure 2 All in One 3D Printer Test model.

2.3 Design of Experiment (DoE)

The design of an experiment was a tool and systematic methodology that allowed researchers to identify how inputs affect outputs as well as collect data to fully comprehend the nature and state of a process. A 2k full factorial design of experiment was applied in this experiment. The purpose of this design was to screen the factors by using only 2 levels with k number of variable. There were total four process parameters been applied in this experiment, thus 16 sets of data will be run in printing process. Table 1 showed the fixed and controlled variables that applied in the experiment.

Table 1 Fixed and controlled variables.

Fixed Factor		**Controlled Factor**			
Factors	**Value**	**Factors**	**Symbol**	**Level**	
				-1	**+1**
Infill density	100%	Printing speed	A	40mm/s	60mm/s
Layer height	0.25mm	Printing temperature	B	190°C	230°C
Bed temperature	60°C	First layer height	C	0.1mm	0.3mm
Nozzle size	0.4mm	Retraction	D	Disable	Enable

After the screening process by DoE done, there were total of 16 sets of data needed to apply in this study. Table 2 showed the 16 sets of data arrangement.

Table 2 16 sets of data screening by full factorial design 2^4.

Run	**Treatment**	**Factors**			
		A (mm/s)	**B (°C)**	**C (mm)**	**D**
1	I	40	190	0.1	Enable
2	a	60	190	0.1	Enable
3	b	40	230	0.1	Enable
4	ab	60	230	0.1	Enable
5	c	40	190	0.3	Enable
6	ac	60	190	0.3	Enable
7	bc	40	230	0.3	Enable
8	abc	60	230	0.3	Enable
9	d	40	190	0.1	Disable
10	ad	60	190	0.1	Disable
11	bd	40	230	0.1	Disable
12	abd	60	230	0.1	Disable
13	cd	40	190	0.3	Disable
14	acd	60	190	0.3	Disable
15	bcd	40	230	0.3	Disable
16	abcd	60	230	0.3	Disable

2.4 Data Collection

After done printing 16 models of specimen, there were 4 sets of data will be collected which were the angle X and Y (overhanging test), number of string (stringing test), depth of hole (hole test), and length of bridge (bridging test). For the overhanging test, the result was the summation of angle X and angle Y. Table 3 showed the data collection sheet that used after printing out the specimens.

Table 3 Data collection sheet.

Run	Angle X (°)	Angle Y (°)	Number of String	Diameter of Hole (mm)	Length of Bridge(mm)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					

A grading system was established and applied to the observed data, including angles X and Y, the diameter of the hole, and the length of the bridge, to reduce the complexity of the next analysis section. The bigger the angle value, the higher the rating value for angles X and Y. For the hole test, the smaller the hole's diameter, the higher the rating score. The bridging test determined the length of the bridge that can be produced. The larger the value of the bridge's length, the higher the rating value. Table 4, 5 and 6 illustrated the rating system of overhang angles, hole diameter, and bridge length respectively.

Table 4 Rating for the angles X and Y.

Angle X (°)	Rating	Angle Y (°)	Rating
15	1	10	0.625
30	2	20	1.25
45	3	30	1.875
60	4	40	2.5
75	5	50	3.125
		60	3.75
		70	4.375
		80	5

Table 5 Rating for the hole diameter.

Diameter of Hole (mm)	Rating
4	5
6	3.333
8	1.667

Table 6 Rating for bridge length.

Length of Bridge(mm)	Rating

2	0.833
5	1.667
10	2.5
15	3.333
20	4.167
25	5

2.5 Response Surface Method (RSM)

The optimization process will be conducted through Response Surface Method (RSM). This method was a collection of mathematical strategies for innovation optimization between numerous explanatory factors in statistics science. RSM was generally utilized coupled with a factorial design to lower the cost of experimenting. This method had a lengthy history and was now utilized in a variety of industrial and manufacturing applications; it is most commonly employed in conjunction with finite element models. RSM was found to be a good solution in the case of manufacturing and modelling uncertainty in general. [9]

Step 1: Using design of experiments (DoE), created a model for the response in terms of factors at the current operating range.

Because the higher-order effects are usually insignificant, response surfaces were frequently approximated by a second-order regression model. The equation of second-order regression model with k number of factors was shown in Equation (2.1). In this section, to fit the quadratic model of the RSM, the full factorial design was enhanced to a central composite design (CCD) with alpha for rotatability, α set to 2 since there were four independent variables. By using the CCD, the second order of regression consisted of 16 factorial points. Table 3.9 showed the process parameter setting of RSM. A statistical software, Minitab was used to establish the experimental plan for RSM. The curvature test and lack-of-fit test were important to analyze the results.

$$y = \beta_0 + \beta_1 x_1 + \cdots \beta_k x_k + \cdots + {\beta_{11}}^2 {x_1}^2 + \cdots {\beta_{kk}}^2 {x_k}^2 + \beta_{12} x_1 x_2 + \cdots \beta_{k-1,k} x_{k-1} x_k + e \quad \text{Eq. 1}$$

Where, β = regression constant, e = error of the model, x = independent variable, y = dependent variable.

Step 2: Experiments in the path of steepest ascent or descent can be used to move closer to the optimum from the existing operating range.

After the optimization process by RSM was done, optimum parameter was then selected. Then, ANOVA test was conducted to the optimum parameter. Analysis of variance (ANOVA) analysis was a statistical analysis tool that is used to compare the means of two or more groups and to study the relationship between the independent and dependent variables. ANOVA analysis was one of the first strategies used in this experiment to determine the components that influence the angles, depth of hole, number of string, and length of bridge. To accurately interpret the results, the P value, along with the F statistic and F test, must be used to determine the significance of the process parameters, and the value of P must be less than the value of alpha (α = 0.05). With F = 0.05, the value of F may be calculated using the number of degrees of freedom and the total number of degrees of freedom of the components. The ANOVA test was done by using Minitab software. This procedure was vital to determine the how significance of every parameters to every responses.

Step 3: Conducted further experiments in the vicinity of the optimum to develop a comprehensive polynomial model for response.

The optimum process parameter was applied in the new printing and the results were recorded according to the angles, depth of hole, number of string, and length of bridge.

Step 4: Optimization of the response and validation of the results.

The regression equation for the responses were then been calculated based on the results from the optimal parameters printing. Comparing the prediction and validation results and determining was that has any improvement on the quality of specimen.

3. Results and Discussion

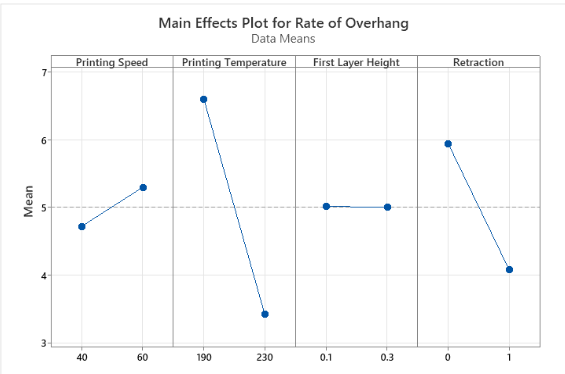
Using the Anycubic Chiron 3D printer, all 16 runs of models were successfully printed. The models were printed in a smaller ratio, which did not affect the results because they were all the same size. The output data was also unaffected by colour differences since using different colours of filament.

3.1 Results

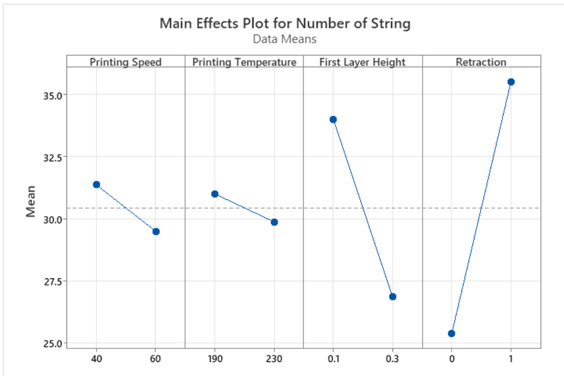
The combination of data collection for all the four responses which were number of strings, rate of overhang angle, rate of hole diameter and rate of bridge length was shown in Table 7 below. By using the Minitab, the main effects plots were plotted to analyze the effect of the process parameters. The main effects plots that presented the relationship between the process parameters to the four responses were shown respectively in Figure 3.

Table 7 Overall result of 16 runs.

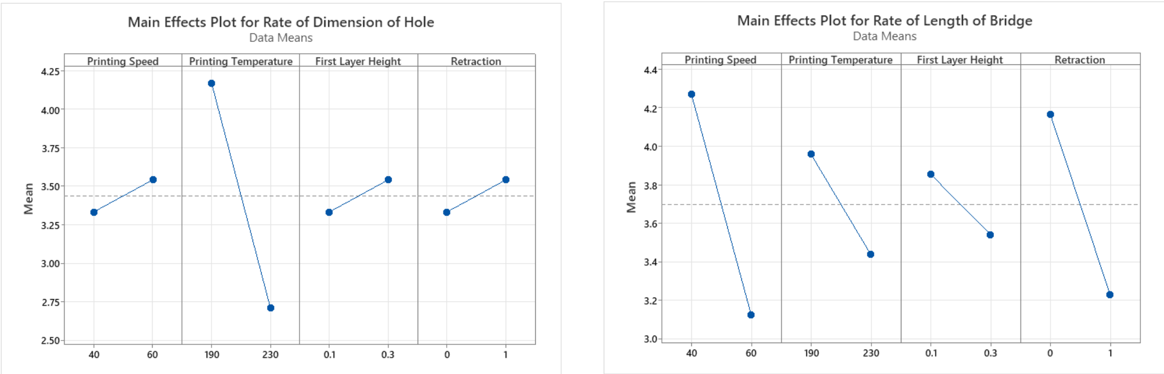
Run	Number of Strings	Rate of Overhang Angle	Rate of Hole Diameter	Rate of Bridge Length
1	45	4.875	3.333	4.167
2	27	7.5	3.333	4.167
3	40	2.625	3.333	2.5
4	42	2.625	3.333	1.667
5	34	6.5	3.333	4.167
6	33	5.25	5	3.333
7	28	1.625	3.333	4.167
8	35	1.625	3.333	1.667
9	41	7.5	5	5
10	24	7.5	3.333	3.333
11	26	2.625	1.667	5
12	27	4.875	3.333	5
13	19	6.5	5	5
14	25	7.125	5	2.5
15	18	5.5	1.667	4.167
16	23	5.875	1.667	3.333



(a)



(b)



(c) (d)

Figure 3 Main effects plots for the (a) rate of overhang, (b) number of strings, (c) rate of hole diameter, and (d) rate of bridge length.

3.2 Discussions

Based on the Figure 3(a), the slightly horizontal line in the first layer height represented there were no effects of this factor on the response rate of overhang. For the printing temperature aspect, it showed that 190°C had a higher rate of overhang effect than 230°C. The amplitude of the main effect increases with the slope of the line. Overall, printing temperature had the highest main effect on the rate of overhang, followed by the retraction, printing speed, and the first layer height did not affect the rate of overhang. The lower the value of printing temperature and disable the retraction, the higher the rate of overhang angle.

For the number of strings, the slightly inclining line in Figure 3 (b) indicates that there were no influence of either of these factors on the number of strings printed. It was evident that 0.1mm had a greater number of strings effect than 0.3mm for the initial layer height. More than the disable setting on the amount of strings, the enable setting in retraction had an impact. With the line's slope, the major effect's amplitude grows. Overall, the first layer height and retraction had the greatest main effects on the number of strings, while the printing temperature and speed had less of an impact. The lower the values of first layer height, printing speed, printing temperature, and enable the retraction, the lesser the number of strings.

Next, the slightly slanted lines in this Figure 3 (c)'s printing speed, first layer height, and retraction show that these independent factors had no influence on the response's rate of hole diameter increase. According to the data on printing temperature, 190°C had a larger rate of the diameter of hole effect than 230°C. With the line's slope, the major effect's amplitude grows. Overall, the rate of hole diameter was most significantly influenced by printing temperature, whereas printing speed, first layer height, and retraction had no serious influence. Low printing temperature, enable the retraction, and high values in printing speed and first layer height, the chance to obtain high rating of hole dimension increased.

According to Figure 3 (d), the slightly slanted lines on the initial layer height and printing temperature demonstrated that these two independent variables had no impact on the rate at which the response's bridge length increased. The bridge length effect occurred more frequently at 40mm/s than at 60mm/s, based on the printing speed data. While the average impact of the disable setting is greater than the enable setting on the rate of bridge length for retraction. The amplitude of the principal effect increases with the slope of the line. Overall, printing temperature and initial layer height had little to no significant impact on the rating of bridge length, which was most strongly influenced by printing speed and retraction. The lower the values of printing speed, printing temperature, first layer height, and disable the retraction, the higher the rate of bridge length.

3.3 Optimal Process Parameter

In this section, the optimal process parameter set was be found by using Minitab to fix the setting. This result was obtained by using the Response Surface Method (RSM). Figure 4 showed the result from response optimizer.

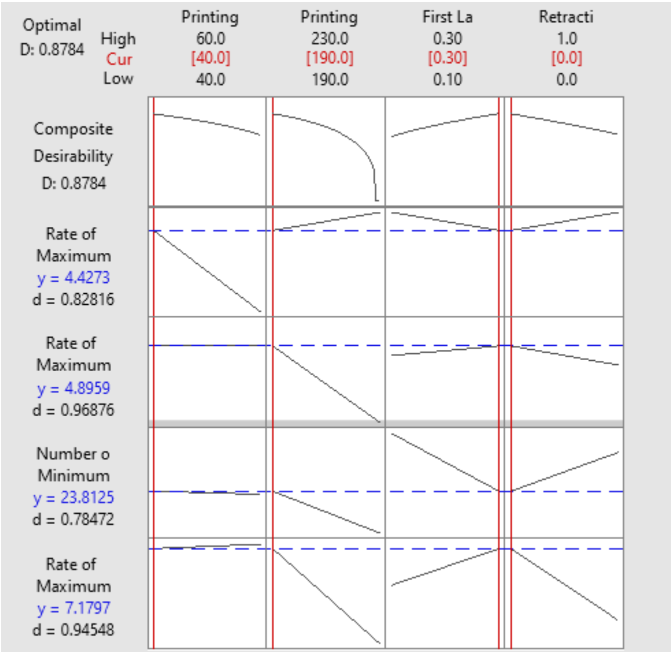


Figure 4 Result from response optimizer.

From the Figure 4, it showed that he optimal process parameter obtained were 40mm/s (printing speed), 190°C (printing temperature), 0.3mm (first layer height), and disable retraction. Besides that, Figure 3.2 predicted that this process parameter will obtain the rate of overhang angle is 7.1797 out of 10; number of strings is 23.8125; rate of hole diameter hole is 4.8959 out of 5; rate of bridge length is 4.4273 out of 5. By using the optimal process parameter given, a validation model was printed out and Figure 6 illustrated the top view and side view of the validation model. Table 8 showed the data collection from the validation model.

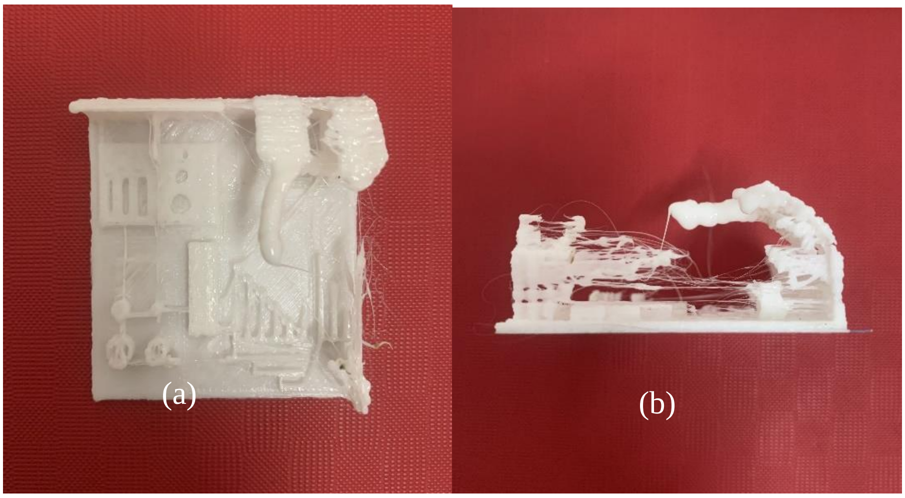


Figure 6 (a) Top view and (b) side view of validation model.

Table 8 Data collection from validation model.

Response	Value	Rating

Angle X	60°	6.5
Angle Y	40°	
Number of Strings	20	-
Diameter of Hole	4mm	5
Length of Bridge	25mm	5

The comparison between the predicted and experimental results was done. The calculation of percentage error from both of the results to simplify the analysis. Table 9 showed the comparison between the predicted and the experimental results in percentage error.

Table 9 Comparison between predicted and experimental results.

Response	**Predicted**	**Experimental**	**Error (%)**
Rate of Overhang	7.1797	4.875	32.10
Number of Strings	23	20	13.04
Rate of Hole Diameter	4.8959	5	2.13
Rate of Bridge Length	4.4273	4.167	5.88

The error was large on the results of rate of bridge length and number of strings. This indicated that this validation model not so approach to the predicted result. For the response of the hole diameter test and the overhang test, the error still acceptable since it was quite low. However, in overall, this validation was good since there were two tests which were hole test and bridge test obtained the highest rank of 5. To test that is this process parameter set was suitable for other model, a simple model named 'XYZ 20mm Calibration Cube' was printed with the same 3D printer. This model was also obtained from website Thingiverse. This was a cube with equivalent length of 20mm each. Figure 7 showed that the XYZ 20mm Calibration Cube model and the printed model was shown in Figure 8.

Figure 7 Example of XYZ 20mm Calibration Cube model.

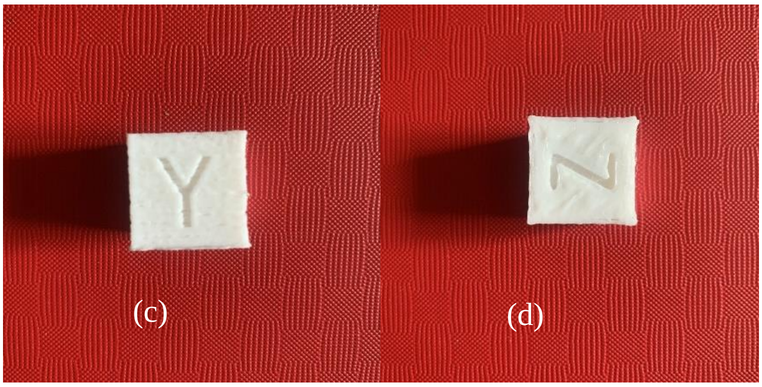


Figure 8 XYZ 20mm Calibration Cube model printed based on optimal process parameter set in (a) isometric view, (b) side view, (c) front view, and (d) top view.

Based on the printed result, it showed that this process parameter set was suitable to print this simple model. There were three dimensions had been measured by using digital Vernier caliper. The dimensions were measured in three axes which were x-, y-, and z-axis and all of the dimensions were measured accurately at 20mm. Besides that, there were no strings appeared on this printed model. In short, the optimum process parameter was good and still acceptable in validation result. The imperfect result on the All in One 3D Printer Test model may because of there was a total of four responses needed to apply in this study. The other reason may cause by the unsuitable of the range of process parameter utilised in this study since this process parameter set was suitable to be applied for XYC 20mm Calibration Cube model.

4. Conclusion

In conclusion, the objectives of the study had been achieved since the optimal process parameter was obtained successfully through Response Surface Method (RSM). Based on the optimum printed model, the defects on the model had been minimized but still not the best model that have no any defects on it. In the other say, the quality of polylactic acid (PLA) 3D printing had been optimized by applying the optimization method, Response Surface Method. There were many limitations confronted in this study. Following were the recommendations suggested for the future study. It is better to use the precise measuring equipment to measure all the dimensions such as Vernier caliper or measuring microscope, not only applying the observation method. Decrease the printing speed in printing the small size of model, this may enhance the quality of the model. In addition, try more experimental runs to obtain more outputs. This can increase the accuracy of the final result. Avoid the modification of the printer and the change of filament materials from the start to the end of the study. Increase the number of independent variables and focus on one to two responses. This enable the researcher to reduce the percentage error. Last but not least, review more and more journals from other researcher to obtain the appropriate and suitable range of process parameter.

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