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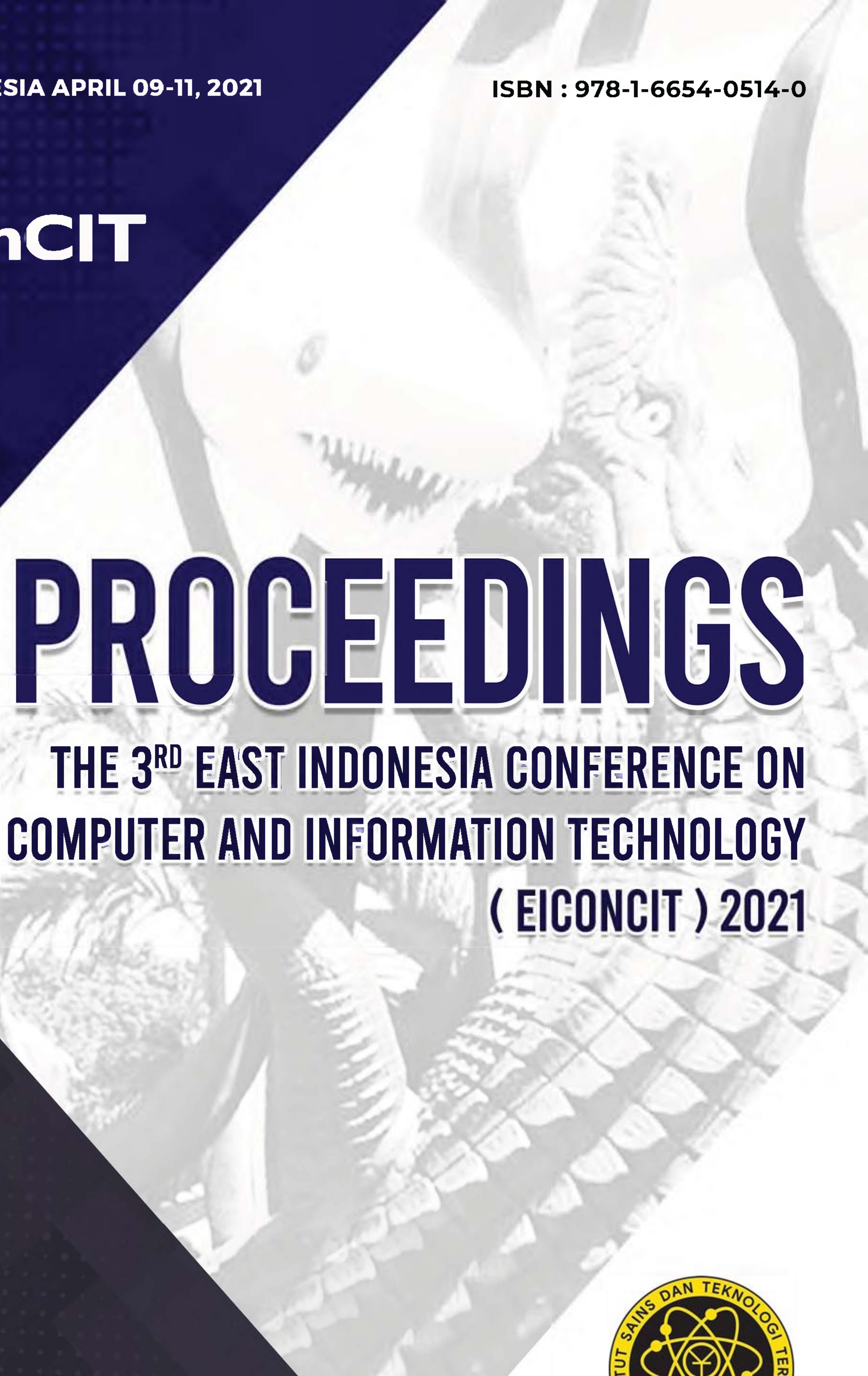

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Table of Content

2021 3rd East Indonesia Conference on Computer and Information Technology (EIConCIT)
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3D Printer Operational Robustness on Polylactic Acid based Product Printing

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***Abstract*—Obtaining consistent printing output quality using a Fused Deposition Modelling (FDM) technology-based 3D printer is not easy. Many operational parameters should be set, including layer, wall thickness, base thickness, infill, printing temperature, bed temperature, cooling fan speed, printing speed. Taguchi method is used to solve these parametrical problems. Two levels of parametrical values are assigned to each parameter to acquire the optimal combination when printing Polylactic Acid (PLA)-based 3D models. Three types of commercial PLA materials are used as the main uncontrollable factor in this experimental study. Cylindrical 3D objects with 35mm (diameter) and 20mm (height) are designed with Computer Aided Design as nominal targets. This research produces three combinations of reliable 3D printer parameter values for three types of quality targets.**

Keywords—3D Printers, FDM, PLA, Robust Design.

I. Introduction

3D printers are the output of Industry 4.0 [1]. It is widely used in product prototyping, 3D modelling, and production. 3D printers are proven to be effective at reducing production errors and optimizing product development time [2], [3]. 3D Printing or additive manufacturing creates physical objects from a geometrical representation by successive addition of material (ISO/PRF 17296-1, 2015) [1], [3], [4]. In general, 3D printer output quality may vary in different geometries [1], [5]–[8]. This is due to the limitations of the 3D printer's intelligence in translating a Numerical Control (NC) program, in which there are various combinations of coordinate positions, geometric movements (X,Y, and Z directions), and 3D printer pre-processing parameters that are set manually [9]. In practice, these parameters have to be set repeatedly so that the quality of the output is as expected [6], [7], [9], [10]. This setup is very time consuming and costly.

There are also significant differences between the various 3D printing technologies and processes in terms of suitable materials [1], [2], [5], [7], [9], [11]. Fused Deposition Modelling (FDM) technology is one of the most popular 3D printing technologies [2], [6], [7], [11]. FDM is a material extrusion-based printing system [4], [11]. However, FDM technology has a weakness because it uses a building process based on the outer surface layer to produce a striped texture [2]. The smoothness of the line/ layer boundaries is influenced by various factors, both controllable and uncontrollable [2], [7], [12]. Some practical problems of FDM technology based-3D printing using PLA (Polylactic Acid) material is hardly to be avoided. The dimensional precision is more out of control, and even warping can occur [8], [11], [13].

Experimental studies were conducted to obtain a reliable combination of 3D printer operational parameters when printing 3D models made from PLA filaments. A cylindrical object is designated as a model for the printout test. A commercial Computer Aided Design (CAD) software is used to generate these models in STL format, converted into G-code by certain translator program so that they can be read by 3D printers [2], [3], [7].

Two operational values are assigned to each parameter which can be controlled by the 3D printer operator. These parameters are layer [8], [12], wall thickness, base thickness, infill, printing temperature [9], [11], bed temperature, cooling fan speed, printing speed [7], [11]. The parameter values are set according to the 3D printer manufacturer's practical/ technical instructions. The variation in the characteristics of commercial PLA [9], [14] causes the material to be an uncontrollable factor (noise) in this study. According to the commercial label, the three PLA materials used have different ranges of physical and thermal characteristics from one another [9], [12], [14].

The value combination of each parameter is arranged into an orthogonal array selected according to the Taguchi method [6][15]–[17]. The 3D printer is operated based on these value combinations [10], [17]. Several dimensions of the printed cylinder on all parameter combinations were measured with a digital vernier calliper.

II. Product Quality And Robust Design

A. Product Quality

In general, product quality is the product's ability to perform its function or fulfill the needs of its users. If described, the definition of a product's quality can be related to its functional suitability, appearance, ease of use, functional performance, functional reliability, operational life, and so on [15], [17]. To maintain product quality, it is necessary to control and supervise the production process on an ongoing basis. In practice, a stable production process is not synonymous with operating a work tool at a uniform operating rhythm and parameters. Several uncontrollable factors –it can come from outside of the production system- make the rhythm and operational parameters have to be changed to obtain a stable product quality [15]–[17].

Quality control is a technical and management activity to measure the characteristics of the output quality, compare it with the output specifications set by the customer, and make appropriate corrections if differences are found between actual and standard performance. Statistical quality control is a problem-solving technique for monitoring, controlling, analyzing, managing, and improving products and production processes using statistical methods [16], [17]. Quality performance can be determined and measured based on quality characteristics which consist of several characteristics or product dimensions [10].

B. *Robust Design*

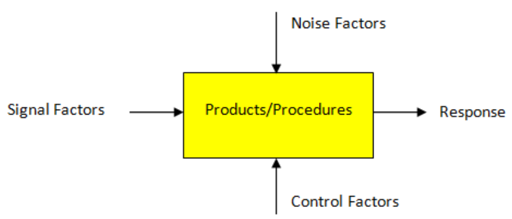
Robust Design, introduced by Genichi Taguchi, is an engineering method to optimize the performance of a process to produce high-quality products quickly/ minimum variations in finished product [9]. Robust Design is very effective at reducing the number of trials required to obtain the optimal combination of operational parameters. Thus, the robust design will save direct and indirect product design and development costs, production facility setup costs, and product quality costs (prevention costs). Robust Design is based on the Taguchi method. Taguchi used Quality Lost Function to evaluate quality loss on a product concerning its optimal quality level [15]–[17].

The matrix which is the main element of the robust design method is called as orthogonal array (OA). This matrix accommodates the value of each factor (controllable / uncontrollable or noise) in certain rules to facilitate the process of implementing, observing, and analyzing experimental results. The type of orthogonal array used depends on the number of factors, and the diversity of values for each factor, and the degree of freedom. All factors and values are considered equally. Signal to Noise Ratio/ SNR (Fig. 1) is used to identify the factors that influence the variation of response [15]. Product design or operation processes consistent with a large SNR value always produce production with optimum quality and minimum variants. According to Taguchi, there are three types of SNR characteristics, namely nominal is the best, smaller-the better, and larger-the better [6], [10], [17].

III. 3D Printer Spesification And Raw Material

A. *3D Printer Specification*

3D Printer (Fig. 2) that tested in this research is JG aurora (Fig 2) -an FDM technology based-3D printer [2]- with the specification presented in Table I.



Objective	S/N ratio
Nominal-the-best	$S/N = -10 \log \bar{y}_i^2/s^2$
Smaller-the-better	$S/N = -10 \log(\frac{1}{n}\sum_{i=1}^{n} y_i^2)$
Larger-the-better	$S/N = -10 \log(\frac{1}{n}\sum_{i=1}^{n} 1/y_i^2)$

Fig. 1. Signal/ Noise Relation

Fig. 2. 3D printer

TABLE I. SPECIFICATION 3D PRINTER

Specifi-cation	Layer thickness	0.1-0.3mm
	Filament Diameter	1.75mm
	Build Size	305*305*320mm
	Printing Accuracy	0.2mm
	Printing Speed	10-150mm/s(Suggest 80mm/s)
	Nozzle Diameter	0.4mm
	Nozzle Temp.	180~240℃
	Hot bed Temp.	Room Temp.~100℃
	Machine Size	536 (length) *480 (width) *543 (Height)
	Machine Weight	13.8kg
	Packing Size	635*590*235mm
	Packing weight	17kg
	Power	300w
Function	Leveling	Manual
	Control Panel	2.8 HD Touch LCD Display
	Display Language	English/Chinese
	Compatible Filament	PLA/ABS/Wood/ ect
	Supported File	STL、OBJ、G-Code
	Hot Bed	Black Diamond Glass Heated platform
	Pause Printing	Support
	Power faukur protection	Support
	Filament Shortage Detection	Support
	U Stick Connection	Support
	Slice Software	Cura/Simplify3D/Slic3r/Jgcreat

B. *Raw Material*

This research uses PLA filament. PLA is known as a bioplastic and derived from biomass, renewable, and environmentally friendly resources, such as corn starch or sugar cane. PLA is biodegradable with characteristics similar to polypropylene (PP) or polyethylene (PE) [2], [11], [12], [14]. PLA is a material most extensively applied in FDM technology for its low melting point, non-poison, non-irritation, and sound biocompatibility. The characteristics of PLA in 3D printing are similar to those of metal in the casting process; begins with melting, distributing materials with different solidification effects towards X, Y (parallel), and Z [4], [13]. PLAs functions as a noise factor in this study.

IV. Measurement

A. *Control Factors, Levelling, and Model*

According to Robust Design procedure, the important step in this research is to select operational factors (parameters) and their values [7]–[9], [11], [15]–[17] that can be controlled by the 3D printer operator. These parameter values are the most frequently used, according to the operational specifications of the 3D printer, and for normal jobs [6], [7],

[9]. Below is a list of factors that are controllable and their two operational values. Cylindrical shape is categorized as complex geometry because it can generate linear motion and curvature on the 3D printer nozzle [11]. Cylindrical shape can represent quality problem on 3D printing [6], [7], [11] in this study. The cylinder design dimensions are 35mm (diameter) and 20mm (height). These two numbers are the nominal targets for the main dimensions of the 3D printer output in this study, printing time is used as the third quality target can be seen in Table II [4], [5].

B. Height Measurement

The height of the object becomes an important indicator of the operational quality of the 3D Printer when printing in the Z- direction [6]. After selecting the orthogonal array (OA) and placing the factors (Table III) into the array, the next step is to conduct an experiment based on predetermined noise [15], [17]. Height measurements are carried out 3 times by taking different angles with a digital vernier calliper with an accuracy level of 0.01 mm. The results of 3 measurements are averaged to produce a high value cylinder design. Here are the results for the first material (PLA1).

C. Diameter Measurement

The length, width, or diameter of the object is an indicator of the operational quality of the 3D Printer when printing in the X or Y direction [6]. Diameter measurements were also carried out 3 times, at the bottom side, middle, and top side of the cylinder. The diameters at the Table IV are the averaged of three positional measurement. Following are the results of measuring the diameter of the first material (PLA1). The diameter of the 3D printed results on the Table IV is generally very interesting, mostly less than 35mm. There is not even a single measurement combination in which Diameter 1, Diameter 2 and Diameter 3 reach a minimum of 35mm. The ability of 3D printers technology to produce accurate nominal dimensions an all directions still needs to be addressed [1], [7], [11].

TABLE II. CONTROL FACTORS

No.	Control factors	Level 1	Level 2
A	Layer	0,1	0,3
B	Wall thickness	1,2	2,2
C	Top/bottom thickness	1,2	2,2
D	Infill	20	60
E	Printing temperature	195	210
F	Bad temperature	50	70
G	Print speed	30	70
H	Fan	125	255

TABLE III. HEIGHT MEASUREMENT (MM)*

PLA1				
No.	***Height 1***	***Height 2***	***Height 3***	∑
1.	20,06	20,09	19,58	19,91
2.	20,04	20,04	20,09	20,05
3.	20,04	19,83	19,93	19,93
4.	19,97	19,98	19,95	19,96
5.	19,95	19,92	19,90	19,92
6.	19,81	19,86	19,87	19,84
7.	20,05	19,96	19,87	19,96
8.	20,15	20,10	20,16	20,13
9.	20,07	20,04	20,06	20,05
10.	20,07	20,07	20,04	20,06
11.	20,14	20,09	20,07	20,1
12.	20,16	20,18	20,14	20,16

D. Printing Time Measurement

The printing time is calculated automatically by 3D printer start from set up to 100% finished as Table V. As an example, the results of fourth experiment on PLA1 is 19.96cm (height), 34.73cm (diameter), and 3 hours 37 minutes 34 seconds on printing time (Fig. 3). And the result of fourth experiment on PLA2 is 19.50cm (height), 34.37cm (diameter) and 3 hours 34 minutes 58 seconds on printing time (Fig. 4)

TABLE IV. DIAMETER MEASUREMENT (MM)*

PLA1				
No.	**Diameter 1**	**Diameter 2**	**Diameter 3**	∑
1.	34,58	34,57	34,45	34,53
2.	34,87	34,83	34,78	34,82
3.	34,78	34,77	34,90	34,81
4.	34,83	34,71	34,67	34,73
5.	34,78	34,81	34,67	34,75
6.	34,80	34,46	34,78	34,68
7.	34,90	34,90	34,92	34,90
8.	34,86	34,86	34,77	34,83
9.	35,04	35,00	34,99	35,01
10.	34,83	34,79	34,80	34,80
11.	34,43	34,70	34,86	34,66
12.	34,84	34,86	35,01	34,90

TABLE V. PRINTING TIME MEASUREMENT

Printing Time (HH:MM: SS)			
No.	***PLA1***	***PLA2***	***PLA3***
1.	02:00:15	02:00:08	02:00:30
2.	02:02:51	01:58:45	01:59:30
3.	03:35:47	03:37:01	03:38:37
4.	03:37:34	03:34:58	03:35:47
5.	02:38:45	02:38:59	02:39:54
6.	03:44:38	03:43:24	03:49:43
7.	00:47:24	01:13:54	01:15:48
8.	00:50:40	00:47:53	00:54:12
9.	01:13:10	01:15:54	01:14:02
10.	00:58:48	01:00:25	00:57:09
11.	00:44:29	01:18:59	01:19:16
12.	00:48:23	00:47:50	00:47:47

Fig. 3. PLA1

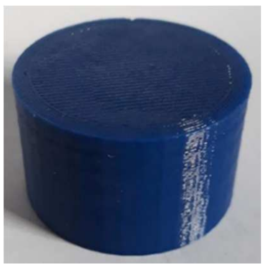


Fig. 4. PLA2

V. Discussion

A. SNR for Height Accuracy

The data obtained will be confirmed in the form of the S/N ratio to find the factors that most influential to the variety of general quality characteristics. S/N quality characteristics that are used in this study is "nominal is the best', refer to the nominal value of cylinder height. The cylinder height is declared good if the cylinder height is close to the target [6], [7], [10], [13]. The calculation is shown as Table VI. The SNR response calculation shows the order of the effect of the parameters starting from the largest, that is layer height, followed by wall thickness, bed temperature, up/down thickness, fan, printing temperature, filling, printing speed. So that the optimal parameter combination for the operation of the 3D printer is; layer height 0.1mm, wall thickness: 1.2mm, top / bottom thickness: 1.2mm, infill: 20, print temperature: 210oC, bed temperature: 50oC, print speed: 70mm s, fan speed: 125. The calculation is shown as Table VII.

B. SNR for Diameter Accuracy

The characteristic that becomes the reference for the second response is the cylinder diameter. The cylinder diameter is declared good if the cylinder diameter is close to the target, The calculation is shown as Table VIII [6], [7], [10], [11]. Recommended parameters combination are layer height 0,1mm, wall thickness: 2,2 mm, top/bottom thickness: 2,2 mm, infill: 60, print temperature:195oC, bed temperature: 70 oC, print speed: 30mm/s, fan speed: 255. The calculation is shown as Table IX. The SNR calculation results related to the accuracy of the Z (height) and X/Y (length / width / diameter) dimensions confirm previous studies that distinguished the quality of 3D printer prints in the Z direction and the XY plane [6].

TABLE VI. RESPONSE FOR HEIGHT ACCURACY

Run.	Factor								Noise			Mean
	Ly	*Wt*	*TBt*	*In*	*Pt*	*Bt*	*Ps*	*Fn*	*1*	*2*	*3*	
1	0,1	1,2	1,2	20	195	50	30	125	19,91	19,99	20,19	20,03
2	0,1	1,2	1,2	20	195	70	70	255	20,05	19,96	19,74	19,92
3	0,1	1,2	2,2	60	210	50	30	125	19,93	19,84	20,06	19,94
4	0,1	2,2	1,2	60	210	50	70	255	19,96	19,5	19,73	19,73
5	0,1	2,2	2,2	20	210	70	30	255	19,92	19,27	20,02	19,74
6	0,1	2,2	2,2	60	195	70	70	125	19,84	19,21	20,11	19,72
7	0,3	1,2	2,2	60	195	50	70	255	19,96	19,35	19,65	19,65
8	0,3	1,2	2,2	20	210	70	70	125	20,13	19,34	19,97	19,81
9	0,3	1,2	1,2	60	210	70	30	255	20,05	19,26	19,93	19,75
10	0,3	2,2	2,2	20	195	50	30	255	20,06	19,16	20,02	19,75
11	0,3	2,2	1,2	60	195	70	30	125	20,1	19,17	19,01	19,43
12	0,3	2,2	1,2	20	210	50	70	125	20,16	20,14	19,71	20,00

Where:
Ly = Layer Height
Wt = Wall Thickness
TBt = Top/Bottom Thickness
In = Infill
Pt = Print temperature
Bt = Bed temperature
Ps = Print speed
Fn = Fan speed

TABLE VII. SNR RESPONSE HEIGHT ACCURACY

Level	Ly	Wt	TBt	In	Pt	Bt	Ps	Fn
1	39,15	38,82	37,51	36,95	35,96	38,75	36,19	37,07
2	33,85	34,18	35,49	36,05	37,04	34,24	36,80	35,93
Delta	5,30	4,65	2,02	0,91	1,09	4,51	0,61	1,13
Rank	1	2	4	7	6	3	8	5

TABLE VIII. RESPONSE FOR DIAMETER ACCURACY

Run.	Factor								Noise			Mean
	Ly	*Wt*	*TBt*	*In*	*Pt*	*Bt*	*Ps*	*Fn*	*1*	*2*	*3*	
1	0,1	1,2	1,2	20	195	50	30	125	34,53	35,16	34,12	34,60
2	0,1	1,2	1,2	20	195	70	70	255	34,82	34,97	34,85	34,88
3	0,1	1,2	2,2	60	210	50	30	125	34,81	34,86	34,76	34,81
4	0,1	2,2	1,2	60	210	50	70	255	34,73	34,37	34,68	34,59
5	0,1	2,2	2,2	20	210	70	30	255	34,75	34,75	34,59	34,70
6	0,1	2,2	2,2	60	195	70	70	125	34,68	34,66	34,60	34,65
7	0,3	1,2	2,2	60	195	50	70	255	34,90	34,9	34,52	34,77
8	0,3	1,2	2,2	20	210	70	70	125	34,83	35	34,37	34,73
9	0,3	1,2	1,2	60	210	70	30	255	35,01	34,74	34,50	34,75
10	0,3	2,2	2,2	20	195	50	30	255	34,80	34,79	34,66	34,75
11	0,3	2,2	1,2	60	195	70	30	125	34,66	34,79	34,85	34,77
12	0,3	2,2	1,2	20	210	50	70	125	34,90	34,43	34,76	34,70

TABLE IX. SNR RESPON DIAMETER ACCURACY

Level	Ly	Wt	TBt	In	Pt	Bt	Ps	Fn
1	50,16	45,56	45,19	46,24	49,28	46,39	48,58	47,74
2	45,74	50,35	50,71	49,67	46,62	49,51	47,32	48,16
Delta	4,43	4,79	5,52	3,43	2,66	3,12	1,25	0,42
Rank	3	2	1	4	6	5	7	8

C. SNR for Printing Time

The characteristic that becomes the reference for the third response is printing time [9]. The quality characteristic is smaller- the better. The faster it takes, the better [6], [7]. The calculation is shown as Table X. The recommended combination for faster printing time are layer height 0,3mm, wall thickness: 1,2mm, top/bottom thickness: 1,2mm, infill: 20, print temperature:195o C, bed temperature: 70o C, print speed: 70mm/s, fan speed: 125. The calculation is shown as Table XI.

TABLE X. RESPONSE FOR PRINTING TIME

Run.	Factor								Noise			Mean
	Ly	*Wt*	*TBt*	*In*	*Pt*	*Bt*	*Ps*	*Fn*	*1*	*2*	*3*	
1	0,1	1,2	1,2	20	195	50	30	125	7215	7208	7230	7217,67
2	0,1	1,2	1,2	20	195	70	70	255	7371	7125	7170	7222,00
3	0,1	1,2	2,2	60	210	50	30	125	12947	13021	13117	13028,33
4	0,1	2,2	1,2	60	210	50	70	255	13054	12898	12947	12966,33
5	0,1	2,2	2,2	20	210	70	30	255	9525	9539	9594	9552,67
6	0,1	2,2	2,2	60	195	70	70	125	13478	13404	13783	13555,00
7	0,3	1,2	2,2	60	195	50	70	255	2844	4434	4548	3942,00
8	0,3	1,2	2,2	20	210	70	70	125	3040	2873	3252	3055,00
9	0,3	1,2	1,2	60	210	70	30	255	4390	4554	4442	4462,00
10	0,3	2,2	2,2	20	195	50	30	255	3528	3625	3429	3527,33
11	0,3	2,2	1,2	60	195	70	30	125	2669	4739	4756	4054,67
12	0,3	2,2	1,2	20	210	50	70	125	2903	2870	2867	2880,00

TABLE XI. SNR RESPON PRINTING TIME

Level	Ly	Wt	TBt	In	Pt	Bt	Ps	Fn
1	-80,19	-75,24	-75,20	-73,97	-75,40	-75,66	-75,90	-75,57
2	-71,22	-76,17	-76,21	-77,45	-76,01	-75,75	-75,51	-75,84
Delta	8,97	0,94	1,02	3,48	0,60	0,10	0,39	0,27
Rank	1	4	3	2	5	8	6	7

CONCLUSION

The combination of operational parameter values for the best 3D printer output quality depends on the quality characteristics required. This can be based on dimensional accuracy (height / Z direction) or diameter dimension / (X-Y dimension), or printing time. For Z-axis dimensional accuration, the recommended parameters combination is; Layer height 0,1mm, Wall thickness: 1,2mm, Top/bottom thickness: 1.2mm, Infill 20, Print temperature: 210, Bad temperature 50, Print speed 70mm/s, Fan speed: 125. For accuration of X/Y-axis dimensional accuration, the recommended parameter combination is; Layer height 0,1, Wall thickness: 2,2, Top/ bottom thickness 2,2, Infill 60, Print temperature: 195oC, Bed temperature: 70oC, Print speed 30mm/s, Fan speed: 255. If X/Y and Z dimensional accuracy is considered simultaneously, recommended parameters for X/Y dimensional accuracy should be prioritized for PLA based product. For faster process, the recommended parameters combination is; Layer height: 0.3mm, Wall thickness: 1.2mm, Top/ bottom thickness: 1,2mm, Infill 20, Print temperature 195oC, Bed temperature: 70oC, Print speed: 70mm/s, Fan speed: 125.

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