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OPTIMIZATION OF PROCESS PARAMETERS IN 3D PRINTING FDM BY USING THE TAGUCHI AND GREY RELATIONAL ANALYSIS METHODS

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ABSTRACT

The 3D printing technology is one of the technologies that is developing currently. This machine can make products easily, quickly, and precisely. 3D printing is used to print models, prototypes/modeling, teaching aids for education, health support devices, product design, and many more in 3D shapes. Fused Deposition Modeling (FDM) is the most popular among others 3D printing techniques. In simple concept, it does not need maintenance regarding solvents or glue. The spare parts can be found easily and cheaply. In this research, we create objects by using Autodesk inventor that is called human denture. Then, it converted to G-Code using Simplyfy3D software version 4.1.2. The G-Code data is used in the 3D printer for making the product. We select parameters to print the product. In this study, we find the optimal parameters of the effect of shrinkage and hardness of the product. The 3 parameters are in this study namely; layer height, print speed, temperature print. The material of human denture is filament PLA +. The Taguchi method and Grey analysis are used to analyze the data result. The results of the analysis for optimal parameters are at Layer Height 0.15 mm, Print Speed 25 mm/s, and Print Temperature 210^{0}C.

Keywords: Layer Height; Print Speed; Print Temperature; Taguchi; Grey Analysis.

1. INTRODUCTION

The presence of 3D printing technology in the world of manufacturing has brought big changes to the world. This technology, which is also known as Additive Layer Manufacturing, has been around since the 1980s. Additive Manufacturing comprises many technologies including subsets such as 3D Printing, Rapid Prototyping (RP), Direct Digital Manufacturing (DDM), Layered Manufacturing, and Additive Fabrication. The application of additive manufacturing is limitless, the initial use of additive manufacturing in the form of rapid prototyping was focused on the visualization of the preproduction model [1].

Recently the meaning of the term Additive Manufacturing has been expanded to cover a broader range of techniques such as extrusion and sintering based processes [2]. 3D Printing is a new breakthrough in the world of Additive Manufacturing technology. This innovation is very popular in all parts of the world, in particular among academia and industry. The emergence of 3D Printing technology is substantial in several industrial fields, especially from an economic perspective. Rapid

Prototyping on mechanical components with techniques and low production volumes in producing prototypes quickly [3].

3D Printing consists of several types of work systems such as Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Digital Light Processing (DLP) etc. The FDM system is an easy 3D Printing system and is widely developed at this time [4]. 3D Printing FDM is conceptually simple to use, does not endanger health related to solvents or glues and most of all printing equipment is cheap and small in size [5].

The working principle of FDM is by continuously inserting a thermoplastic filament into a small, heated chamber, then it will melt so that it develops into a very thick liquid. The melt is then extruded through the nozzle and then placed on a heated table following a pattern that has been designed by the software and will reproduce the desired object geometry, for printing in 3D Printer it can be entered as a CAD file [6].

Research related to product design and optimization of the production process is critical to be able to increase productivity and product quality. Quality is achieved through design optimization to minimize costs in obtaining and maintaining a competitive position in the world market [7]. The use of experimental design methods at these stages is crucial to improve quality by optimizing the factors that influence the overall production process [8].

The Taguchi method is a popular method used in the molding industry to obtain the best quality parts. This method only uses response tables and graphs of experimental data for analysis, and then directly finds the combination of levels that gives the optimal response [9]. The Taguchi method is employed for the optimization of one response. Optimization for more than one response will be obtained when using the Taguchi method followed by the Gray Relational Analysis (GRA) and Principal Component Analysis (PCA) methods [10].

Through GRA, the Gray Relational Grade (GRG) value will be obtained to evaluate a large number of responses. As a result, optimization of multiple responses can be converted to the optimization of a single GRG [11] and Principal Component Analysis is a multivariate statistical method that selects a small number of components to describe the variance of several original responses [12].

Based on this description, this research was conducted to figure out the optimum parameters of the product manufacturing process in 3D Printing FDM with the shrinkage and hardness response of the material using the Taguchi and Gray Relational Analysis methods to convert multiple responses into one response and weighting values using the Principal Component Analysis approach.

2. METHODS

Research on the optimization of 3D Printing Fused Deposition Modeling process parameters in product manufacturing is carried out in a sequence of steps as follows in figure 1.

2.1. Testing Materials and Schemes

The tool used in this research is a 3D printer with the Anet A8 type FDM system which uses the Fillament PLA + material, the material specifications can be seen in Table 1. This material is used in product modeling, prototyping/modeling, props for education, health support tools, product design, and various needs to print in the 3-dimensional form [13]. The product manufacturing process is conducted by combining machine parameters such as Layer Height, Print Speed, and Print Temperature with the product model made of human dentures.

Table 1. Data Sheet of PLA+ Filament

Name	**PLA+ (Polylactic Acid)**
Print Temperature	205 - 225 °C
First Layer Temperature	215 °C
Density	1.24 kg/m3
Diameter Filament	1.75 mm (Accuracy: 1.7 – 1.8 mm)
Tensile Yield Strength	65 Mpa
Flexural Strength	75 Mpa

Flexural Modulus	3642 Mpa
Impact Strength	7 kJ/m^2

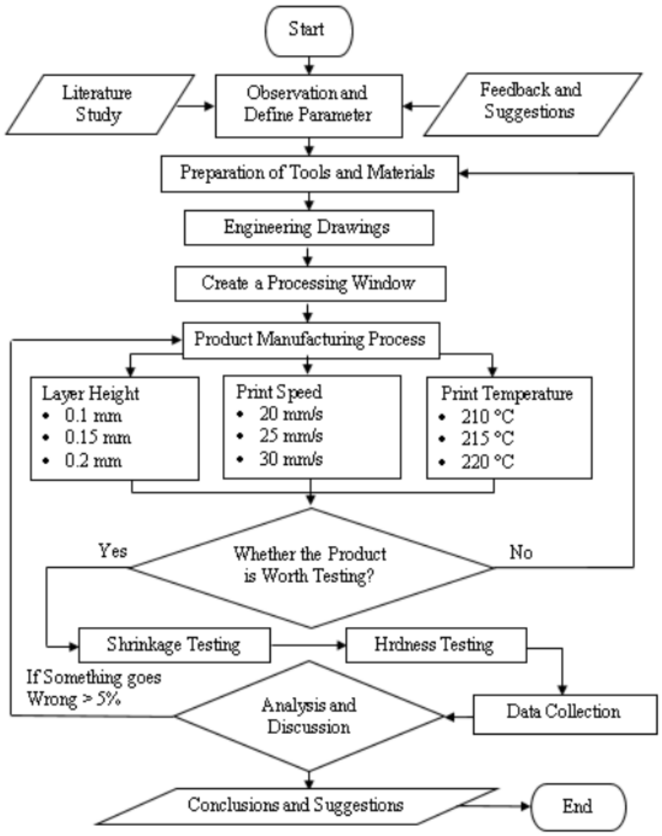


Figure 1. Research Flowchart

2.2. Research Set Up

The steps in the research set-up are presented in Figure 1. At this stage, the initial parameter determination was also determined based on literature studies and recommendations from the PLA + filament manufacturer. Making 3D objects using the Autodesk® Inventor® CAD application, the 3D image files are then saved in the STL (*.stl) format. Next is the STL file (*.stl). Processed in the slicing software (Simplify 3D), at this stage, the 3D object will be created layer by layer with variations of Layer height, Print Speed, and Print Temperature which will be set in the Simplyfy 3D slicer software version 4.1.2.

At the setup stage, the dimensions and 3D shape of the printed object will also be determined. The dimensions of the printed objects for this study are products in the form of human dentures with the dimensions shown in Figure 2.

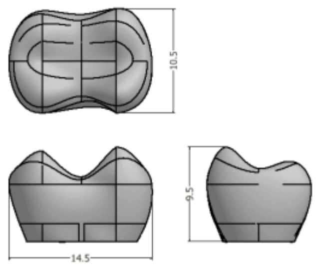


Figure 2. Test Specimen Dimensions and Shapes

2.3. Experimental Design

There are three process parameters used in this study. The selected process parameters are Layer Height (mm), Print Speed (mm / s), and Print Temperature (^{0} C). In the experimental design, each process parameter has three levels. Such a design can also be called an Orthogonal Array L_9 (3) 4 design, the number of factor combinations is nine. The Taguchi method is one of the effective ways to find improved processing parameters experimentally. Before the Taguchi experiment, the level of control factor to be selected had to be decided in advance through the Processing Window [14]. The experimental results from the Processing Window can be seen in Figure 3.

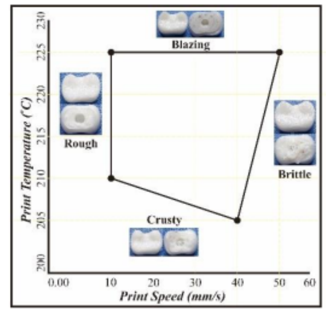


Figure 3. Processing Window

Layer Height will be clogged if it is lower than 0.10 mm and unable to print if it is more than 0.30 mm, so the Layer Height value range is set 0.10-0.30 mm. For Print Speed, the result will be rough when the speed is below 10 mm / s and it will be brittle when the speed is above 50 mm / s, so the Print Speed value range is set to 10-50 mm / s and for Print Temperature if it is lower than 205 ^{0} C, it will get crusty and if it is higher than 225 ^{0} C it will burn, so the Print Temperature range is set to 205-225 ^{0} C. The process parameters and each level used in this study are shown in Table 2.

Table 2. Process Parameters and Each Level

Process Parameter	Unit	Level 1	Level 2	Level 3
Layer Height	mm	0.1	0.15	0.2
Print Speed	mm/s	20	25	30
Print Temperature	^{0} C	210	215	220

The responses observed in this study were shrinkage and hardness of the material. The use of Gray Relational Analysis combined with the Taguchi Method to optimize the result parameters proves that this methodology is efficient for solving multi-response decision-making problems [15].

3. RESULTS AND DISCUSSION

3.1. Product Print Process

a. Designing a product using Autodesk® Inventor® Professional 2017 Software and changing the file format to .STL, the product design is shown in Figure 2.

b. Open the Simplyfy 3D Software, then select the "Import" menu to enter the .STL file that will be printed into the Simplyfy3D Software then save the .gcode from the Simplyfy3D Software onto the SD Card

c. Turn on the 3D Printer until the Display looks like Figure 4.

Figure 4. Main display of the 3D Printer

d. Press the menu button and then on the Display that appears select the menu "Init. SD card".

e. Then Select Menu "Print from SD" as shown in Figure 5.

Figure 5. *Print from SD*

f. Then select the .gcode file that will be printed, then wait for the Nozzle and Bed temperature to match the .gcode settings then after that the 3D Printer starts working.

g. After the product printing process is complete, then the testing process is continued. The print results of the finished product are shown in Figure 6 below.

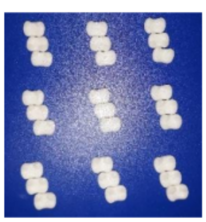


Figure 6. Print Results of Human Dentures

3.2. Test result

The results of the shrinkage and hardness test of the product material are shown in Table 3. Data processing for the hardness test uses the Brinell method and data processing for the shrinkage test uses equation (1).

$$L_S = \frac{Design\ Part - Actual\ Part}{Actual\ Part} \times 100\ (\%) \quad (1)$$

Table 3. Test Result

No. Eks.	LH (mm)	PS (mm/s)	PT (^{0} C)	Shrk. (%)	Har. (kg/mm²)
1	0.1	20	210	1.976	9.588
2	0.1	25	215	1.895	11.048
3	0.1	30	220	1.979	10.738
4	0.15	20	220	0.758	10.992
5	0.15	25	210	1.757	11.186
6	0.15	30	215	1.558	10.922
7	0.2	20	215	1.069	10.048
8	0.2	25	220	1.539	10.232
9	0.2	30	210	1.545	9.644

*) LH : *Layer Height*
PS : *Print Speed*
PT : *Print Temperature*

3.3. Taguchi Method

According to Soejanto (2009). several advantages of the Taguchi method are as follows [16]:

a. The level of efficiency of the experimental design is higher because it can conduct research that involves many factors and levels.

b. Obtain a process that produces a product that is consistent and robust against disturbances. that is uncontrollable factors.

The objective of this experiment is to obtain optimal 3D Printing process parameter settings in the product manufacturing process. where for the shrinkage response SN Ratio the "Smaller is Better" condition is used because the smaller the deviation value to the dimensions indicates the better shrinkage in the experiment. For the SN Ratio hardness is used in the condition "Larger is Better" because the greater the value of hardness. the better.

SN Ratio is a design for transforming repetitive data into a value which is a measure of the variations that arise. The SN ratio value is calculated depending on the type of quality characteristic of each response [17].

An example of calculating the shrinkage SN Ratio with the characteristics of the response quality. the smaller the better the first combination is as follows:

$$S/N = -10 \ \log \ [\textstyle\sum_{i=1}^{n} \frac{yi^2}{n}]$$

$$S/N = -10 \ \log \ [\frac{1.976^2}{1}]$$

$$S/N = -10 \log 3.905$$

$$S/N = -5.916$$

From the calculation results of each SN Ratio for each response. then the roundedness SN Ratio value is calculated through a combination of levels of each factor. from the SN Ratio roundedness value. the optimum value for the production process parameter will be obtained whose value can be seen in Table 4 below:

Table 4. SN Response to Roundness Ratio of Influence Factors

Level	Shrinkage			Hardness		
	Layer Height	***Print Speed***	***Print Temperature***	***Layer Height***	***Print Speed***	***Print Temperature***
1	-5.799	-1.363	-4.863	20.37	20.17	20.10
2	-2.113	-4.731	-3.328	20.85	20.68	20.56
3	-2.701	-4.520	-2.422	19.98	20.36	20.55
Delta	3.686	3.368	2.441	0.87	0.51	0.46
Rank	1	2	3	1	2	3

Because the shrinkage response is Smaller is Better. the smallest SN Ratio roundedness value is the optimal parameter value for the product manufacturing process. so the best combination of factors for each parameter is Layer Height Level 2 (0.15 mm). Print Speed Level 1 (20 mm) / s) and Print Temperature Level 3 (220 oC). Whereas for the hardness response is Larger is Better. the optimal parameter value for the product manufacturing process is obtained by a combination of factors such as Layer Height Level 2 (0.15 mm). Print Speed Level 2 (25 mm / s). and Print Temperature Level 2 (215 oC).

3.4. Multirespon Optimization Using Gray Relational Analysis

Calculation of S / N Ratio for Each Response

The SN Ratio value used in the Gray Relational Analysis (GRA) approach is the calculation result of the previous Taguci experiment.

Normalized S / N Ratio

Normalization is carried out to transform the value of the S / N ratio into a value ranging from zero to one. The normalization process is conducted based on the quality characteristics of the SN Ratio response. The method used for the normalization process is following the characteristics of the response variable which includes the bigger the better (Larger is Better). the smaller the better (Smaller is Better). and focused on a certain value (Nominal is Best). The equation used in the normalization process for responses with the characteristic "the bigger the better" is (2):

$$X_i(k) = \frac{x_i(k) - min x_i(k)}{max \, x_i(k) - min x_i(k)} \quad (2)$$

The normalization process for responses with the characteristic "the smaller the better" uses the following equation (3):

$$X_i(k) = \frac{max \ x_i(k) - x_i(k)}{max \, x_i(k) - min x_i(k)} \quad (3)$$

with:

max $x_i(k)$ = The greatest value of *Xi(k)*

min $x_i(k)$ = The smallest value of *Xi(k)*

An example of calculating the normalized S / N ratio for the shrinkage response in the first combination is as follows:

$$X_i(k) = \frac{max \ x_i(k) - x_i(k)}{max \ x_i(k) - min x_i(k)}$$

$$X_i(1) = \frac{2.407 - (-5.916)}{2.407 - (-5.929)}$$

$$X_i(1) = 0.998$$

Deviation Sequence Value Calculation

The value of the deviation sequence Δ0. i (k) is the absolute difference between the maximum normalized values for each response. The deviation value is then used to calculate the Gray Relational Coefficient (GRC). The deviation sequence is calculated using equation (4).

$$\Delta\, O_i\,(k) = |\, X_o^*\,(k) - X_i^*(k)\,| \qquad (4)$$

Where:

$X_o^*(k)$ = The largest normalized value of S/N

$X_i^*(k)$ = The normalized value of S / N in the i^{th} experiment

An illustration of calculating the value of Δ0. i (k) the shrinkage response in the first combination is as follows:

$$\Delta_{0.i}(k) = \left|\, X_0^*(k) - X_i^*(k) \,\right|$$
$$\Delta_{0.i}(1) = \left|\, 1 - 0.998 \,\right|$$
$$\Delta_{0.i}(1) = 0.002$$

Calculation of Gray Relational Coefficient (GRC)

GRC is the relationship between ideal conditions and the actual response conditions from the Deviation Sequence value that has been obtained [10]. The GRC value is calculated based on the value of Δ0. i (k) for each response. An example of calculating the shrinkage response GRC value in the first combination is as follows:

$$\gamma i\,(k) = \frac{\Delta min + \zeta \Delta max}{\Delta O_i(k) + \zeta \Delta max} \qquad (5)$$

$$\gamma i\,(1) = \frac{0.000 + 0.5\ x\ 1.000}{0.002 + 0.5\ x\ 1.000}$$

$$\gamma i\,(1) = 0.996$$

Where:

Δmin = The lowest value of the series of deviations

Δmax = The highest value of the series of deviations

ζ = The coefficient of difference is between 0 and 1. The Distinguishing Coefficient value used is generally 0.5

$\Delta_{0.i}(k)$ = Deviation value of experiment i^{th}

The low Gray Relational Coefficient value for Smaller the Better suggests that the experimental results have a close relationship with the best normalized value for the response. The GRC for each response is converted into one multi-response value called Gray Relational Grade (GRG) using the Principal Component Analysis (PCA) method through the help of the Minitab 19 application.

Principal Component Analysis is a multivariate statistical method that selects a small number of components to explain the variants of some of the original responses [18]. Principal Component Analysis is used to estimate the appropriate weighted value so that several relatively important characteristics can be explained accurately and objectively [19]. Calculate the Gray Relational Grade (GRG) using the following equation:

$$\Gamma(x^0.x_i) = \sum_{k=i}^{n} \beta\, j\, \gamma(x^0(k).x_i(k)) \qquad (6)$$

Bk represents the k-weight value of the response characteristic and the weight value is obtained from the squared value of the selected main component eigenvector. The PCA value chosen was PC1 because it met the requirements for selecting the main component where the eigenvalue = 2.3111> 1. the cumulative variance between 70% to 80%. which is 77%. and the angle on the Scree Plot show the largest change in eigen values for PC1. The results of the Principal Component Analysis values can be seen in Table 5 as follows.

Table 5. Principal Component Analysis Value

Response Variable	PC1	PC1 Squares
Shrinkage	0.707	0.449
Hardness (BHN)	0.707	0.449

Suppose the first observation in Table 2 with the GRC value of each response is Shrinkage of 0.996 and Hardness (BHN) of 0.333. The value of the Gray Relational Grade can be obtained by calculating the following:

$$\Gamma(x_0.x_i) = \sum_{j=i}^{n} \beta\, j\, \gamma(x^0(j).x_i(j))$$

$$\Gamma(x_0.x_i) = (0.449\ x\ 0.996) + (0.449\ x\ 0.333)$$

$$\Gamma(x_0.x_i) = 0.663$$

The results of the calculation of S / N ratio. normalization of the S / N ratio. Deviation Sequence Value. Gray Relational Coefficient (GRC) value. and Gray Relation Grade (GRG) value for each response in each combination are shown in Table 6 as follows.

Table 6. Gray Relational Analysis Calculation Value

Ex. No	S/N Ratio		S/N Normalisation		Deviation Sequence		Grey Relational Coefficient		GRG	Rank
	Shrk.	Har.	Shrk.	Har.	Shrk.	Har.	Shrk.	Har.		
1	-5.916	19.634	0.998	0	0.002	1	0.996	0.333	0.663	5
2	-5.552	20.865	0.955	0.915	0.045	0.084	0.917	0.856	0.887	2
3	-5.929	20.626	1	0.740	0	0.259	1	0.658	0.825	3
4	2.407	20.830	0	0.892	1	0.107	0.333	0.823	0.572	6
5	-4.895	20.974	0.876	1	0.124	0	0.801	1	0.899	1
6	-3.851	20.770	0.751	0.847	0.249	0.152	0.667	0.766	0.713	4
7	-0.579	20.045	0.358	0.307	0.642	0.692	0.438	0.419	0.427	9
8	-3.745	20.199	0.738	0.421	0.262	0.578	0.656	0.463	0.558	7
9	-3.778	19.681	0.742	0.035	0.258	0.964	0.659	0.341	0.499	8

*) Shrk. : Shrinkage
Har. : Hardness

3.5. 3D Printing FDM Print Results

The outcomes of the dentures made by the FDM system 3D Printing can be seen in Figure 7. When viewed from the geometric shape, the dentures generated have a good shape or the same as the 3D CAD drawing made. However, these dentures have a flaw in the quality of the resulting surface. The surface quality of the dentures is less flat and jagged.

This jagged surface profile is produced by the performance of the FDM 3D Printing system. The 3D Printing FDM system uses a 1.75 mm diameter filament as the raw material. This filament is then processed into thin threads with a diameter of 0.15 mm (according to the Layer Height setting) by the Extruder. These thin threads are then arranged layer by layer until they become the desired shape. Therefore. the jagged surface of these dentures is an effect of the extrusion process of Filament 3D Printing.

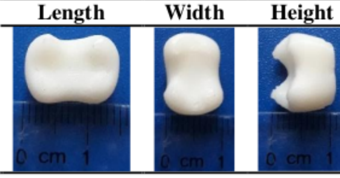
	Length	Width	Height
Finished product			

Figure 7. Results of 3D Printing of Dentures.

Best Parameter Level Setting

Confirmation experiments were carried out for establishing the recommended optimal process parameters for shrinkage and hardness values. this experiment can be seen in Table 7. The superior shrinkage and hardness values were achieved compared to the previous L9 experiment. However, the weakness of the Taguchi method can be overcome by using Gray Relational Analysis and produces a good final value of shrinkage and hardness.

Table 7. *Confirmation Experiments for the Taguchi and Gray Relational Analysis methods*

Methodology	Responses	Optimum Levels	Experiment Values	
			Penyusutan (mm)	Kekerasan (kg/mm²)
Taguchi	Shrinkage	$A_2B_1C_3$	0.758	10.992
Taguchi	Hardness	$A_2B_2C_2$	1.951	11.504

Grey Relational Analysis	Shrinkage & Hardness	$A_2B_2C_1$	1.757	11.186

4. CONCLUSION

There are always defects and it may not be flawless in the printing process. how to minimize defects and achieve the best print quality is one of the major concerns in this research. The use of the Taguchi and Gray Relational Analysis methods for the multi-response quality characteristics can optimize the printing process parameters.

The Taguchi design was used to enhance the manufacturing parameters of dentures that have superior shrinkage and hardness by performing a minimum number of trials. The orthogonal array L9 was used in experimenting. the S / N ratio term quality indicator was carried out to determine the optimal level and significant contribution of each factor to the response. the experimental optimal design value of the three parameters selected in this case is not limited to the combination of levels that have been set. The trial confirmation was carried out at the optimal level as suggested by the Taguchi method.

Gray Relational Analysis is performed to obtain a single optimal process parameter setting for both responses. Gray Relational Analysis suggests optimal process parameter settings. specifically Layer Height 0.10 mm. Print Speed 30 mm/s and Print Temperature 220 ^{0}C.

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PAGE 1

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Missing "," You may need to place a comma after this word.

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PAGE 2

Run-on This sentence may be a run-on sentence. Proofread it to see if it contains too many independent clauses or contains independent clauses that have been combined without conjunctions or punctuation. Look at the "Writer's Handbook" for advice about correcting run-on sentences.

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PAGE 3

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Sp. This word is misspelled. Use a dictionary or spellchecker when you proofread your work.

Sentence Cap. Remember to capitalize the first word of each sentence.

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PAGE 4

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