A Multi-Objective Optimization Framework for Manufacturing Defect Reduction in Material Extrusion 3D Printing

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Background

- Material extrusion 3D printing (ME3DP) is a versatile and accessible additive manufacturing technique, but it is limited by defects induced by manufacturing parameters.
- These defects, such as warping, poor layer adhesion, and dimensional inaccuracy, arise during the fabrication process.
- However, no prior study has applied the "Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA)" method to control such defects by considering temperature and key material design components used in fabrication, specifically nozzle temperature, heated bed temperature, layer thickness, and infill density.

Objectives

- To assess whether the MOORA method can identify the best alternative processing parameter sets for reducing defects in parts produced using the ME3DP technique.

Experimental Method

- The design structures (Design 1, Design 2, and Design 3) were produced using Polylactic acid (PLA) in a ME3D printer
- Multiple sets of processing parameters were used to fabricate the design structures. The minimum and maximum parameter sets were identified for making a finished part.
- The support structures were removed from the sample after fabrication and weighed using a digital measurement scale.

Theory: MOORA Method

The MOORA technique is commonly applied to optimize process parameters, select materials, and assess system performance. It integrates both desirable and undesirable criteria through a ratio-based approach, transforming a decision matrix into a ranking system derived from the sample configuration.

In short, the method simultaneously considers beneficial and non-beneficial attributes to generate a ranked list of alternatives.

Normalize Decision Matrix Equation [1]:

$$x_{ij}^{*} = x_{ij} \Big/ \left[\sum_{i=1}^{m} x_{ij}^{2}\right]^{1/2}$$

Here, $j = 1, 2, \ldots, n$

$$x = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}$$

Assessment Values Equation [1]:

$$y_i = \sum_{j=1}^{g} w_j x_{ij}^{*} - \sum_{j=g+1}^{n} w_j x_{ij}^{*}$$

Here, $j = 1, 2, \ldots, n$

The weight (w) is determined by the Shannon Entropy Weight method.

Performance Indices or Project Outcomes $(\boldsymbol{p_{ij}})$ Equation [2]:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}$$

Entropy $(\boldsymbol{E_j})$ Measurement Equation [2]:

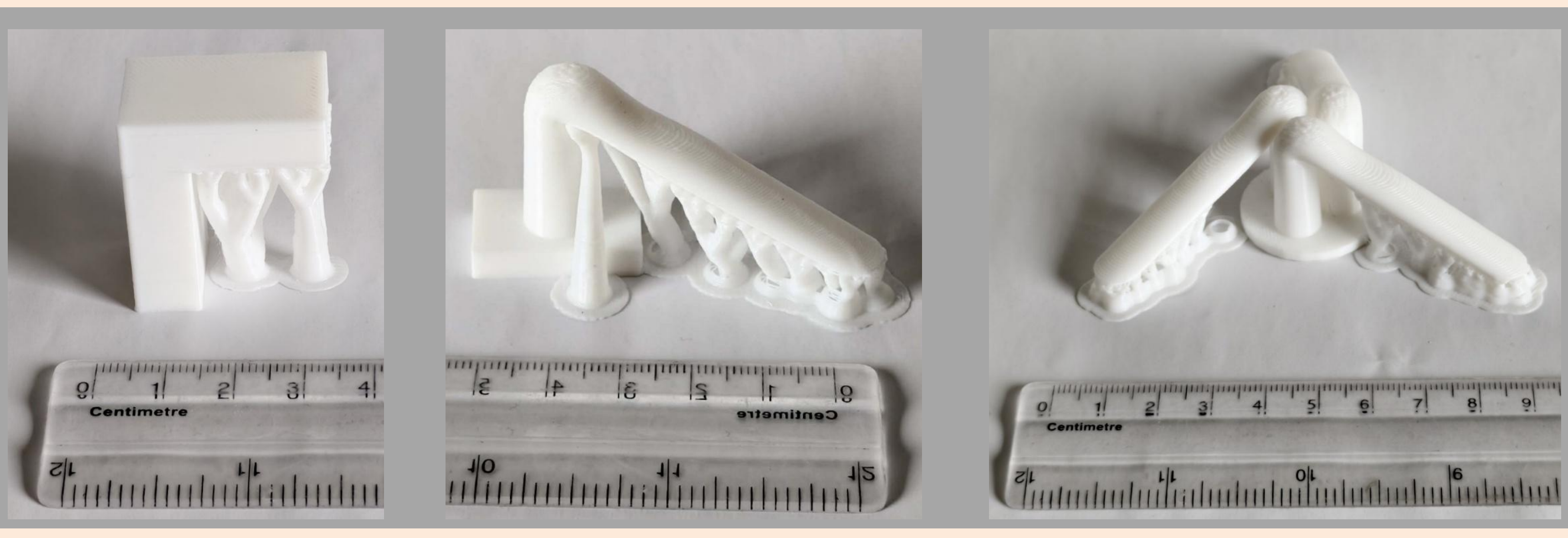
$$E_j = -k \sum_{i=1}^{m} p_{ij} \ln p_{ij}$$

Here, $k = \frac{1}{\ln(m)}$

Entropy-Based Weight Equation [2]:

$$w_j = \frac{1 - E_j}{\sum_{j=1}^{n} (1 - E_j)}$$

Sample Design



ME3DP Processed Design 1, Design 2, & Design 3 with Support

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Results

				Design 1				n = 7
Processing	Criteria/ Alternative	Beneficial	Beneficial	Beneficial	Beneficial	Beneficial	Non-beneficial	Non-beneficial
Alternatives	Parameters	Layer thickness	Nozzle Temperature	Print Speed	Printing Time	Mass	Infill density	Bed Temperature
		(mm)	(°C)	(mm/s)	(sec)	(grams)	(%)	(°C)
A1	Layer thickness	0.04	220	100	3646	4.385	15.00	55
A2	Layer thickness	0.36	220	100	858	4.585	15.00	55
A3	Nozzle Temp	0.24	180	100	1170	4.39	15.00	55
A4	Nozzle Temp	0.24	250	100	1170	4.415	15.00	55
A5	Print Speed	0.24	240	5	7223	4.39	15.00	55
A6	Print Speed	0.24	240	500	1075	4.425	15.00	55
m = 6								
Weight		0.12038	5.79E-03	0.49712	0.37657	0.00013	4.28E-16	4.28E-16

				Design 2				n = 7
Processing	Criteria/ Alternative	Beneficial	Beneficial	Beneficial	Beneficial	Beneficial	Non-beneficial	Non-beneficial
Alternatives	Parameters	Layer thickness	Nozzle Temperature	Print Speed	Printing Time	Mass	Infill density	Bed Temperature
		(mm)	(°C)	(mm/s)	(sec)	(grams)	(%)	(°C)
A1	Layer thickness	0.08	220	100	3103	3.945	15.00	55
A2	Layer thickness	0.32	220	100	1058	4.49	15.00	55
A3	Nozzle Temp	0.24	180	100	1185	2.915	15.00	55
A4	Nozzle Temp	0.24	240	100	1185	2.86	15.00	55
A5	Print Speed	0.24	240	5	3657	2.865	15.00	55
A6	Print Speed	0.24	240	500	1160	2.82	15.00	55
m = 6								
Weight		0.08710	6.88E-03	0.66765	0.21128	0.02708	5.75E-16	5.75E-16

				Design 3				n = 7
Processing	Criteria/ Alternative	Beneficial	Beneficial	Beneficial	Beneficial	Beneficial	Non-beneficial	Non-beneficial
Alternatives	Parameters	Layer thickness	Nozzle Temperature	Print Speed	Printing Time	Mass	Infill density	Bed Temperature
		(mm)	(°C)	(mm/s)	(sec)	(grams)	(%)	(°C)
A1	Layer thickness	0.1	220	100	3637	8.255	15.00	55
A2	Layer thickness	0.32	220	100	2706	10.93	15.00	55
A3	Nozzle Temp	0.24	180	100	3003	8.685	15.00	55
A4	Nozzle Temp	0.24	240	100	3003	8.75	15.00	55
A5	Print Speed	0.24	240	5	14450	8.955	15.00	55
A6	Print Speed	0.24	240	500	2945	8.955	15.00	55
m = 6								
Weight		0.05798	6.02E-03	0.58399	0.34664	0.00538	5.03E-16	5.03E-16

Parameters	**Alt.**	**MOORA**	**Rank**
Min	A1	0.26666	**3**
Max	A2	0.20533	**4**
Min	A3	0.19492	**6**
Max	A4	0.19565	**5**
Min	A5	0.38010	**2**
Max	A6	0.56051	**1**

Parameters	**Alt.**	**MOORA**	**Rank**
Min	A1	0.27489	**2**
Max	A2	0.23131	**3**
Min	A3	0.21874	**5**
Max	A4	0.21931	**4**
Min	A5	0.19977	**6**
Max	A6	0.71409	**1**

Parameters	**Alt.**	**MOORA**	**Rank**
Min	A1	0.20152	**5**
Max	A2	0.20378	**3**
Min	A3	0.20132	**6**
Max	A4	0.20199	**4**
Min	A5	0.34699	**2**
Max	A6	0.63454	**1**

Discussion

- The design influenced the rank estimation.
- The top-ranked alternative is not always the best choice, as a higher printing speed can cause internal material defects. Since data were collected only from finished parts and no microstructural analysis was performed, this information is not captured in the results.

[1] Chakraborty, S., Datta, H. N., Kalita, K., & Chakraborty, S, Opsearch, 60(4), 1844-1887 (2023).
[2] Wu, J., Sun, J., Liang, L., & Zha, Y, Expert Systems with Applications, 38(5), 5162-5165 (2011).