ORIGINAL SCIENTIFIC PAPER

COST-EFFICIENT ADDITIVE MANUFACTURING: UNRAVELING THE ECONOMIC DYNAMICS OF MATERIAL EXTRUSION (MEX) TECHNOLOGY

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ABSTRACT

Material Extrusion (MEX), a prevalent form of additive manufacturing (AM), plays a pivotal role in creating three-dimensional objects layer by layer. Investigating MEX printing parameters is crucial, impacting mechanical properties, roughness, material usage, build time, and dimensional accuracy. This study focuses on the economic dimensions of MEX, essential for widespread technology adoption. Understanding of the economic aspects of MEX is essential for maximizing the benefits of this additive manufacturing technology. It allows for the development of efficient, cost-effective, and sustainable manufacturing practices, contributing to its widespread adoption across diverse industries. Employing the Box-Behnken Design (BBD), the research systematically evaluates total costs, amalgamating material and power costs, providing nuanced insights into MEX economic dynamics. Analysis of variance (ANOVA) uncovers the significant impact of printing parameters, with build orientation emerging as pivotal. The optimization process aligns efficiency with cost-effectiveness, validated through robust regression equations. This study, directly relevant to management and business economics, positions itself at the forefront of advancing additive manufacturing, offering practical guidance for economic and operational optimization, particularly in industries adopting MEX technology.

***Keywords**: Material Extrusion (MEX), Printing Parameters, Design of Experiments (DoE), Box-Behnken Design (BBD), Cost-effectiveness, Efficiency*

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INTRODUCTION

Additive manufacturing (AM), commonly referred to as 3D printing technology, was pioneered by Charles Hull in the mid-1980s [1], [2]. Since its inception, AM has undergone rapid development and enhancement through various methods, all centered around the fundamental principle of layer-by-layer construction. Presently, this technology finds applications across diverse industrial sectors, including aerospace [3], automotive [4][5][6], medical [7][8][9], and even the food industry [10]. According to the ASTM standard, AM manufacturing processes are categorized into seven main categories, Binder Jetting (BJT), Directed Energy Deposition (DED), Material Extrusion (MEX), Material Jetting (MJT), Powder Bed Fusion (PBF), Sheet Lamination (SHL), VAT Photopolymerization (VPP) [11][12][13]. In the MEX category, Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM), has been trademarked by Stratasys since 1991 [14]. MEX stands out as a cost-effective and versatile technology, earning it significant favor among users. Polymer AM, a subset of this technology, was valued at approximately $11 billion in the market in 2020, with projections estimating a substantial growth to over $55 billion by 2030 [15], [16]. MEX technology presents numerous advantageous characteristics, including its cost-efficiency, adaptability to various materials including biodegradable polymers [17], [18], capability to fabricate structurally robust parts compatible with reinforced and composite materials, thus facilitating the development of lightweight yet durable components [19], [20] user-friendly operation, straightforward maintenance, and implementation, along with its non-hazardous nature [21], [22]. Similar to any technological system, MEX technology involves distinct printing and structural parameters that affect mechanical properties, volume, quality, printing time, and finally cost of the printed part. These parameters are illustrated in Figure 1. which showcases an Ishikawa diagram delineating MEX parameter [23]. Researchers have investigated various combinations of parameters to enhance the optimization of MEX process parameters, aiming to achieve optimal mechanical properties, cost-effectiveness, dimensions, and time efficiency. For instance, Baich et al. [24] explored different parameter combinations with a focus on achieving optimal mechanical properties, cost-effectiveness, dimensions, and time efficiency in the context of a growing number of MEX printers. The findings highlighted the decreasing trend in print cost and material cost, emphasizing the significance of print cost over material cost in influencing overall production costs, especially in entry-level printers. Brook et al. [25] conducted research on variable MEX, where they adapted an AM system with a variable-diameter nozzle for polymer deposition. This adaptation aimed to optimize build time and print resolution independently. Meanwhile, Dani et al. [26] focused on cost optimization in manufacturing a prototype connecting rod using MEX. Their study involved fabricating the model at different orientations ranging from 0° to 90°.

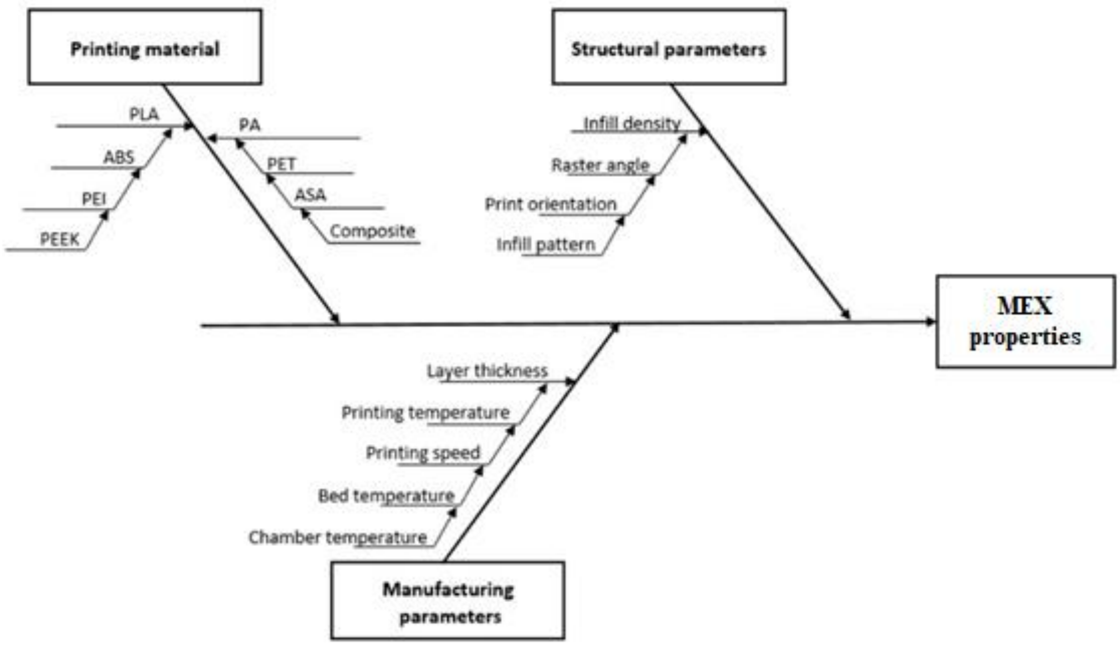

Figure 1. Ishikawa diagram of MEX parameters [23]

This varied orientation impacted parameters such as the build time, number of layers, support material, and build material, directly influencing manufacturing costs. Durgun and Ertan [27] investigated the effects of raster angle and part orientation on mechanical properties and production cost of MEX-printed parts. Their findings suggest that part orientation has a more significant influence than raster angle on the resulting mechanical properties. In the study conducted by Raut et al. [28], the influence of built-up orientation on both the mechanical properties and overall cost of MEX parts was examined. The experimental analysis revealed a substantial impact of the built orientation on the tensile, flexural characteristics, and the overall cost of the MEX parts.

Examining the influence of printing parameters on printing time, building volume, and total cost in AM carries significant economic implications, particularly in terms of resource efficiency and cost-effectiveness [29]. The optimization of printing parameters directly correlates with operational costs in MEX processes, presenting opportunities for substantial economic savings in various industries [30]. In the context of this study, our focus centers on the investigation of three critical printing parameters—layer thickness, build orientation, and printing speed—using a Box-Behnken Design (BBD). By employing statistical tools such as analysis of variance (ANOVA) and contour plots, the primary objective is to discern the noteworthy contributions of these printing parameters to the responses, namely printing time, building volume, and total cost. This meticulous exploration aims to provide valuable insights that not only enhance the economic efficiency of MEX but also contribute to the broader discourse on sustainable and cost-effective additive manufacturing practices. Additionally, a validation study was performed to confirm the obtained regression equation from the ANOVA. The study findings reveal a strong association between the anticipated and experimentally fine-tuned values. Overall, the outcomes of this investigation provide valuable insights into the influence of MEX printing parameters on the overall cost of printed parts.

EXPERIMENTAL METHODOLOGY AND OPTIMIZATION PROCESS

Black colour EcoPLA filament, a nontoxic, biodegradable 3D printing material with 1.75 mm diameter and ± 0.05 mm tolerance, was used in this study [31], [32]. A dog bone according to the American Society for Testing and Materials (ASTM) standards (D638) was used in this study.

Design of Experiments (DoE)

The Design of Experiments (DoE) stands as a methodical and statistically rigorous approach that occupies a central role in the domain of research and development. It furnishes a well-structured methodology for examining the influences of multiple variables, their interactions, and for efficiently optimizing processes. Various DoE methodologies are employed in the study of process parameters' impact in MEX, including Response Surface Methodology (RSM) [33], Box-Behnken Design (BBD), Taguchi design [34], [35], and Central Composite Design (CCD) [36]. In this investigation, we leveraged the capabilities of DoE, specifically employing the BBD, to advance our comprehension of the intricate relationships between printing parameters and material properties within the realm of MEX technology. BBD, a form of experimental design integrated into statistical analysis and modeling, constitutes a response surface methodology commonly utilized for the optimization of process parameters.

In this study, the Box-Behnken Design (BBD) utilized adheres to a three-level factorial design strategy, wherein the factors under scrutiny are systematically investigated at low, medium, and high levels. The design is meticulously structured through a series of points, establishing a three-level factorial design, which is then supplemented with additional points to formulate a central composite design. This integration of the central composite design is particularly valuable as it enables the assessment of the curvature of the response surface in the proximity of optimal factor settings. A noteworthy advantage inherent in the BBD lies in its capacity to yield meaningful outcomes with a reduced number of experimental runs compared to a full factorial design, resulting in heightened efficiency and cost-effectiveness. Additionally, the BBD offers a robust approximation of the response surface within the designated area of interest, rendering it an invaluable tool for the optimization process.

Box-Behnken Design Methodology

The L15 Box-Behnken Design (BBD) array is widely adopted for experimentation, featuring fifteen trials, including three center-point repetitions. Figure 2.provides a visual representation of the BBD combinations, depicting a cube with the center point (0,0,0), and other viable combinations denoted as points distributed across the cube facets and edges. It is crucial to emphasize that BBD exclusively considers midpoints of edges and the center point, totaling thirteen points—comprising twelve edge points and the center point, replicated thrice to yield fifteen experiments. This triplication of center points enables the assessment of pure error in the experimental process, enhancing the precision and reliability of parameter estimates. The ironing process, focusing on spacing between passes, path speed, and flow rate, constituted the three parameters under investigation, each with three levels detailed in Table. These levels were selected based on slicer software recommendations. The formulation of 15 experimental sets with diverse process parameters is detailed in Table 2, executed through statistical software MINITAB 21.

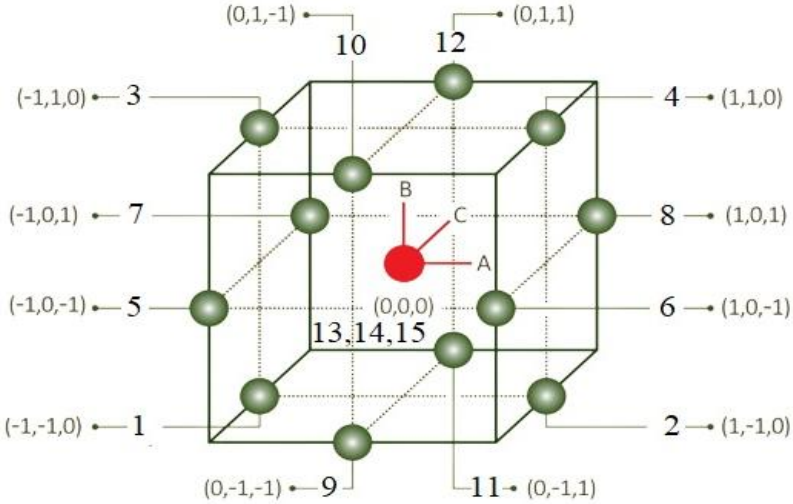

Figure 2. Box-Behnken design of design points

Table1.: BBD parameter design

Printing Parameter	Codes	levels		
		-1	0	1
Layer thickness (mm)	A	0.2	0.3	0.4
Build orientation (°)	B	0	45	90
Printing speed (mm/s)	C	30	50	70

Table 2: BBD experimental design and the output results

Run No.	A	B	C	Printing time (hour)	Building volume (cm^3)	Total cost ($)
1	0.2	0	50	0.200	0.890	0.040
2	0.4	0	50	0.133	8.414	0.047
12	0.3	90	70	0.567	19.713	0.098
13	0.3	45	50	0.617	38.946	0.170
5	0.2	45	30	1.083	40.629	0.193
4	0.4	90	50	0.433	20.675	0.091
6	0.4	45	30	0.600	41.831	0.179
14	0.3	45	50	0.617	38.946	0.170
7	0.2	45	70	0.833	40.629	0.181
3	0.2	90	50	0.533	13.944	0.076
10	0.3	90	30	0.567	19.713	0.098
9	0.3	0	30	0.233	9.135	0.051
11	0.3	0	70	0.133	9.135	0.037
15	0.3	45	50	0.617	38.946	0.170
8	0.4	45	70	0.467	41.831	0.173

RESULTS AND DISCUSSION

Table 2 presents the outcomes derived from the Box-Behnken Design (BBD) in our study. The focus of this section is on the comprehensive evaluation of the total cost associated with the MEX technology, which encompasses both material and power costs.

The total cost (Ct) is determined by the sum of the material cost (Cm) and the power cost (Cp), expressed mathematically as:

$$Ct = Cm + Cp \quad (1)$$

Where, Ct represents the total cost, Cm is the material cost, and Cp is the power cost.

For the material cost (Cm), the calculation is based on the filament price, which is set at 0.08$/m [37]. This parameter is a crucial component in understanding the overall cost dynamics, as it directly influences the economic feasibility of the printing process. The power cost (Cp) is calculated using the printing power consumption and the corresponding price. Specifically, the printing power consumption is determined to be 0.125kWh [38], and, in Hungary, the price per kilowatt-hour (kWh) is 0.393$/kWh [39]. This information is pivotal for assessing the energy-related expenses associated with the MEX technology. By considering both material and power costs, we aim to provide a comprehensive understanding of the economic implications associated with different printing parameters as investigated through the Box-Behnken Design. This cost analysis is essential for optimizing the printing process in MEX technology and making informed decisions regarding parameter adjustments for enhanced properties and cost-effectiveness.

ANOVA of The Printing Parameters for Printing Time, Building Volume, and Total Cost

In this investigation, we employed an analysis of variance (ANOVA) methodology to discern the intricate relationship between printing parameters and their respective impacts on the response variable. This method allowed us to pinpoint the most influential factors by determining the contribution percentages of each printing parameter. The ratios between the total adjusted sum of squares and the individual adjusted sum of squares were calculated for linear (A, B, and C), quadratic (AA, BB, and CC), and 2-way interaction terms (AB, AC, and BC). Here, A signifies the layer thickness (mm), B denotes build orientation (º), and C corresponds to printing speed (mm/s). The outcomes of the ANOVA analysis, detailed **Table 3**, elucidated the contribution percentages of printing time, building volume, and total cost. Notably, the Fisher value 'F' served as the criterion to identify statistically significant contributors to the response, with a threshold set at an 'F' value exceeding 4 [40].

Table 3: Comparison of ANOVA response results

Source	DF	F-value			P-value			Contribution percentage (%)		
		Printing time	Building volume	Total cost	Printing time	Building volume	Total cost	Printing time	Building volume	Total cost
Model	9	6.89	89.32	84.6	0.023	0	0			
Linear	3	9.52	25.75	23.41	0.016	0.002	0.002			
A	1	9.15	8.8	0	0.029	0.031	0.998	13.65%*	1.09%	0.00%
B	1	17.35	68.44	68.05	0.009	0	0	25.88%*	8.46%*	8.88%*
C	1	2.07	0	2.17	0.21	1	0.2	3.08%	0.00%	0.28%
Square	3	11.01	242.21	229.97	0.012	0	0	49.27%*	89.83%*	90.02%*
AA	1	0.41	0.31	0.21	0.55	0.599	0.664	1.27%	0.16%	0.61%
BB	1	28.68	702.06	667.34	0.003	0	0	44.87%*	88.72%*	88.76%*
CC	1	2.1	7.68	4.98	0.207	0.039	0.076	3.13%	0.95%	0.65%
2-Way Interaction	3	0.15	0.01	0.41	0.928	0.998	0.751	0.65%	0.00%	0.16%
AB	1	0.02	0.04	0.27	0.894	0.85	0.627	0.03%	0.00%	0.03%
AC	1	0.24	0	0.13	0.644	1	0.738	0.36%	0.00%	0.02%
BC	1	0.18	0	0.85	0.691	1	0.399	0.26%	0.00%	0.11%
Error	5							7.46%	0.62%	0.65%
Total	14									

*The substantial contribution of the ironing process parameters.

The results from the analysis of variance (ANOVA) offer a comprehensive understanding of the intricate relationship between printing parameters and their impact on the response variables—printing time, building volume, and total cost. The linear effects (A, B, C) showcase significant contributions, with build orientation ('B') emerging as a major factor influencing printing time (25.88%), building volume (8.46%), and total cost (8.88%). Additionally, layer thickness ('A') significantly impacts printing time (13.65%). The quadratic effects (AA, BB, CC) play a crucial role, collectively explaining a substantial portion of the variability in printing time (49.27%), building volume (89.83%), and total cost (90.02%). Notably, the quadratic term 'BB' (build orientation^2) stands out with the highest contribution among the quadratic effects. While the 2-way interaction effects (AB, AC, BC) contribute modestly, they add nuance to the understanding of the relationships between printing parameters. The error term reflects unexplained variability, constituting 7.46% for printing time, 0.62% for building volume, and 0.65% for total cost.

These findings collectively emphasize the significance of considering multiple printing parameters in the optimization process. The identified influential factors, specially build orientation and layer thickness, provide actionable insights for enhancing efficiency, minimizing material usage, and controlling costs in the context of our study. The comprehensive nature of this analysis positions our research at the forefront of advancing additive manufacturing practices with practical implications for industries seeking economic and operational optimization.

Mean Effect Plot (MEP) for The Total Cost

The investigation into the influence of printing parameters on the total cost in MEX technology has revealed nuanced trends that are essential for the economic optimization of the additive manufacturing process. The analysis considered three key parameters: layer thickness, build orientation, and printing speed, each contributing distinctively to the overall cost dynamics, and Fig. 2 illustrates the MEP of these parameters. Regarding layer thickness, the observed fluctuations in total cost with varying layer thickness underscore the sensitivity of the MEX process to this parameter. The substantial decrease in total cost from 0.2 mm to 0.3 mm, representing a percentage change of approximately -25.92%, is noteworthy, suggesting that thinner layers may enhance economic efficiency. However, a subsequent increase in total cost from 0.3 mm to 0.4 mm, with a percentage change of approximately 34.90%, emphasizes the need for careful consideration in selecting the optimal layer thickness for minimizing costs. Build orientation emerged as a pivotal factor, exhibiting a remarkable increase in total cost at 45 degrees, with a percentage change of approximately 311.50%, and a subsequent significant decrease at 90 degrees, with a percentage change of approximately -49.49%. This trend highlights the intricate relationship between the orientation of printed layers and the resulting economic implications. The steep increase at 45 degrees may be attributed to increased complexity or additional support requirements, while the decrease at 90 degrees suggests a potential for cost savings, possibly due to improved structural efficiency. Finally, the influence of printing speed on total cost is evident from the observed trends. A substantial decrease in total cost at 50 mm/s, representing a percentage change of approximately -35.04%, is followed by an increase at 70 mm/s, with a percentage change of approximately 43.88%. This suggests that a moderate printing speed, such as 50 mm/s, may strike a balance between efficiency and cost-effectiveness. However, an understanding of the trade-off between speed and cost is crucial, as excessive speeds might lead to increased material wastage or compromised build quality.

The findings emphasize the importance of a holistic approach to parameter selection in MEX technology. Optimal layer thickness, build orientation, and printing speed are essential considerations for achieving economic efficiency, and the observed trends with percentages provide a quantitative basis for decision-making. The detailed analysis of trends in printing parameters, including the percentage changes, contributes to the ongoing dialogue on the economic feasibility of MEX technology, guiding future research and application in the field.

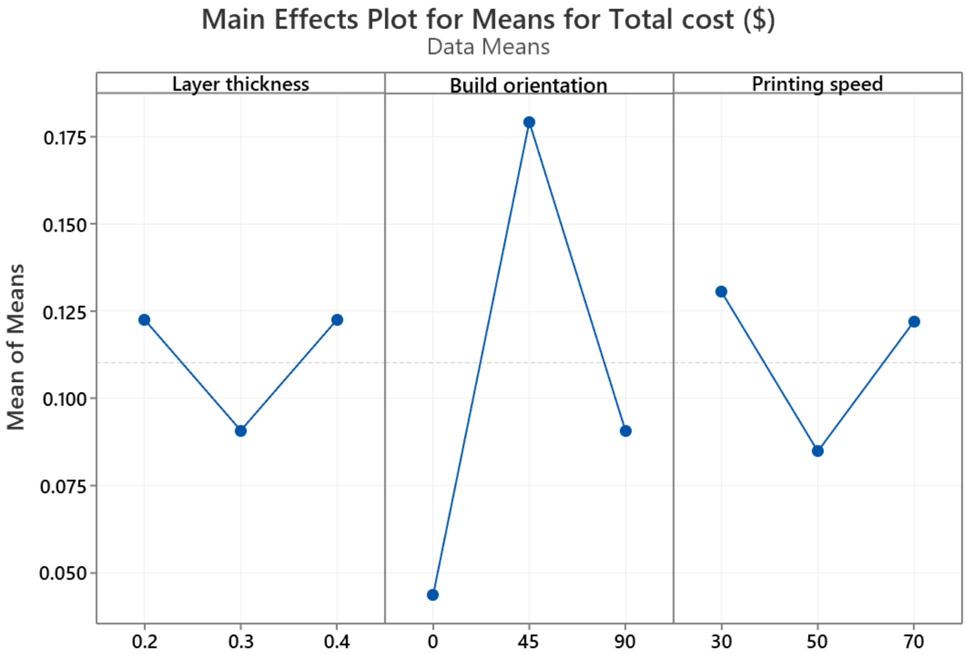

Fig. 2. Mean effect plot of the total cost

Validation Study

In this empirical inquiry, a series of regression equations has been developed to characterize and elucidate the patterns observed in crucial economic attributes. The quadratic structure of these equations is applied to forecast printing time, building volume, and total cost, denoted by **Equations (2) to (4)** respectively. These regression models are derived from empirical responses, relying on three fundamental predictor variables: layer thickness, build orientation, and printing speed.

$$\text{Printing time (hour)} = 1.815 - 4.29\,A + 0.01778\,B - 0.0310\,C + 3.96\,A*A - 0.000164\,B*B + 0.000224\,C*C - 0.0019\,A*B + 0.0146\,A*C + 0.000028\,B*C \quad (2)$$

$$\text{Building volume (cm}^3\text{)} = 11.6 + 57.6\,A + 1.3594\,B - 0.716\,C - 58\,A*A - 0.013524\,B*B + 0.00716\,C*C - 0.044\,A*B - 0.000\,A*C - 0.00000\,B*C \quad (3)$$

$$\text{Totoal cost (\$)} = 0.1510 - 0.173\,A + 0.005012\,B - 0.00296\,C + 0.194\,A*A - 0.000054\,B*B + 0.000024\,C*C + 0.000465\,A*B + 0.00072\,A*C + 0.000004\,B*C \quad (4)$$

Where A, B, and C denote layer thickness, build orientation, and printing speed, respectively.

The disparity between the predicted and experimental values was not substantially significant. Examination of Figure 4. depicting the correlation graph between predicted and experimental data for all responses, illustrates a strong correlation between the two datasets.

In summary, the experiment aimed to ascertain the most favorable printing parameters, resulting in the determination of an optimal configuration: a layer thickness of 0.266667 mm, a build orientation of 0^o, and a printing speed of 56.2626. The composite desirability, computed at 0.962340, was achieved to minimize Printing Time, Building Volume, and Total Cost. Equal weight and importance were assigned to the selection criteria for desirability. Leveraging the response optimizer feature in Minitab software, a multi-response prediction was conducted to pinpoint the optimum printing parameters. The specifics of the desirability criteria selection are detailed in Table 4.Following this, a validation analysis was undertaken to compare the optimized predicted response data with the optimized experimental response data. This analysis aimed to showcase the high level of consistency between the regression equation and the experimental data, visually represented in Figure 5-7

Table 4:: Desirability criteria for responses

Response	Goal	Lower	Target	Upper	Weight	Importance
	Minimum		0.133333	1.0833	1	1
	Minimum		0.889503	41.8307	1	1
	Minimum		0.036550	0.1932	1	1

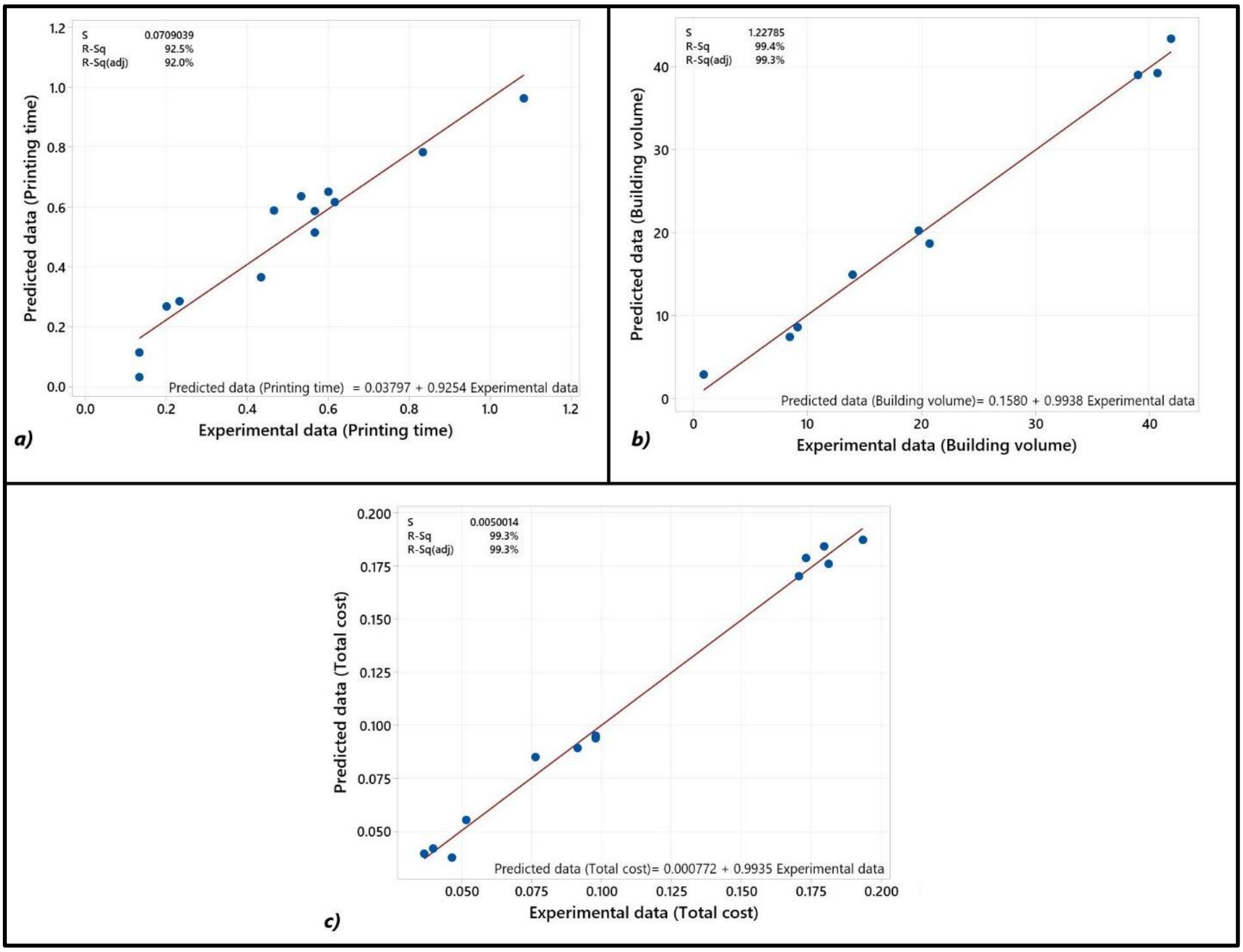

Figure 4:Correlation graph of a) printing time, b) building volume, and c) total cost

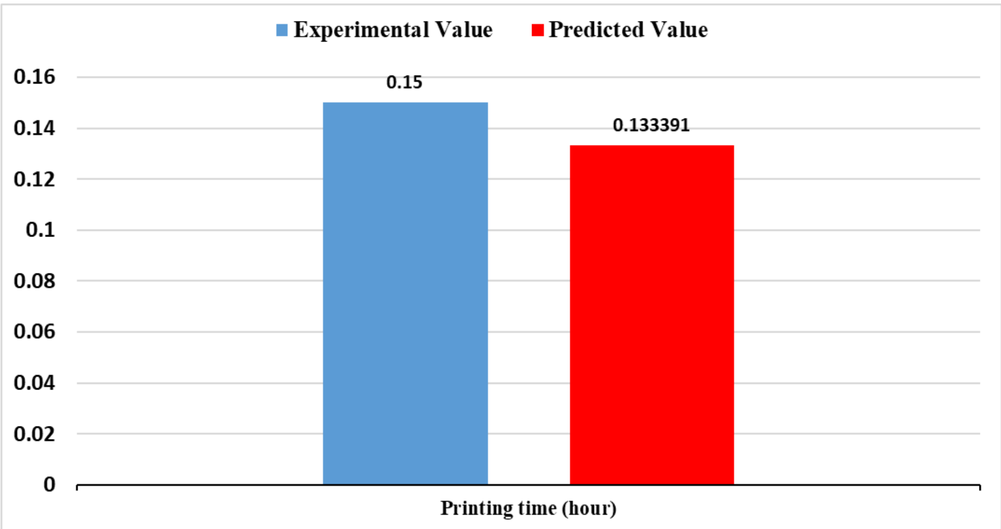

Figure 5:Validation analysis for printing time

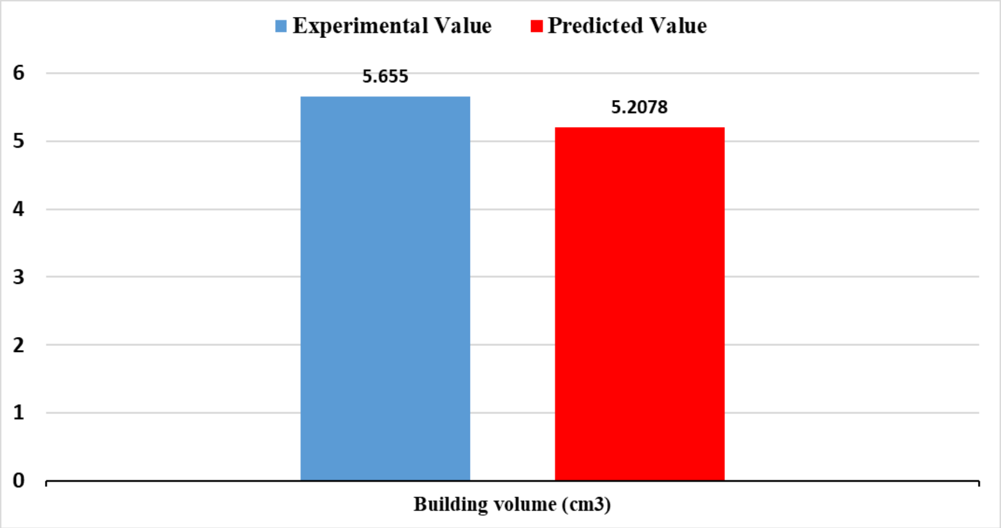

Figure 6: Validation analysis for building volume

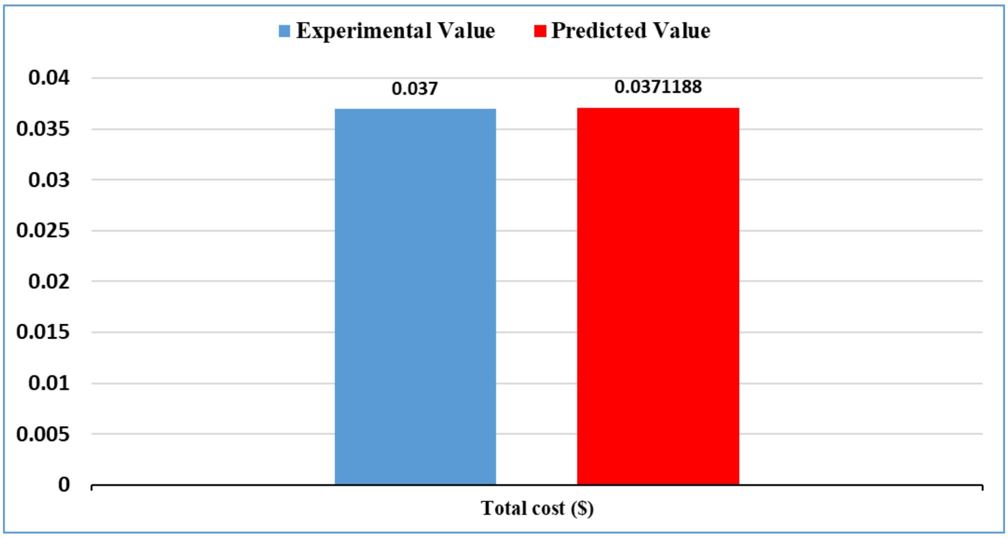

Figure 7:Validation analysis for total cost

CONCLUSION

This study systematically investigated the economic implications of various printing parameters in MEX technology using the Box-Behnken Design (BBD). The meticulous evaluation of total cost, encompassing both material and power costs, provided valuable insights into the economic feasibility of the MEX printing process.

The ANOVA analysis elucidated the intricate relationship between printing parameters and their impacts on critical response variables—printing time, building volume, and total cost. The linear and quadratic effects demonstrated significant contributions, with build orientation emerging as a major influencer across all response variables. The comprehensive ANOVA results quantified the contribution percentages of each parameter, emphasizing the nuanced dynamics of the MEX printing process. The optimization process led to the identification of optimal printing parameters, aligning with the scope of enhancing efficiency and cost-effectiveness. The validation study further affirmed the reliability of the developed regression equations, providing a robust foundation for forecasting crucial economic attributes in MEX technology.

These findings contribute directly to the overarching themes of management and business economics by offering actionable insights for industries engaged in additive manufacturing. The identified optimal parameters present a practical guide for decision-makers seeking to balance efficiency and cost considerations within the dynamic landscape of MEX technology.

In light of focus on economics, business, and management, this research serves as a valuable resource, bridging the gap between cutting-edge technology and economic considerations in the realm of additive manufacturing. The comprehensive nature of this study positions it at the forefront of advancing additive manufacturing practices with direct relevance to sectors keen on economic and operational optimization.

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