Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 12(1): 403-411, 2022
Journal of the Institute of Science and Technology, 12(1): 403-411, 2022
ISSN: 2146-0574, eISSN: 2536-4618
Makine Mühendisliği / *Mechanical Engineering* **DOI: 10.21597/jist.903159**
Araştırma Makalesi / *Research Article*
Geliş tarihi / Received: 26.03.2021 **Kabul tarihi / Accepted: 07.02.2022**

Atıf İçin: Korkut V, Yavuz H, 2022. Açık-Kaynaklı 3B Yazıcılarda Enerji ve Zaman Gereksinimini Azaltmada Etkili Parametrelerin İncelenmesi. Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 12(1): 403-411.

To Cite: Korkut V, Yavuz H, 2022. Examining the Influential Parameters on Reducing both Energy and Time Requirements in Open-Source 3D Printers. Journal of the Institute of Science and Technology, 12 (1): 403-411.

Açık-Kaynaklı 3B Yazıcılarda Enerji ve Zaman Gereksinimini Azaltmada Etkili Parametrelerin İncelenmesi

Volkan KORKUT[1,*], Hakan YAVUZ[2]

ÖZET: Katmanlı imalat ailesinde yaygın olarak tercih edilen cihazlar olan Fused Filament Fabrication (FFF) tipi 3D yazıcılara olan ihtiyaç gün geçtikçe artmaktadır. Bu cihazların geliştirilmesi sayesinde kullanım alanlarının artmasına ek olarak, işlem kolaylığı ve maliyeti de azalmaktaya başlamıştır. Basılan parçaların mekanik dayanımını arttırmayı amaçlayan çok sayıda çalışma mevcuttur. Dolayısıyla, çevre dostu bir üretim süreci için yapılan çalışmalar da gittikçe daha nitelikli hale gelmektedir. Bu amaçla, dayanımı yüksek olduğu bilinen özellikte bir numune üzerinde, harcanan enerji ve üretim süresi üzerinde detaylı incelemeler yapılmıştır. Numune üretiminde ihtiyaç duyulan güç ve zaman tüketimi belirli bir deneysel sıraya göre ölçümlenmiştir. Deneyler, Taguchi tabanlı Deneysel Planlama yöntemi temel alınarak planlanmıştır. Deneysel sonuçların yorumlanmasında, mühendislikte yaygın olarak kullanılan, güçlü birer istatistiksel araç olan Sinyal-Gürültü Oranı ve ANOVA analizlerinden yararlanılmıştır. Analizler sayesinde büyükten-küçüğe sırayla, platform sıcaklığı, katman kalınlığı, baskı hızı ve nozzle sıcaklığı parametrelerinin, tüketilen güç ve harcanan zaman üzerinde etkili olduğu gözlemlenmiştir. Parametrelerin yüzde oranda etkileri de belirlenmiş olup, en verimli üretim işlemini sağlayabilecek optimum parametrik kombinasyon da elde edilmiştir. Yapılan doğrulama deneyleri sayesinde istatistiksel hipotezlerin doğruluğu da kanıtlanmıştır. Sonuç olarak, her baskı işlemi için geçerli olabilecek, sıradan bir parçanın üretimi için gereken enerji miktarını ve işlem süresini aynı anda ve önemli ölçüde azaltacak parametreler açığa çıkarılmıştır.

Anahtar Kelimeler: 3B yazıcı, enerji yönetimi, FFF işlemleri

Examining the Influential Parameters on Reducing both Energy and Time Requirements in Open-Source 3D Printers

ABSTRACT: The need for Fused Filament Fabrication (FFF) type 3D printers in additive manufacturing family is increasing day by day. In parallel to the accelerating developments in these devices, the technical difficulties and the cost of operation have started to decrease in time. There are numerous studies available in the way to enhance the mechanical properties of parts printed with these devices. However, the energy and the time management in the printing processes have also become a new focus of today's research for more eco-friendly operations. In this study, the amount of energy and the time consumed during the printing period are examined in detail. The experiments are planned in accordance with the Taguchi method for Design of Experiments. Signal-to-Noise Ratio and ANOVA analysis, which are widely accepted and powerful statistical tools in the field of experimental engineering, are used to interpret the results. It is observed that the parameters of platform temperature, the layer thickness, the printing speed and the nozzle temperature are the most influential process parameters on the required power and time respectively. The percentage contributions of these parameters to the process performance is also presented. Furthermore, the optimal combination of parameters with suitable levels were obtained in order to minimize both the power and the time requirement for printing processes. The statistical hypothesis are verified by the confirmatory experiments. As a result, the parameters that significantly reduce the amount of energy and processing time for the production of a part applicable to most printing processes are revealed.

Keywords: 3d printing, energy management, FFF processes

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INTRODUCTION

Fused Filament Fabrication (FFF) type 3D printers are an attractive option for manufacturing industry due to their low running costs compared to other conventional options. For a product designer, an engineer or a manufacturer, the 3D printers stand as an effective solution. It allows both fast and inexpensive production of visual and/or functional prototypes for highly customized parts. The manufacturing methodology is based on depositing layers upon layers until the full shape of the real object is obtained. The contour limits of the layers are received from the CAD file which previously processed in the slicer software in form of G-Codes. Having an advantage of producing a physical object through the digital design made the FFF devices favorable choice in manufacturing industry. The fields such as rapid prototyping (Gibson et al., 2014. Rajpuhorit, 2018), household items production (Song et al,. 2018), part replacement and tooling (Rajpuhorit, 2018) have already adopted this technology. Regarding the parts' quality, many studies have been conducted in order to strengthen the part, promoting the surface finish with various materials for wider functionality in part's use (Griffiths et al., 2016). From an engineering perspective, the time, the material and the energy consumption still must be considered besides the quality. That is, the printing operations need to be eco-friendly in the way to contribute the sustainable environment (Wohler assoc., 2018). Technically, many parameters are considered in a printing process those determine the quality, the durability of the part and the material/energy consumed during the production. Therefore the built parameters must be configured taking into account all of these output aspects.

In the study of (Suarez, 2020 and Gutirrez et al,. 2019), the parameters of layer thickness, print head speed and the size of the design have been focused in the view of the energy efficiency. The operating temperatures for the system in order to make the solid material into a viscoelastic form is another field of the polymer science. By controlling the heating process efficiently, the study presented by Griffiths et al (2016) and McAlister (2014) proved that the need of energy can be decreased in certain circumstances. Moreover the cost estimation of the process depending the material-energy consumption also effected by the complexity of the shape. This is because the detailed geometries require the relatively slower printing speeds leading to longer printing operations (Watson and Taminger, 2018; Baumers et al., 2012). The axial motion of FFF machines relies on Computer Numerical Control (CNC) machines. So far, the energy consumption of material removal based CNC processes were investigated and understood in detail. However, in the study of Faludi et al (2015), the FFF devices were examined in the aspect of energy consumption by comparing them to the conventional CNC operations. It is stated that it is crucial to divide the FFF operations into the main steps of warm-up (preperation), actual operation, idle time and post-processing. This is because the use of FFF machines increase dramatically in the last decade which result in increased energy consumption. Parallel to this expression, the investment cost would expected to exceed 10 billion dollars by the 2022 as reported by (Forster, 2015).

At the present times, open-source and self-built devices are gaining popularity due to the high price/performance ratio (Tymrak, 2014). Numerous studies on mechanical, metallurgical and chemical properties, have been conducted on parts printed with open source devices (Liu, 2017; Kumar, 2010). As well as the final product characteristics which have been adequately researched, there is a need for more detailed investigation of the energy use during the manufacturing process. Because, their modifiable concept requires an additional effort in order to prevent the energy/time waste. Considering the printing devices are electro-mechanical systems, mechanical setup and the digital parameters need to be configured in a harmony. In this study, certain parameters are selected those have proven to be significant effect on time, material and energy consumption according to the past studies. The different setting of these parameters are combined to be manufactured for the examining purposes. The experimental results are then evaluated using various statistical approaches in order to reveal the optimum conditions in terms of the energy management.

MATERIALS AND METHODS

The 3D printing operation can be categorized according to operational steps from the electrical energy consumption aspect as shown in the Table 1.

Table 1. The operational steps of the 3d printing process

Preperation	Printing Period	Post-printing
Bed heating	Built parameters	Cooling
Nozzle heating	Motorised motion	Idling
Calibration	Extrusion	
Priming	Heating	
Idling	Idling	

Each print session requires some kind of preparation step. During these steps, the nozzle and the deposition bed must be sufficiently heated. Meanwhile, the appropriate distance between the bed and the nozzle tip should generally be calibrated before each print for proper extrusion and adhesion. Also a clean nozzle must be provided by evacuating the residual material left from previous prints (priming). When the printing is initiated, the motors should provide the smooth axial motion in order to extrude the semi-molten polymer into the appropriate coordinates on to the heated bed. After the job is accomplished, it is necessary to wait for the part to be cooled for a sufficient time avoiding the plastic defects. Additionally, an additional time should be accounted for the side components those drain energy such as controllers, sensors, lightening and LCD monitor during the whole process (the idle time).

The most important factor for determining the consumed energy in the process is the built parameters. That is, the time, the amount of material and the consumed energy strictly depend on the build parameters defined in the slicer software. In this investigation, the parameters of layer thickness (LT), nozzle temperature (NT), heated platform temperature (PT) and travel speed (TS) have been selected as a focus parameters since they are responsible from the energy management according to the literature (Song, 2018. Suarez, 2020. McAlister, 2014. Baumers, 2012.). The desing of experiments were planned based on Taguchi L_9 Orthogonal Array table. In Table 2, three different level settings for the selected parameters are presented.

Table 2. The selected parameters with their level settings

Parameters	Level 1	Level 2	Level 3
Layer Thickness (mm)	0.1	0.2	0.3
Nozzle Temperature (°C)	195	205	215
Platform Temperature (°C)	60	70	80
Travel Speed (mm/s)	50	65	80

The Orhogonal Array desing provides finding solid process parameters by minimizing the variance of input parameters over the output responses. By the design, the noise (uncontrollable disturbing factors) on the inputs are aimed to be reduced as much as possible. In this way, the deviation in the desired target is minimized. When the deviation is reduced, the effectiveness of the inputs over the output response become more distinct. The relation between the input and the output is measured by the Signal-to-Noise (S/N) Ratio which corresponds the quantitative measure of the process performance. In the Taguchi analyses, the S/N Ratio is desired to be high since it represents the improved quailty of the job

(Roy, 2010). From an engineering point of view, this method provides minimum but sufficient number of experiments while ensuring the validity of the obtained results to be generalised. Effort, test times, and product costs are the most important aspects of engineering. Therefore, this method was preferred also in this study. The experimental order has been presented with the relevant parameter combinations in Table 3.

Table 3. The parameter combinations according to L_9 Taguchi array

Experiment number	Parameters			
	LT (mm)	NT (ºC)	PT (ºC)	TS (mm/s)
1	0.1	195	60	50
2	0.1	205	70	65
3	0.1	215	80	80
4	0.2	195	70	80
5	0.2	205	80	50
6	0.2	215	60	65
7	0.3	195	80	65
8	0.3	205	60	80
9	0.3	215	70	50

In the testing procedure, the standart test specimen defined by the American Society for Testing and Materials was used (D638 Type 5, ASTM, 2012). In this way, it was possible to examine the parts, in terms of strength and energy consumption. The samples have been first prepared int the open-source Cura slicer then the printing process initiated. As a material, the Polylactic Acid (PLA) filament was used having a 1.75 mm in diameter (Shenzhen Esun Industrial Co., Ltd). The 9 different samples with three replication have been printed, one at a time (Figure 1.b).

The time duration and the power consumed for the printing processes have been recorded individually via the professional power analyser (Fluke 43B Power Quality Analyser, Figure 1.c) and mean results have been taken for each part.

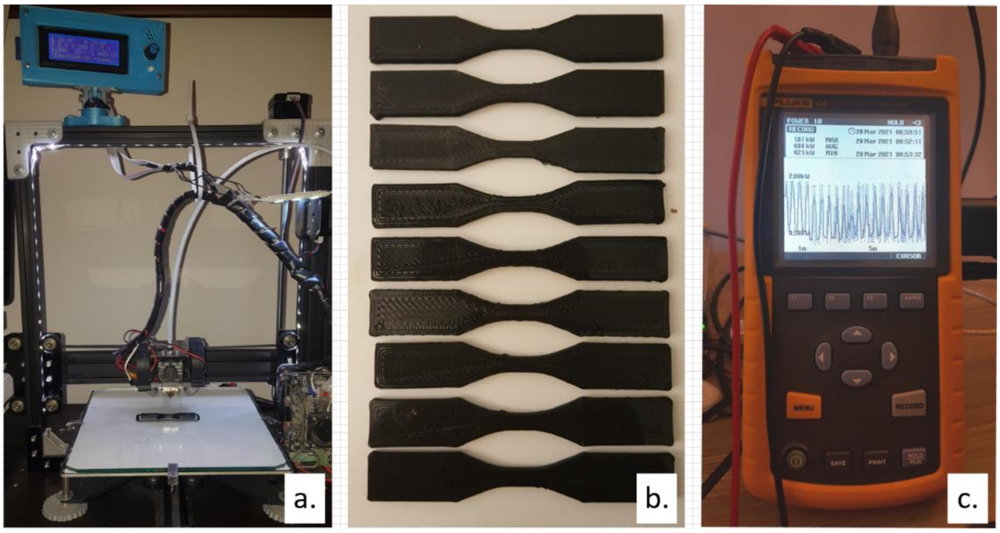

Figure 1. a. Printer setup **b**. The batch one of three sample group **c.** Power analyser

As a manufacturing device, the cartesian type, self-assembled 3D printer have been used having the Marlin 2.0 open-source firmware installed on MKS Gen L v1.0 control board (Figure 1.a). The axial motion has been provided by individual Nema 17 stepper motors for each axis (x, y and z). The rest of the device specifications as well as the fixed parameters for the test samples are presented in the Table 4.

Table 4. Fixed parameters for printing

Fixed Parameters;	
Print size	20 x 20 x 20 cm
Platform surface	Smooth glass
Nozzle diameter	0.4 mm
Layer cooling	2 external fans
Line width	0.5 mm
Wall thickness	0.8 mm
Infill density	30%
Infill type	Grid

In the next section, the obtained results taken from the online monitoring has been presented.

RESULTS AND DISCUSSION

In experimental session, the recorded data of the energy consumption and the processing times for each printing step have been summerized in the Table 5. The data represents the average of the three replications with their standard deviations for each sample.

Table 5. The energy and the time consumed for the samples

Exp. No	**Energy consumed (Wh)**						**Processing time (s)**					
	Bed heating	**Nozzle heating**	**Print session**	**Idle time**	**TOTAL**	**%Std[1]**	**Bed heating**	**Nozzle heating**	**Print session**	**Idle time**	**TOTAL**	**%Std[1]**
1	9.18	2.02	21.08	7.5	39.78	4.18	214	126	712	1413	2465	4.2
2	14.09	2.12	21.91	7.32	45.44	2.80	315	129	621	1576	2641	3.11
3	20.9	1.99	21.57	8.15	52.61	4.3	483	147	560	1733	2923	3.87
4	14.33	2.16	11.31	7.48	35.28	4.02	318	127	340	1567	2352	3.68
5	21.58	2.15	16.47	8.01	48.21	3.28	478	136	417	1710	2741	3.43
6	9.17	2.1	10.1	7.18	28.55	3.78	208	158	368	1431	2165	4.04
7	21.01	1.89	9.19	8.4	40.49	3.9	490	131	263	1720	2604	4.21
8	8.87	2.21	6.13	7.23	24.44	3.6	223	120	229	1400	1972	2.91
9	14.06	2.07	11.4	7.2	34.73	2.99	320	157	299	1539	2315	3.06
10	8.6	2.1	4.83	7.22	22.75	3.51	217	128	207	1350	1902	3.64

[1] *Std: Standard deviation*

The data have been examined with the S/N Ratio analysis in accordance with the Taguchi analyses. Since the S/N Ratio analysis is used for revealing the impact amount of the input parameters over the desired output; it becomes possible to sort the parameters over the energy consumption and the manufacturing times. In other words, the main effects of the parameter levels can be ranked according to their effects via the S/N Ratios. As mentioned previously, the higher S/N Ratio corresponds the higher impact over the output; That of the consumed energy during the process as it is subjected in this study. The ratios revealed have been schematized the graph given in the Figure 2.

Owing to the analysis, it was determined which parameter was effective on energy and time consumption. The numerical values belonging to the graph were also given in the Table 6.

Table 6. Response table for S/N Ratios

Level	**LT**	**NT**	**PT**	**TS**
1	-65.52	-64.85	-63.81	-64.95
2	-64.62	-64.69	-64.71	-64.81
3	-64.16	-64.76	-65.79	-64.54
Delta	1.36	0.16	1.98	0.41
Rank	**2**	**4**	**1**	**3**

Figure 2. Main effects of the parameter levels due to the S/N Ratios

Regarding the rankings (importances), the change in the platform temperature, layer thickness, travel speed and the nozzle temperature have a significant effect on both the consumed energy and the spent time respectively. Furthermore, the parameter combination of PT at 60 ^{o}C, LT at 0.3 mm, TS at 80 mm/s and NT at 205 ^{o}C is revealed to be the best candidate for minimizing both the power need and manufacturing time.

In the following, the effects of the parameters were investigated in more details by revealing their percentage contributions over the energy management.

The percentage contributions of the parameters can be determined by applying ANOVA (Analysis-of-Variance) analyses. In ANOVA analysis, the S/N ratios found in the Taguchi analyses are accounted for revealing the percentages of each parameter in accordance with their effectivenesses. In this way, the dominant parameters presenting the contribution of above %5 can be interpreted with their exact amount of the percentages (Roy, 2010). According to the S/N Ratios, the ANOVA tables have been generated using Minitab software.

Table 7. ANOVA tables for energy consumption and total processing time

Energy consumption					**Processing time**				
Parameter	**DF**	**Adj SS**	**Adj MS**	**Contribution**	**Parameter**	**DF**	**Adj SS**	**Adj MS**	**Contribution**
LT	2	252.815	126.408	37.88%	**LT**	2	224908	112454	31.92%
NT	2	1.267	0.634	0.19%	**NT**	2	802	401	0.11%
PT	2	393.250	196.625	58.92%	**PT**	2	466177	233088	66.17%
TS	2	20.052	10.026	3.00%	**TS**	2	12663	6331	1.80%
Total	**8**			**100.00%**	**Total**	**8**			**100.00%**

In the ANOVA tests for energy consumption, the contribution of PT and LT has been calculated as to be 58.92% and 37.88%. For processing time, the contribution of PT and LT has been calculated as to be 66.17% and 31.92% respectively. These parameters are then counted as dominant parameters where the rest (TS and NT) are observed to have a minor effect with below 5% percent in contribution. It should be noted that the error adjustment has been made during the percentile calculations on the sum of squares (SS) and mean of squares (MS) as shown in the Table 7.

Confirmation Tests

Until this point, the series of preliminary experiments have been conducted and the outputs were investigated using statistical approaches. As a result, the effects of the selected parameters have been revealed with their percentage contributions. Moreover, a new found combination have been obtained as; PT at 60 °C, LT at 0.3 mm, TS at 80 mm/s and NT at 205 °C.

In the light of the statistics, the prediction of the energy and the time spent can be minimized by using the parameters with revealed levels in a part manufacturing. To confirm this expression, a new specimen has been manufactured using this combination as a complementary testing. Tests were conducted using the same fixed parameters. The power consumption were monitored via the same online power analyser (Figure 3).

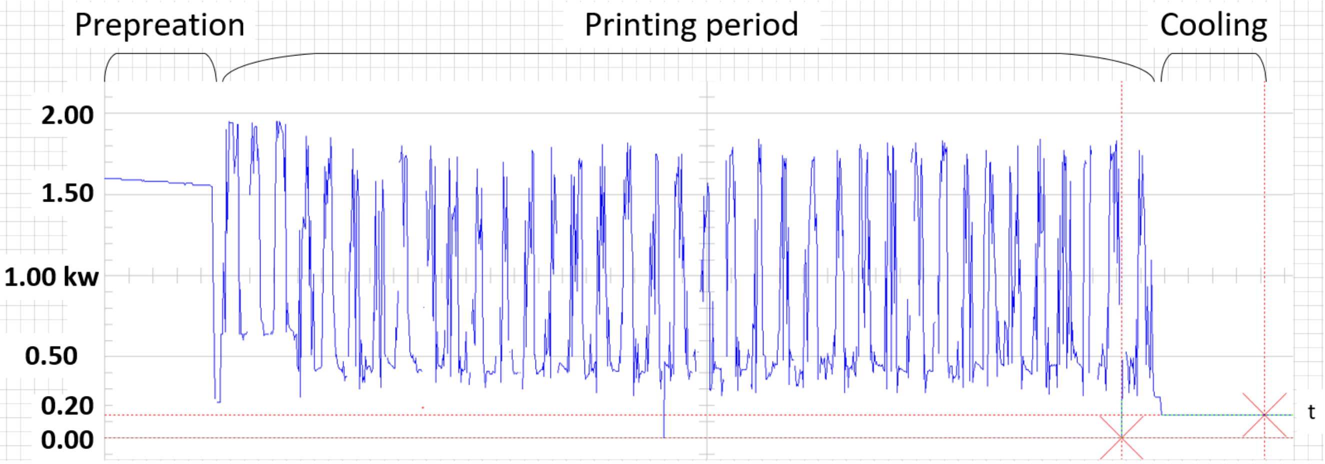

Figure 3. The representative capture of the online recording during the printing

The confirmative tests were also repeated for three times. The mean results of the outputs have been give in the Table 8.

Table 8. Confirmation test results

Outputs	Bed heating	Nozzle heating	Print session	Idle time	TOTAL
Energy consumed (Wh)	8.6	2.1	4.83	7.22	22.75
Processing time (s)	217	128	207	1350	1902

The comparison between the results of the confirmative sample and the previously printed samples have been made as shown in the Figure 4.

Regarding the Figure 4, it was observed that the sample having the suggested combination consumed the minimum energy among the previous samples with the 22.75 Wh of energy consumption. In other words, the new found combination provided 6.91% energy efficiency within 10 samples. Moreover, the time required for the job has been reduced significantly.

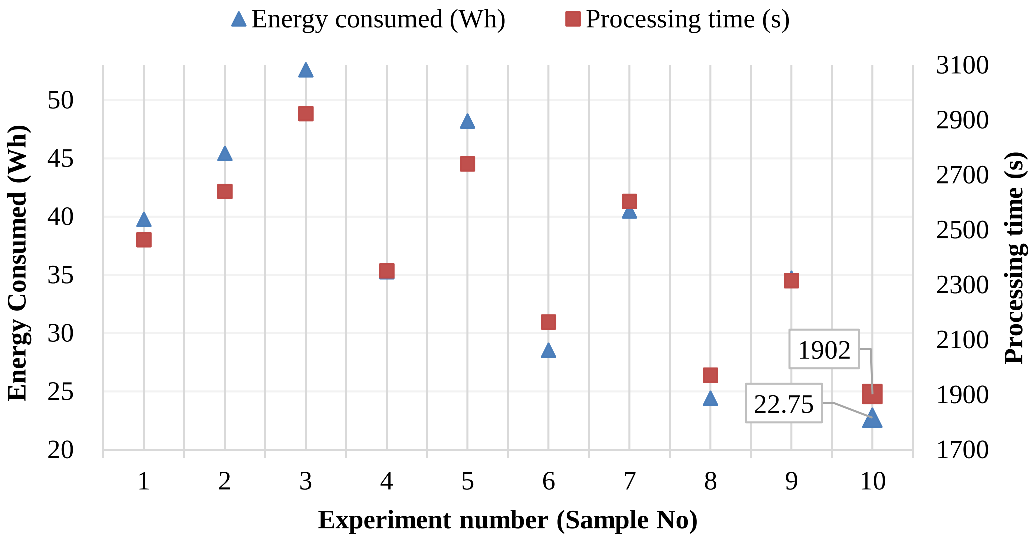

Figure 4. The comparison graph between the samples

CONCLUSION

The examinations over the actual printing processes are conducted via an open-source and modifiable device. The results are interpreted with the helpings of the powerful tools of engineering such as precise online monitorizing, Taguchi and ANOVA analysis. The study is finalized by confirmative test procedure.

Owing to the experiments, it has been observed that the layer thickness and platform temperature parameters valid for each printing process have a significant effect on both power consumption and processing time. Because when these parameters are optimally adjusted according to the job, as also recorded in the tests, the energy consumption can be reduced within shorter printing times. The effects of these parameters on the need of energy-time have also been supported by revealing their percentage contributions. As a result, a reduction of 6.91% in energy consumption has been achieved. In addition, the printing time was also reduced significantly. According to the confirmation tests, the experiments have shown a good agreement with the statistical approaches. With this study, the parameters those should be taken into account while calculating the need of energy-time have been revealed with their effect amounts. In this way, it is provided to the users that which parameters those need to be focused specifically and it is contributed to more eco-friend printing operations to be achieved.

ACKNOWLEDGEMENTS: This study was made possible with the generous supports from the mechanical engineering laboratories of both Adana Alparslan Türkeş Science and Technology University and Çukurova University.

Conflict of Interest: The authors declare that they have no conflict of interest.

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