ANALYSIS OF PROCESS PARAMETERS OF THE ENDER-3 V2 SERIES 3D PRINTER ON THE TENSILE AND COMPRESSIVE STRENGTH OF PLA FILAMENT TEST SPECIMEN USING TAGUCHI METHOD

Mohammad Yazid Diratama
Manufacture Engineering Department
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: yazid.polman@gmail.com

Muhammad Rizki Gorbyandi Nadi
Foundry Engineering Department
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: rizkigorby@gmail.com

Dedy Ariefijanto
Manufacture Engineering Department
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: dedy@me.polman-bandung.ac.id

Andri Suhendri
Manufacture Engineering Department
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: andriqsindo@gmail.com

Irfan Maulana
Manufacture Engineering Department
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: irfnnmlnaa17@gmail.com

ABSTRAK

FDM (*Fused Deposition Modeling*) telah muncul sebagai salah satu teknologi manufaktur aditif paling populer dalam beberapa tahun terakhir, yang memiliki kemampuan untuk menghasilkan objek dengan desain yang rumit. Dalam proses ini, objek dibuat lapis demi lapis menggunakan bahan polimer termoplastik. Salah satu mesin FDM yang terkenal adalah printer 3D seri Ender-3 V2. Kekuatan dan kualitas objek yang dicetak dipengaruhi oleh parameter proses utama, yaitu *infill density*, kecepatan pencetakan, dan ketebalan dinding. Penelitian ini bertujuan untuk menganalisis daMPak dari parameter proses ini yaitu; *infill density*, kecepatan pencetakan, dan ketebalan dinding terhadap kekuatan tarik dan tekan filament polylactic acid (PLA) dengan menggunakan Metode Taguchi. Spesimen standar ASTM D638 dan ASTM D695, yang dicetak pada printer 3D seri Ender-3 V2, digunakan. Desain susunan ortogonal Taguchi $L^4(2^3)$ menggabungkan kombinasi parameter proses: *infill density* (50,75)%, kecepatan cetak (30, 60) mm/s, dan ketebalan dinding (0,8, 1,2) mm, yang mewakili kualitas bagian yang dicetak. Hasil menunjukkan bahwa respons kekuatan tekan terutama dipengaruhi oleh *infill density*, sedangkan respons kekuatan tarik sebagian besar dipengaruhi oleh ketebalan dinding. Dengan demikian dapat disimpulkan bahwa kecepatan cetak yang lebih rendah menghasilkan kekuatan tarik dan tekan yang lebih tinggi. Untuk kerapatan objek sangat dipengaruhi oleh infill density dan ketebalan dinding hal ini dperkuat dengan hasil pemeriksaan mikrostruktural.

Kata kunci: FDM (Fused Deposition Modeling), kekuatan tarik, kekuatan tekan, Metode Taguchi, parameter proses, polylactic acid.

ABSTRACT

FDM (Fused Deposition Modeling) has emerged as one of the most popular additive manufacturing technologies in recent years, possessing the capability to produce objects with intricate designs. In this process, the object is constructed layer by layer using thermoplastic polymer materials. One notable FDM machine is the Ender-3 V2 series 3D printer. The strength and quality of the printed object are influenced by key process parameters, namely infill density, printing speed, and wall thickness. This research aims to analyze the impact of these process parameters; infill density, printing speed, and wall thickness on the tensile and compressive strength of polylactic acid (PLA) using the Taguchi Method. Standard specimens of ASTM D638 and ASTM D695, printed on the Ender-3 V2 series 3D printer, were employed. The Taguchi $L^4(2^3)$ orthogonal array design incorporated a combination of process parameters: infill density (50, 75) %, printing speed (30, 60) mm/s, and wall thickness (0.8, 1.2) mm, representing the quality of the printed parts. The results indicate that the compressive strength response is primarily influenced by infill density, while the tensile strength response is predominantly influenced by wall thickness. Thus, it can be concluded that lower printing speeds produce higher tensile and compressive strengths. The object density is greatly influenced by infill density and wall thickness, as confirmed by the results of microstructural examination.

Keywords: *FDM (Fused Deposition Modeling), tensile strength, compressive strength, Taguchi Method, process parameters, polylactic acid.*

1. INTRODUCTION

Technological developments in this modern era are growing rapidly and significantly, especially in the manufacturing industry. 3D printing is a technology in the manufacturing industry that is revolutionary technology using additive manufacturing techniques to produce three-dimensional objects with complex shapes that cannot be easily fabricated by conventional fabrication technologies. 3D printing works where materials are arranged layer by layer with computer control to produce three-dimensional objects. Additive manufacturing frequently used in the manufacturing industry: direct metal deposition (DMD), inkjet modeling (IJM), selective laser sintering (SLS), stereolithography (SLA) and fused deposition modeling (FDM). Currently, the FDM manufacturing process can be applied in many applications, but optimized process parameters play an important role to guaranteeing the quality of products, reducing time and costs [1].

The development of 3D printing technology is closely tied to advances in design software. Solidworks stands out as one such software, facilitating the creation of 3D models in stereolithography (STL) format, and enabling the subsequent printing process using a 3D printer. In 3D printing, filament plays a crucial role as it fills the shape of objects. Several choices of polymer filament materials include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), nylon, polyethylene terephthalate glycol (PETG), and polycarbonate (PC). For this research, PLA filament was employed an environmentally friendly material boasting a density of 1.24 g/cm^3 a printing temperature range of 180°C-210°C, and a bed temperature of 70˚C [16].

Several studies have explored the impact of 3D printing process parameters on tensile and compressive strength. These studies tested various parameters, including nozzle temperature, extrusion width, infill density, and infill pattern. Notably, infill density and nozzle temperature play a significant role in influencing the tensile strength response [2]. Another study, mentioned in the subsequent journal, highlighted that wall thickness emerges as the most dominant parameter affecting tensile strength response [17]. Additionally, when examining tensile strength with PLA filament, it was confirmed that layer thickness affects the tensile strength response [5]. Meanwhile, regarding PLA filament was investigated using a vertical print orientation of 0°, along with a combination of honeycomb infill pattern parameters and a nozzle temperature of 205°C. This combination resulted in a maximum tensile strength response of 42.5 MPa [6].

In a study focusing on compressive strength, Zhu et al. [3] examined the impact of layer thickness, infill density, and print speed on components made from PLA material. The study's findings highlight the substantial influence of layer thickness and infill density. Another study by Dave et al. [18] identifies infill density as the most crucial process parameter affecting compressive strength, a conclusion supported by Singh et al. [9], who obtained same as the results with Dave's research. Additionally, Abbas et al. [8] confirmed that layer thickness is indeed a significant influencing factor.

However, there is still limited comprehensive research on the effect of FDM process parameters infill density, printing speed, and wall thickness on the tensile and compressive strength. This paper presents a comprehensive review of FDM process parameters, encoMPassing infill density (%), printing speed (mm/s), wall thickness (mm), nozzle, layer thickness (mm), infill pattern, printing temperature, and printing orientation. The research involves specimens based on ASTM D638 and ASTM D695, incorporating statistical design of experiments (DOEs) and optimization techniques. This development aims to enhance the technology, enabling it to produce products with increased accuracy, improved quality, and the desired properties.

2. METHOD

This study applied the conceptual framework design to scrutinize the entire research process. The concept comprises four main stages: planning, creating, testing and gradual data processing, and ultimately leading to the formulation of a conclusion.

2.1 *Materials and Design Specimens*

In the present investigation, the material used for the mechanical test sample model in this study is PLA. Table 1. shows the properties of the PLA filament used in the present study. All mechanical test samples were printed using an Ender-3 V2 series 3D printer based on the FDM process using PLA filament. Initially, a 3D model of the mechanical test sample was designed using SolidWorks and then converted into an STL file. STL file is then imported into the slicing software wherein all the process parameters have been adjusted to fabricate the specimens, then after STL file was sliced. Finally, a G-code file that contained the printing instruction was generated and transferred to the 3D printer.

Table 1. Material properties of PLA filament

Material properties	
Density	1.24 g/cm^3
Tensile strength	51 MPa
Bending strength	86 MPa
Impact strength	10.5 J/m^3
Recommend printing temperature	190 – 230 °C
Filament diameter	1.75 ± 0.03 mm
Product net weight	1Kg/2.2 lb

Tensile specimens were specimens in ASTM D638 type I [4], and compressive samples were square cylinders in ASTM D695 [9]. The tensile and compressed specimens printed by standard were shown in Figure 1 and Figure 2.

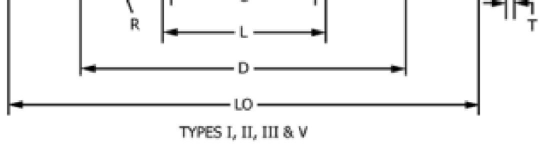


Figure 1. Tensile design specimens

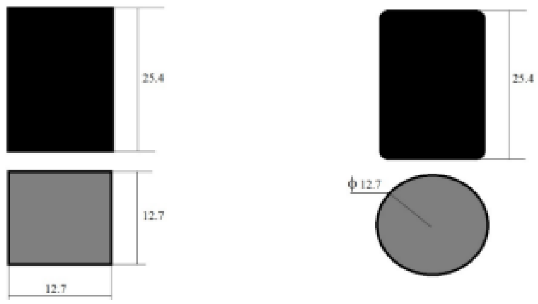


Figure 2. Compressive design specimens

2.2 *Design of Experiment*

The Taguchi Method is an experiment that aims to achieve robustness and reliability in product or process design by minimizing variation and sensitivity to external factors, thus enhancing overall quality and performance. Moreover, the method is widely used to reduce the total time required for this experiment and a factorial experiment with replication and randomization was conducted. The key focus is on finding the optimal settings for various parameters to ensure that the system or product performs consistently under different conditions. In this study, the parameters are divided into two categories, namely constant parameters and variable parameters. The constant parameters in this study are the wall thickness of 0.2 mm [3] and the vertical printing orientation 0° [6]. While the variable parameters used in this study are infill density (%), printing speed (mm/s), fill density (%) and wall thickness (mm). These three parameters are chosen cause based on the literature review; these parameters are the most influencing factor for the tensile and compressive strength in 3D printing FDM Processes [17][5][3]. The process parameters and levels are shown in Table 2.

Table 2. Processing parameter and their levels

Process parameters	Level	
	1	2
Infill density (%)	50	75
Printing speed (mm/s)	30	60
Wall thickness (mm)	0.8	1.2

Design of experiment (DOE) has been performed using Minitab software. Taguchi's method has been performed in L_4 (2^3) and a total of twelve samples with three replications have been printed, as shown in Table 3.

Table 3. Experimental of L4 orthogonal array

Exp.	Infill density (%)	Printing speed (mm/s)	Wall thickness (mm)
1	50	30	0.8
2	50	60	1.2
3	75	30	1.2
4	75	60	0.8

2.3 *Experimental Tests*

Tensile testing was carried out using a Zwick/Roell Z250 machine, with a loading rate of 0.5 mm/min. While the compressive tests was carried out using a A Hung Ta 8501 machine, with a loading rate of 1 mm/min. Additionally, the Olympus GX71 machine (optical type) was utilized to conduct the microstructure examination.

3. RESULTS AND DISCUSSIONS

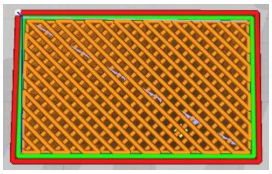
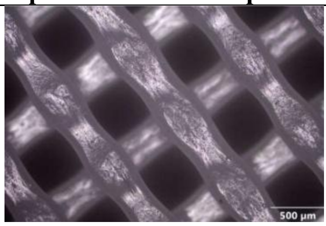
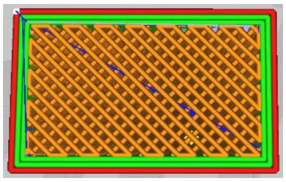
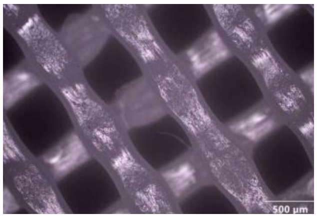
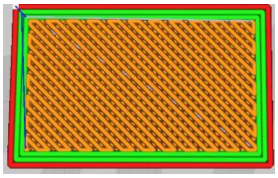
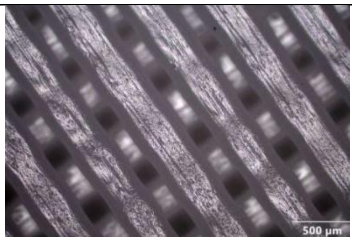
3.1 *Taguchi Method*

Table 4. Results of tensile and compressive strength testing

Exp. Number	Infill density (%)	Printing speed (mm/s)	Wall thickness (mm)	Average tensile strength (MPa)	Average compressive strength (MPa)
1	50	30	0.8	12.96	35.63
2	50	60	1.2	18.83	39.56
3	75	30	1.2	21.83	60.5
4	75	60	0.8	17.7	51.7

Larger extrusion width has more mass being extruded resulting in longer time for cooling process. Generally, a larger extrusion tends to produce larger contact between layers leading to an increase of bond strength [10]. But this study shows different results. Table 5 shows that the 3rd experiment (infill density of 75%, printing speed of 30 mm/s and wall thickness of 1.2 mm) is stronger than the other experiments. It could be suggested that in the slicing process using the slicer software, the arrangement of the infill density of 75% produces a denser surface and smaller gaps, as illustrated by Table 4 of the slicing result. It was described that there are differences in geometric detail observed in the output that can be attributed to process parameters.

Table 5. Gap result of specimens from slicing software

Gap Structure by software	Gap Structure in Real Specimen	Parameters
		• Infill density (%) = 50 • Printing speed (mm/s) = 30 • Wall thickness (mm) = 0.8
		• Infill density (%) = 50 • Printing speed (mm/s) = 60 Wall thickness (mm) = 1.2
		• Infill density (%) = 75 • Printing speed (mm/s) = 30 Wall thickness (mm) = 1.2

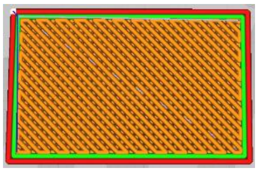
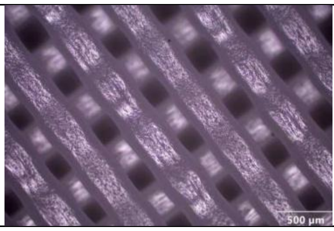
		• Infill density (%) = 75 • Printing speed (mm/s) = 60 Wall thickness (mm) = 0.8

Figure 3 shows that infill density and wall thickness have a significant impact on tensile strength. For the Compression strength is seen to increase only with increasing infill density while print speed and wall thickness have no significant effect on compressive strength as shown by Figure 4.

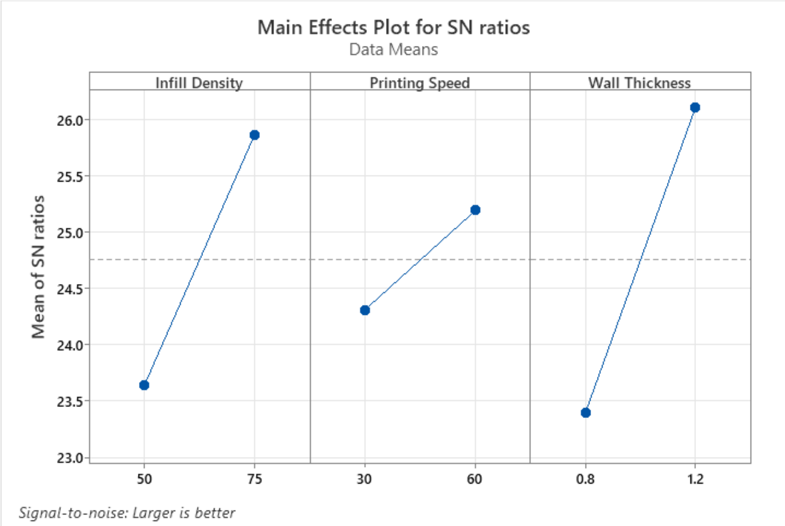


Figure 3. Main effect of process parameters on tensile strength

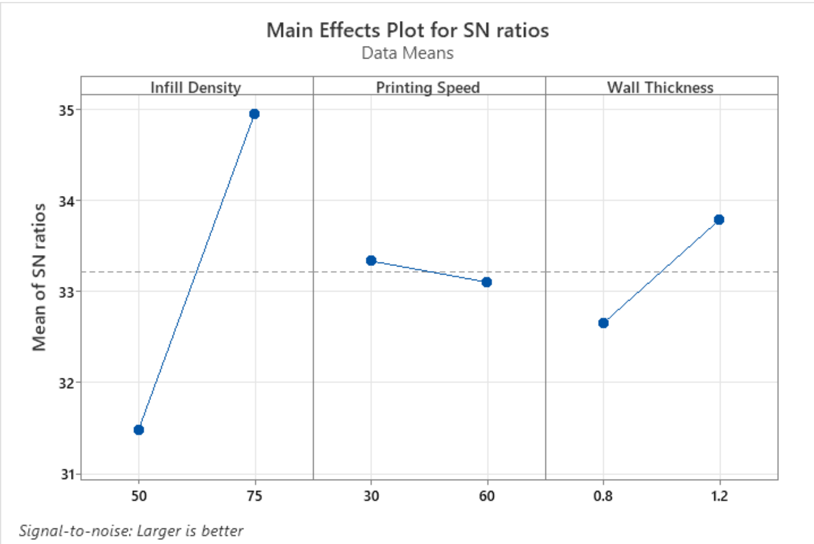


Figure 4. Main effect of process parameters on compressive strength

3.2 *Analysis of Variance*

An analysis of variance (ANOVA) is an efficient statistical testing method. This method can test the significant degree of influence of relevant factors on the experimental results throughout the experiment. The variance analysis table of tensile and compressive strength was obtained by using the data analysis software Minitab, as presented in Tables 6 and 7.

According to the table, it is evident that the tensile strength response is mainly affected by infill density, whereas the compressive strength response is primarily influenced by wall thickness. Despite the minimal impact of printing speed, lower printing speeds lead to increased tensile and compressive strength.

Table 6. Variance analysis of tensile strength

Factors	Degree of Freedom	Contribution	Adjacent sum of squares	Adjacent means of squares	Fisher's value	Probability
Infill density	1	30.84%	44.467	44.467	16.26	0.004
Printing speed	1	1.62%	2.341	2.341	0.86	0.382
Wall thickness	1	52.36%	75.501	75.501	27.61	0.001
Error	8	15.17%	21.880	2.735		
Total	11	100%				

Table 7. Variance analysis of compressive strength

Factors	Degree of Freedom	Contribution	Adjacent sum of squares	Adjacent means of squares	Fisher's value	Probability
Infill density	1	87.64%	1026.75	1026.75	1528.66	0.000
Printing speed	1	1.52%	17.76	17.76	26.45	0.001
Wall thickness	1	10.38%	121.60	121.60	181.05	0.000
Error	8	0.46%	5.37	0.67		
Total	11	100%				

Referring to Figure 5 and Figure 6, the interaction shows how increasing infill density results in higher tensile strength and higher compressive strength. Furthermore, the interaction of wall thickness and printing speed shows that increasing wall thickness results in higher tensile strength. The effect on printing speed can be seen in that lower printing speeds contribute to greater tensile strength, which means that optimal printing speed control can also influence the mechanical properties of printed outcomes as well. Meanwhile, compressive strength shows that the interaction increases wall thickness and decreases printing speed resulting in higher tensile strength.

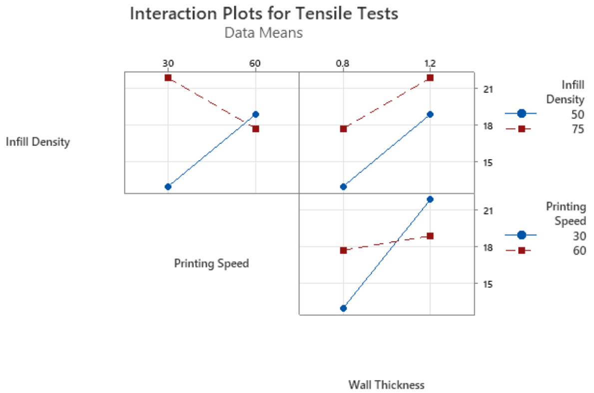


Figure 5. Interaction plots of tensile strength

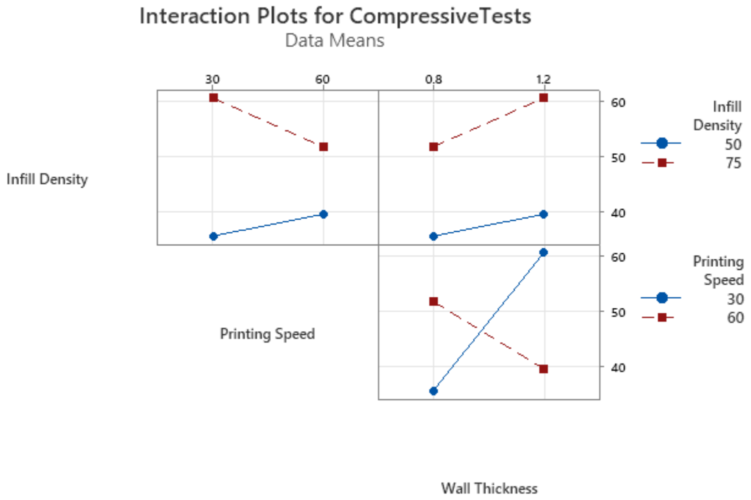


Figure 6. Interaction plots of compressive strength

4. CONCLUSION

This study concludes that from the experimental results on the effect of process parameters, namely infill density, wall thickness, and print speed, on the tensile and compressive strength of PLA-based scaffolds printed using the Ender-3 V2 3D printer in accordance with ASTM D638 Type I and ASTM D695 indicate that: Optimal tensile and compressive strength levels were obtained with an experimental combination of three process parameters: 75% infill density, 1.2 mm wall thickness, and 60 mm/s print speed, the results of the Taguchi method and ANOVA analysis concluded that the compressive strength response was primarily influenced by infill density, while the tensile strength response was primarily influenced by wall thickness, although print speed had a minimal impact, lower print speeds resulted in higher tensile and compressive strengths, and microstructural examination show that infill density and wall thickness significantly affect the density of the object.

REFERENCES

[1] O. A. Mohamed, S. H. Masood and J. L. Bhowmik , "Optimization of fused deposition modeling process parameters: a review of current research and future prospects," *Adv Manuf,* vol. 3, p. 42–53, 2015.

[2] A. W. Nugroho and C. Budiantoro, "Improving the tensile properties of 3D printed PLA by optimizing the processing parameter," *Journal of Energy, Mechanical, Material, and Manufacturing Engineering,* vol. 4, no. 1, p. 29–36, 2019.

[3] Z. Yu, Y. Gao, J. Jiang, H. Gu, S. Lv, H. Ni, X. Wang and C. Jia, "Study on Effects of FDM 3D Printing Parameters on Mechanical Properties of Polylactic Acid," in *IOP Conference Series: Materials Science and Engineering*, Jiaozuo, 2019.

[4] ASTM International, *Standard Test Method for Tensile Properties of Plastics,* West Conshohocken: ASTM International, 2022.

[5] O. Luzanin, D. Movrin and M. Plancak, "Effect of layer thickness, deposition angle, and infill on maximum flexural force in FDM-built specimens," *Journal for Technology of Plasticity,* vol. 39, no. 1, pp. 49-57, 2014.

[6] R. Ardiansyah, Z. S. Suzen and E. Erwansyah, "Pengaruh Parameter Proses Terhadap Kekuatan Tarik Produk 3d Printing Menggunakan Filamen Polylactic Acid (PLA) Buatan R3d Maker," *Jurnal Indonesia Sosial Teknologi,* vol. 2, no. 12, pp. 2153-2164, 2021.

[7] R. Singh, G. Singh, J. Singh and R. Kumar, "Investigations for tensile, compressive and morphological properties of 3D printed functional prototypes of PLA-PEKK-HAp-CS," *Journal of Thermoplastic Composite Materials,* vol. 34, no. 10, p. 1408–1427, 2021.

[8] T. F. Abbas, F. M. Othman and H. B. Ali, "Effect of infill Parameter on compression property in FDM Process," *Int. Journal of Engineering Research andApplication,* vol. 7, no. 10, pp. 16-19, 2017.

[9] S. S. Raj, A. Kuzmin, K. Subramanian and S. Sathiamoorthyi, "Philosophy of Selecting ASTM Standards for Mechanical Characterization of Polymers and Polymer Composites," *Materiale Plastice,* vol. 58, no. 3, pp. 247-256, 2021.

[10] T. J. Coogan and D. O. Kazmer, "Bond and part strength in fused deposition modeling," *Rapid Prototyping Journal ,* vol. 23, no. 2, pp. 414-422, 2017.

[11] A. Khalid, N. H. Hassan, N. A. A. Bakar and A. F. Baharuden, "Business Intelligence Dashboard for Driver Performance in Fleet Management," in *IC4E 2020: 2020 the 11th International Conference on E-Education, E-Business, E-Management, and E-Learning*, Osaka , 2020.

[12] X. Wang and H. Shi, "Research on the Function Optimization of the Bulk Grain Transportation Central Control System," in *IOP Conference Series Earth and Environmental Science* , Hangzhou, 2020.

[13] A. Azab, A. Karam and A. Eltawil, "A simulation-based optimization approach for external trucks appointment scheduling in container terminals," *International Journal of Modelling and Simulation ,* vol. 40, no. 5, pp. 321-338, 2020.

[14] K. M. Agarwal, P. Shubham, D. Bhatia, P. Sharma, H. Vaid and R. Vajpeyi, "Analyzing the Impact of Print Parameters on Dimensional Variation of ABS specimens printed using Fused Deposition Modelling (FDM)," *Sensors International,* vol. 3, 2022.

[15] D. Firka, "Statistical, technical and sociological dimensions of design of experiments," *The TQM Journal,* vol. 23, no. 4, pp. 435-445, 2011.

[16] C. Grabowik, K. Kalinowski, G. Ćwikła, I. Paprocka and P. Kogut, "Tensile tests of specimens made of selected group of the filament materials manufactured with FDM method," in *MATEC Web of Conferences*, Iaşi, 2019.

[17] N. A. Sukindar, M. k. a. M. ariffin, B. T. H. T. Baharudin and M. I. S. Ismail, "Analysis On The Impact Process Parameters On Tensile Strength Using 3d Printer Repetier-Host Software," *ARPN Journal of Engineering and Applied Sciences,* vol. 12, no. 10, pp. 3341-3346, 2017.

[18] H. Dave, S. Rajpurohit, N. H. Patadiya and S. J. Dave, "Compressive Strength of PLA Based Scaffolds: Effect of Layer Height, Infill Density And Print Speed," *International Journal of Modern Manufacturing Technologies,* vol. 11, no. 1, pp. 21-27, 2019.