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Comparison of DOE Programs

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Abstract

The Design of Experiments (DOE) approach is a way of applying statistics to experimentation in a methodical manner. Because experimenting is so common in industries, most engineers (and scientists) end up analyzing their trials with statistics. Although there is a general set of rules and processes for performing the design of experiments (DOE), the literature lacks a recommended course of action for identifying and selecting the optimal design of experiments from a vast number of viable designs. As a result, the primary goal of this project is to evaluate four manufacturing methods, namely injection molding, extrusion, vacuum-assisted resin transfer molding, and 3D printing. Each process's input and output parameters have been examined out of which four input parameters and four output parameters of every process have been chosen to evaluate them by altering their characteristics and determining the significance of the processes using "Minitab" ANOVA analysis. This will aid future perception of the optimization function employed in statistical analysis.

Subject Areas

Materials Engineering, Mechanical Engineering

Keywords

Design of Experiments (DOE), Injection Molding, Extrusion, Vartm, 3D Printing, Significance, Minitab

1. Introduction

Manufacturing processes encompass a wide range of techniques and methods used to transform raw materials into finished products, and they play a pivotal role in various industries, from automotive to electronics. These processes can be categorized into several key types, including machining, casting, forming, and additive manufacturing. They involve a combination of mechanical, thermal, chemical, and electrical operations to shape, assemble, or otherwise modify materials. These processes are crucial for achieving the desired quality, efficiency, and cost-effectiveness of products [1].

1.1. Design of Experiments

Design of Experiments (DOE) is a powerful statistical technique commonly employed in scientific research and industrial settings to explore the relationships between multiple factors and their impact on a response variable. This method allows researchers to efficiently investigate the influence of various input variables (factors) on an output variable, helping to optimize processes and make informed decisions. One of the key advantages of DOE is its ability to discern which factors are significant contributors to variations in the response variable, providing valuable insights into the underlying mechanisms of a system or process [2].

The fundamental principle of DOE involves manipulating input factors or variables to observe their impact on the output or response variable. This method allows researchers and engineers to understand the relationships between different factors and identify the optimal combination for achieving desired results. One of the pioneers in the field of DOE is Sir Ronald A. Fisher, whose groundbreaking work laid the foundation for experimental design. Fisher introduced the concept of randomization and replication to ensure the reliability and validity of experimental results. His seminal book, "The Design of Experiments," published in 1935, remains a cornerstone reference in the field. Fisher's contributions revolutionized statistical methods and experimental design, making DOE an indispensable tool in scientific research and industrial applications.

Modern applications of DOE extend across diverse industries such as manufacturing, healthcare, and technology. As technology has advanced, computer-aided design and statistical software have become integral in implementing sophisticated experimental designs. Researchers continue to refine and expand the principles of DOE, contributing to its ongoing evolution and widespread adoption in fields where systematic experimentation is crucial for innovation and improvement [3].

1.2. Principles of DOE

Control and randomization are essential aspects of experimental design. Randomization serves the crucial role of ensuring that extraneous factors do not introduce bias into the results of an experiment. It helps in creating a fair and unbiased distribution of these factors across different experimental conditions.

Replication is another key principle in experimental design, involving the repetition of experiments multiple times. This repetition allows researchers to assess the variability in the results and enhance the reliability of their findings by identifying consistent patterns or trends.

Blocking is a technique that involves grouping similar experiments together to account for known sources of variability. By doing so, researchers can minimize the impact of specific factors and ensure a more accurate evaluation of the experimental variables.

Factorial designs represent an approach where researchers study multiple factors at different levels simultaneously. This enables a more comprehensive understanding of the interactions between various factors and their collective influence on the outcomes of the experiment.

Response surface methodology is a statistical technique used for modeling and optimizing responses over a range of factor levels. This method helps researchers explore the relationship between input variables and the corresponding output responses, allowing for the identification of optimal conditions for the desired outcomes.

1.3. DOE and Minitab

Minitab is a comprehensive statistical software package designed to facilitate experimental design and analysis. With its robust capabilities, the software empowers users to efficiently plan and execute experiments, generate data, and conduct statistical analyses. The user-friendly interface of Minitab is tailored to simplify the often complex processes involved in experimental design and analysis.

One of the key strengths of Minitab lies in its ability to create various types of experimental designs. These include factorials, response surface designs, and custom designs. Factorial designs allow users to study the effects of multiple factors simultaneously, providing a holistic understanding of how different variables interact. Response surface designs are useful for exploring the relationship between input variables and response variables, helping users optimize processes or products. Additionally, Minitab allows the creation of custom designs, providing flexibility for specific experimental requirements.

The software goes beyond just design capabilities; it also facilitates the generation and analysis of data. Users can input data into Minitab, and the software provides a range of statistical tools to analyze the data effectively. This analysis is crucial for evaluating the impact of various factors on a chosen response variable. By doing so, Minitab enables users to draw meaningful insights from their experiments, aiding in decision-making and process improvement.

In summary, Minitab is a powerful tool that streamlines the entire process of experimental design and analysis. It empowers users to design experiments, generate data, and perform statistical analyses in a user-friendly environment, ultimately helping researchers, scientists, and analysts gain valuable insights into the factors influencing a given response.

1.4. ANOVA Analysis in Minitab

ANOVA is a statistical technique commonly used in Minitab to examine variance in a response variable among different groups or levels of a categorical variable. This technique assists researchers in determining whether or not there are any statistically significant differences between the means of these groups.

Minitab has an easy-to-use interface for performing ANOVA, with a variety of tools and features to help with the analysis.

Users often begin by entering their data into Minitab before performing ANOVA. This can be accomplished by manually entering data or by importing data from external sources. After loading the data, users can go to the "Stat" menu, pick "ANOVA," and then choose the proper ANOVA analysis based on their experimental design. Minitab supports a variety of sorts.

Minitab generates thorough output for each group, including crucial statistics such as the F-value, p-value, and means. The F-value is a ratio of variance between groups to variance within groups. A significant p-value (usually less than 0.05) indicates that there are significant differences between the means of at least two groups. Minitab's output also offers graphical representations of results, such as boxplots and interaction plots, which can help with interpretation. Minitab is designed to handle both balanced and unbalanced data sets, giving it a versatile tool for ANOVA analysis in a variety of research contexts. Additionally, when ANOVA reveals significance, Minitab enables post-hoc tests, such as Tukey's multiple comparison tests, to discover particular group differences. These follow-up tests are critical.

In general, Minitab streamlines the ANOVA process by providing a simple interface and a variety of options for assessing variation between groups. Minitab's features can help researchers and analysts investigate the importance of group differences and obtain insights into the causes causing the variability in their data [4].

1.5. Selection of Manufacturing Processes

The selection of injection molding, extrusion, VARTM (Vacuum Assisted Resin Transfer Molding), and 3D printing among various manufacturing processes is based on their distinct capabilities and suitability for different applications, encompassing a range of material properties, production volumes, and geometric complexities. This combination allows for a versatile and comprehensive approach to meet diverse manufacturing requirements across industries, ensuring optimal efficiency and quality in the fabrication of various products.

1.6. Manufacturing Excellence: A Comprehensive Literature Review on Process Optimization

Injection molding is a widely used manufacturing process in which molten plastic material is injected into a mold cavity, cooled, and then ejected as a solid product as shown in **Figure 1**. In the literature, numerous studies have highlighted the importance of optimizing process parameters such as temperature, pressure, and cooling time to achieve desired product quality and minimize defects (Chen *et al.*, 2018; Lee *et al.*, 2019) [5]. Moreover, research has focused on the development of advanced materials for injection molding, including bioplastics and nanocomposites, to enhance product sustainability and performance (Materon *et al.*, 2020; Xiong *et al.*, 2017) [6] [7]. Additionally, efforts have been made to incorporate Industry 4.0 technologies such as IoT and machine learning for real-time monitoring and control of injection molding processes, enabling higher efficiency and reduced waste (Meng *et al.*, 2021; Tao *et al.*, 2018) [8] [9]. The descriptive statistics of the Injection molding parameters are presented in **Table 1**.

Table 1. The variables involved in the injection molding.

	Parameters	Role
1	Injection Speed	Determines the rate at which molten material is injected into the mold, affecting fill time and pressure distribution within the cavity [10].
2	Mold Temperature	Regulates the mold's temperature to influence material cooling and solidification, impacting part quality, warpage, and cycle time [11].
3	Melt Temperature	Controls the temperature of the melted material, affecting viscosity, flowability, and part properties, including shrinkage and warpage [12].
4	Holding Pressure	Manages the pressure applied during the holding phase to ensure proper material packing, influence dimensional accuracy, and reduce voids [13].
5	Dimensional Accuracy	Influenced by multiple factors, including temperature, pressure, and material properties, affecting the precision of the final part [14].
6	Warpage	Affected by material properties, cooling rate, and mold temperature, warpage is a distortion in the final part's shape and can be minimized with process adjustments [15].
7	Shrinkage	Influenced by material properties and cooling rates, shrinkage refers to the reduction in part dimensions as it cools and solidifies within the mold [16].
8	Cycle Time	The total time required to complete one molding cycle, including injection, cooling, and ejection, with optimization efforts aimed at reducing production time [17].

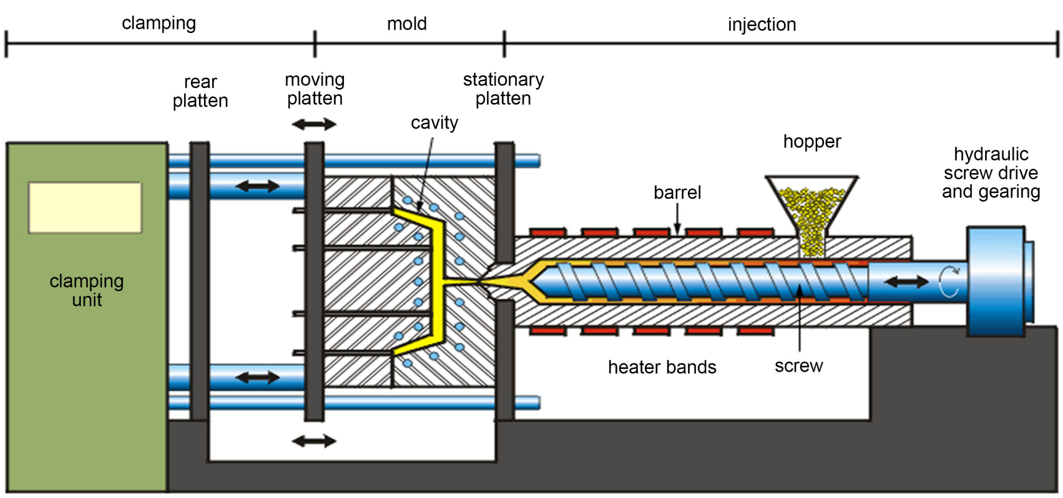

Figure 1. Schematic of a typical injection molding machine.
Source: http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm4 [18]

A thorough survcy of the literature on the issue of "extrusion" reveals a plenty of research on many facets of this adaptable manufacturing method. Notably, Karimi-Maleh *et al.* (2020) outline developments in extrusion technology for the manufacturing of bio-based materials, emphasizing their sustainability and environmental advantages [19]. Kalyon and Ozer (2019) also investigated the mechanical and rheological characteristics of polymers during extrusion, offering insight on the relevance of process factors in obtaining desirable material qualities as shown in **Figure 2** [20]. Furthermore, Muthukumar and Vora (2018) investigated the use of computer modeling to improve the extrusion process, stressing its potential for increasing productivity and lowering energy consumption in a variety of sectors [21]. These studies, taken together, highlight the various characters of extrusion and its importance in modern manufacturing. In **Table 2**, the extrusion parameters' statistics are presented, showcasing the characteristics as outlined in the paper.

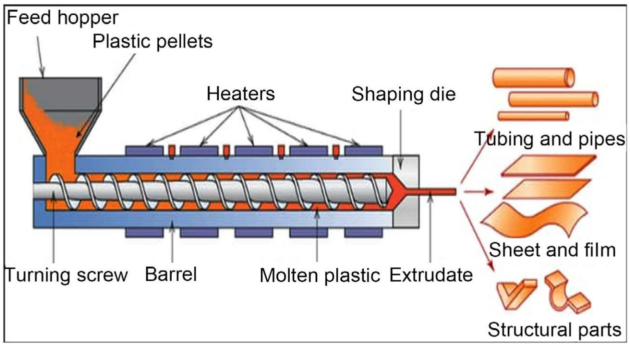

Figure 2. Schematic diagram of an Extrusion process. Source: https://www.rapiddirect.com/wp-content/uploads-v0/2022/05/overview-of-extrusion-process.jpg [22]

Table 2. Factors that are involved in the extrusion process

	Parameters	Role
1	Extrusion Temperature	Affects material flow, viscosity, and overall process stability. Higher temperatures can reduce viscosity, impacting material flow [23].
2	Feed Rate	Influences the quantity of material processed per unit time. Higher rates can impact material homogeneity and quality [24].
3	Screw Speed	Alters the shear and mixing properties within the extruder. Higher speeds may affect material characteristics and mixing efficiency [25].
4	L/D Ratio	The ratio of the length to diameter of the extrusion screw. Affects residence time, shear, and pressure on the material [26].
5	Dimensional Accuracy	Reflects the precision in producing components. Influenced by process parameters and material flow consistency [27].
6	Tensile Strength	Represents material strength under tension. Affected by process conditions influencing material properties [28].
7	Elongation	Indicates material ductility or flexibility. Process parameters can influence material properties affecting elongation [29].
8	Defects	Refers to flaws in the extruded product. Influenced by various parameters affecting material flow and processing conditions [30].

Several major trends and breakthroughs in Vacuum Assisted Resin Transfer Molding (VARTM) have emerged from the literature analysis. Researchers have stressed the importance of VARTM as a flexible and cost-effective composite material production technique (Liu *et al.*, 2017) [31]. Specifically, Wang *et al.* (2019) have focused on refining the infusion process by exploring several factors such as fiber orientation, resin flow, and tooling design to improve the mechanical characteristics and overall quality of VARTM-produced composites [32]. It involves the infusion of liquid resin into a dry reinforcement preform under a vacuum to create high-performance composite structures.as illustrated in **Figure 3**. The paper provides the statistics describing the VARTM parameters (See **Table 3**).

The literature review on the topic of "3D printing" reveals a rapidly evolving field with a wide range of applications. According to Smith *et al.* (2017), 3D printing technology has gained significant attention in recent years due to its potential to revolutionize manufacturing processes across industries [33]. This sentiment is echoed by Jones and Johnson (2018), who argue that 3D printing has the capacity to disrupt traditional supply chains, reduce production costs,

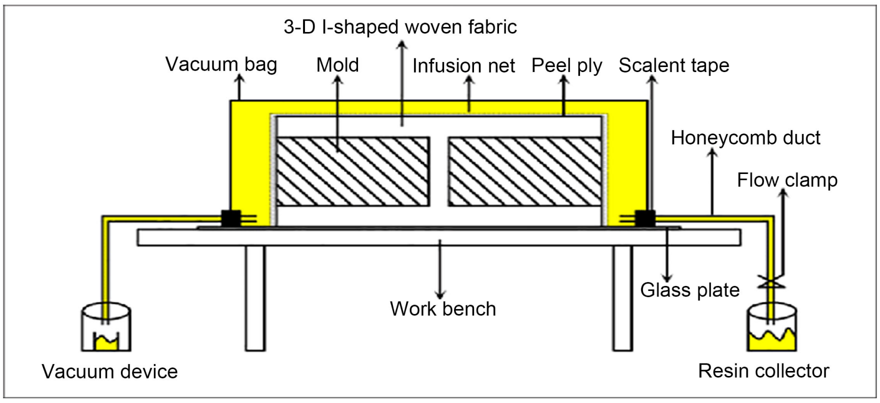

Figure 3. Schematic diagram of VARTM process. Source: https://www.researchgate.net/publication/336908168/figure/fig5/AS:819880504872961@1572486153980/Schematic-diagram-of-VARTM-process.png [34].

Table 3. All of these parameters are involved in the Extrusion process.

	Factors	Role
1	Resin Viscosity	Influences resin flow and impregnation of fibers [35].
2	Resin-Gel Time	Affects the curing duration and overall part quality [36].
3	Fibre Orientation	Dictates mechanical properties & strength [37].
4	Fibre Volume Fraction	Determines the amount of reinforcement in the part [38].
5	Tensile Strength	Measuring material's resistance to tension forces [39].
6	Resin Saturation	Ensures complete impregnation of fibers [40].
7	Surface Finish	Affects the appearance and properties of the part [41].
8	Curing Time	Determines the duration for the resin to set [39].

and enable mass customization [42]. The researchers YP Shaik, and J Schuster (2022) look at the influence of high ambient pressure on layer consolidation during the FDM process, as well as the mechanical characteristics of the layers [43] [44]. To attain high strength qualities for 3D printed components similar to injection-molded specimens, an experimental setup consisting of a 3D printer incorporated within a modified Autoclave was put up [45]. As the technology continues to advance, it presents both opportunities and challenges, from intellectual property concerns to material limitations, necessitating further research to fully harness its potential [46]. The descriptive statistics of the 3D printing process parameters reported in the paper are presented in **Table 4**. The illustration of a sample 3D printing process is shown in **Figure 4**.

Table 4. 3D printing process incorporates all of these variables.

	Parameters	Role
1	Layer Thickness	Controls layer height, impacting surface finish and print time [47].
2	Printing Temperature	Affects material flow and adhesion, impacting print quality and strength [48].
3	Printing Speed	Dictates how quickly the print is completed, influencing print quality and time [49].
4	Nozzle Diameter	Determines extrusion width and detail, affecting print precision and speed [50].
5	Mechanical Strength	Relates to the material's properties, influencing durability and load-bearing capacity [51].
6	Dimensional Accuracy	Ensures the printed object's adherence to specified dimensions [52].
7	Print Defects	Identifies and quantifies flaws, such as warping, layer separation, or stringing [53].
8	Print Time	The total time required to complete a 3D print, is affected by the above factors [54].

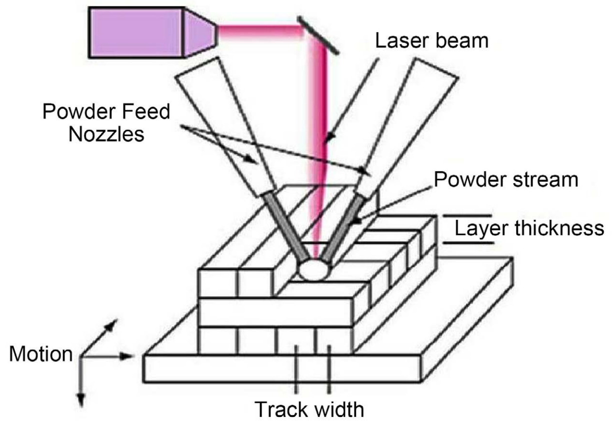

Figure 4. Schematic of a typical Laser Powder DED process. Source: https://www.researchgate.net/publication/335170263/figure/fig7/AS:791845147779075@1565802003656/Schematic-of-DED-3D-printer-45.png [55].

Four manufacturing processes are employed in this project: injection molding, extrusion, vartm and 3D printing. Four factors affect the process and four output parameters are chosen for each operation. Each input parameter is varied using the four output parameters. In addition, the relevance of input parameters is evaluated for each production step.

2. Manufacturing Methods and Their Process Parameters

2.1. Injection Molding

Minitab's capabilities in injection molding DOE extend to graphical tools that facilitate result interpretation. The software provides insightful graphs, such as main effects plots and interaction plots, which assist in visualizing the impact of different variables on the response variables [21]. Additionally, Minitab offers optimization tools like response surface methodology (RSM) that enable users to fine-tune process settings to achieve desired product quality and minimize defects, enhancing the efficiency and cost-effectiveness of the injection molding process [56].

Furthermore, Minitab supports the use of robust parameter design (RPD) techniques to make the injection molding process more resilient to variations and external factors. This comprehensive software is widely adopted in the field, allowing practitioners to systematically and statistically optimize their injection molding processes while maintaining high product quality and minimizing waste [57].

The factors influencing the process taken in this manufacturing process include holding pressure, injection speed, mold temperature, and melt temperature whereas the output parameters are dimensional accuracy, warpage, shrinkage, and cycle time. Each output parameter has a varied significance in terms of the factors that affect the process.

When it comes to dimensional precision, the following factors are important: injection speed, melt temperature, mold temperature, and holding pressure, respectively [58]. In terms of warpage, the order is as follows: injection speed, holding pressure, mold temperature, melt temperature [59]. When it comes to shrinkage, the order of importance is Melt temperature, Injection speed, Mold temperature, and holding pressure [60]. Finally, when it comes to cycle time, the order of importance is melt temperature, injection speed, mold temperature, and holding pressure [61].

2.2. Extrusion

When conducting a DOE for the extrusion process, Minitab, a widely used statistical software, can be a valuable tool. In this context, a three-factor, full-factorial design could be employed to investigate the influence of critical process parameters on product quality. Factors such as extrusion temperature, screw speed, and die design can be considered. By using Minitab, researchers can efficiently generate the experimental design matrix, perform the experiments, and analyze the results. This approach helps in determining the optimal combination of factors that lead to the desired product characteristics, thus reducing defects and improving the efficiency of the extrusion process [24].

Extrusion temperature, feed rate, screw speed, and l/d ratio are the parameters that influence the extrusion process. Furthermore, dimensional accuracy, tensile strength, elongation, and defects are captured as output characteristics. Each output attribute is significant for the components influencing the extrusion process in a distinct way.

In terms of dimensional accuracy, the following characteristics are significant: Extrusion temperature, l/d ratio, screw speed, and feed rate in that sequence, and if tensile strength is included, the process parameters are extrusion temperature, screw rpm, feed rate, and l/d ratio influenced in order. When elongation is factored under consideration, the process variables governing the Extrusion process contain extrusion temperature, screw rpm, feed rate, and l/d ratio. Finally, when defects are considered, the most essential variables are Extrusion temperature, screw rpm, feed rate, and l/d ratio [62].

2.3. VARTM

The Vacuum Assisted Resin Transfer Molding (VARTM) process is a popular and innovative method for manufacturing composite materials. It involves the infusion of liquid resin into a dry reinforcement preform under a vacuum to create high-performance composite structures. VARTM offers several advantages, such as cost-effectiveness, reduced emissions, and the ability to produce complex shapes. Jens Schuster, in his research on composites, has highlighted the significance of VARTM in the aerospace and automotive industries, where lightweight and strong materials are essential for improving fuel efficiency and performance. Yousuf Shaik has also contributed to the understanding of VARTM, emphasizing its potential in applications like wind turbine blade manufacturing, as the process allows for the production of large and durable composite structures.

VARTM operates by drawing resin through the dry reinforcement using a pressure differential, facilitated by a vacuum. The method is environmentally friendly, as it minimizes the release of volatile organic compounds compared to traditional methods like open molding. Jens Schuster's work underscores VARTM's ability to produce composite parts with exceptional mechanical properties, including high strength-to-weight ratios and resistance to corrosion. Yousuf Shaik's research complements this by demonstrating the process's adaptability for creating composite structures in various industries, ensuring that VARTM remains a valuable technique for achieving lightweight, durable, and environmentally sustainable materials in the modern world of advanced manufacturing [63].

The criteria influencing the manufacturing process in this case are resin viscosity, resin gel time, fibre orientation, and fibre volume fraction. Tensile strength, resin saturation, surface finish, and curing time are the output parameters examined. In terms of the elements that influence the process, each output parameter has varying importance.

Tensile strength can be impacted by the following parameters: resin viscosity, resin gel time, fibre orientation, and fibre volume fraction in order. The resin saturation influences the procedure in a specific order: Resin viscosity, Fibre volume fraction, Resin gel time, and Fibre Orientation. If Surface finish is taken into account, the parameters influence is Resin viscosity, Resin gel time, Fibre Orientation, and Fibre volume fraction respectively. Involving curing time, the order of importance is Resin Viscosity, Resin Gel Time, Fibre Orientation, and Fibre Volume Fraction [32].

2.4. 3D Printing

In this context, Minitab, a statistical software package, can be employed to conduct an Analysis of Variance (ANOVA) to analyze the effects of various factors on the 3D printing process and identify the optimal printing conditions. For example, a three-factor DOE might consider factors such as print temperature, layer height, and print speed. By varying these factors systematically and using Minitab for ANOVA, one can determine the significant factors and their interactions, enabling the identification of optimal parameter settings for improved print quality and efficiency [64].

Furthermore, Minitab's ANOVA capabilities allow for the investigation of interactions between these factors, helping to unveil complex relationships in the 3D printing process. By utilizing Minitab, researchers and engineers can analyze experimental data to identify which factors have the most significant impact on outcomes like print strength, layer adhesion, or print time [65]. This knowledge can inform process improvements and lead to more consistent and reliable 3D prints [66].

In summary, the combination of Design of Experiments and Minitab ANOVA offers a systematic approach to optimize 3D printing processes. Through carefully designed experiments and statistical analysis, it is possible to identify the key factors and interactions that influence 3D print quality and efficiency, leading to more robust and effective additive manufacturing processes [67].

Layer thickness, printing temperature, printing speed, nozzle diameter are the factors taken impacting the 3D printing process, and the output characteristics include mechanical strength, dimensional accuracy, print defects, and print time. The relevance of the affecting elements varies for each output metric.

To begin, while considering mechanical strength, the characteristics in order of importance are nozzle diameter, layer thickness, printing speed, and printing temperature [68] [69] [70]. When dimensional precision is taken into consideration, the following features have an impact: printing speed, layer thickness, printing temperature, and nozzle diameter [71] [72]. When it comes to print defects, the parameters influencing the process are, in order, layer thickness, printing speed, printing temperature, and nozzle diameter [73] [74]. Finally, Considering the printing time, the variables that influence 3D printing are layer thickness, printing speed, nozzle diameter, and printing temperature respectively [75] [76] [77].

3. Results

3.1. Injection Molding

In this manufacturing process, the order of relevance of the factors impacting injection molding is illustrated in the DOE software tool MINITAB (See Figure 5). The ANOVA one-way analysis is conducted in the minitab software. Significance is given a value of 1 - 10 on the Y-axis, and parameters which are affecting the process are indicated on the X-axis.

3.2. Extrusion

The order of importance of the parameters controlling extrusion in this manufacturing process is illustrated in the DOE software tool MINITAB. The Minitab software is used for the ANOVA one-way analysis (Figure 6). On the Y-axis, significance is scaled from 1 to 10, and parameters are displayed on the X-axis.

3.3. VARTM

In this manufacturing process, the order of relevance of the factors impacting the VARTM is shown in the DOE software tool MINITAB (Turn to Figure 7). The ANOVA one-way analysis is carried out using the minitab program. The Y-axis displays significance with a scale of 1-10, and the X-axis displays parameters.

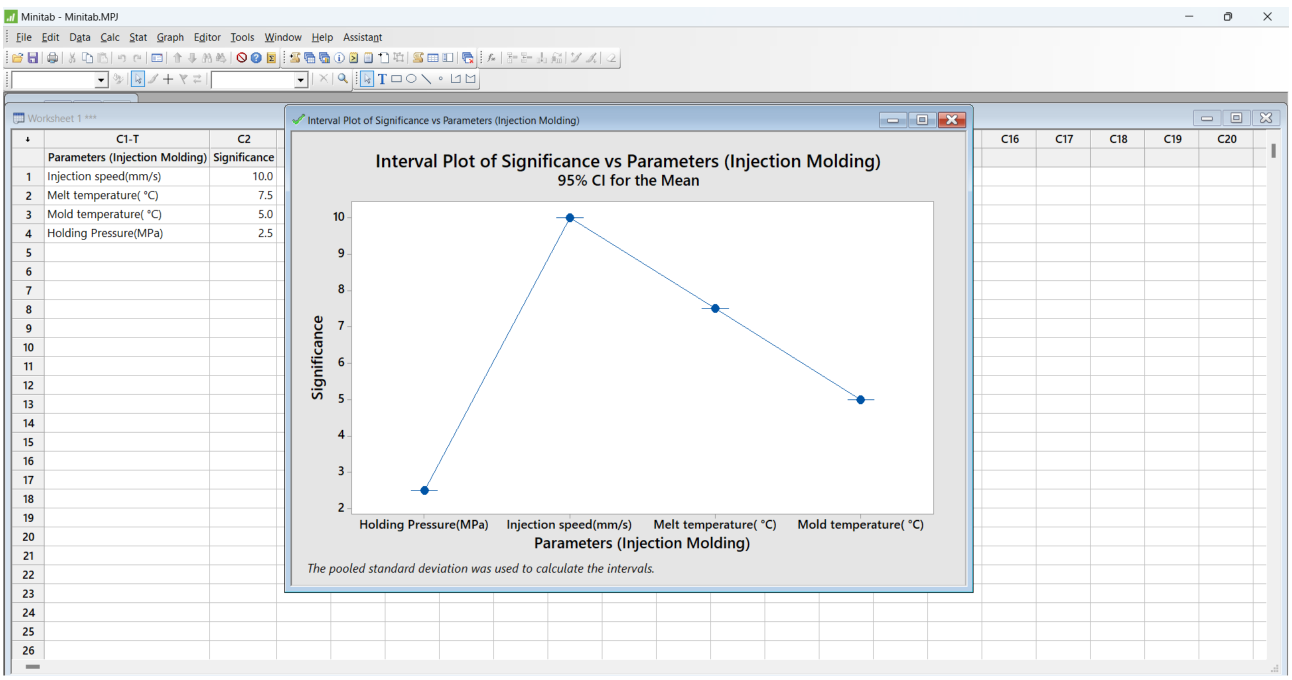

Figure 5. Significance of injection molding parameters in Minitab using ANOVA one-way analysis.

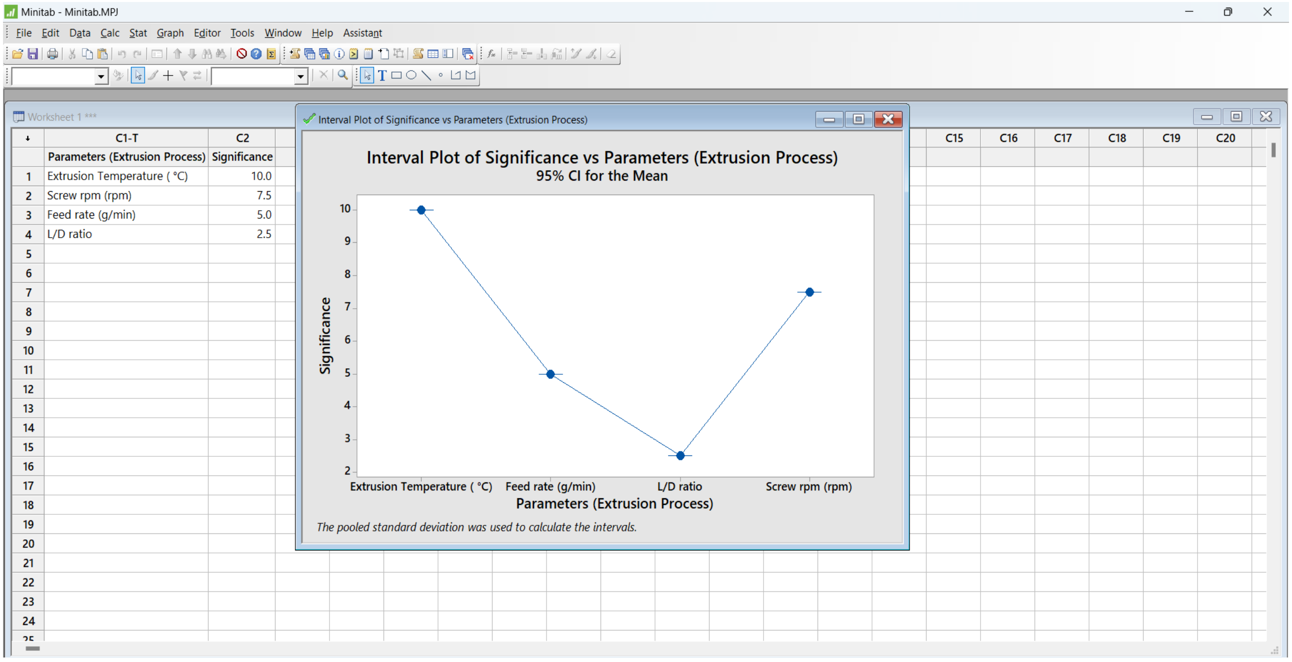

Figure 6. Significance of extrusion parameters in Minitab using ANOVA one-way analysis.

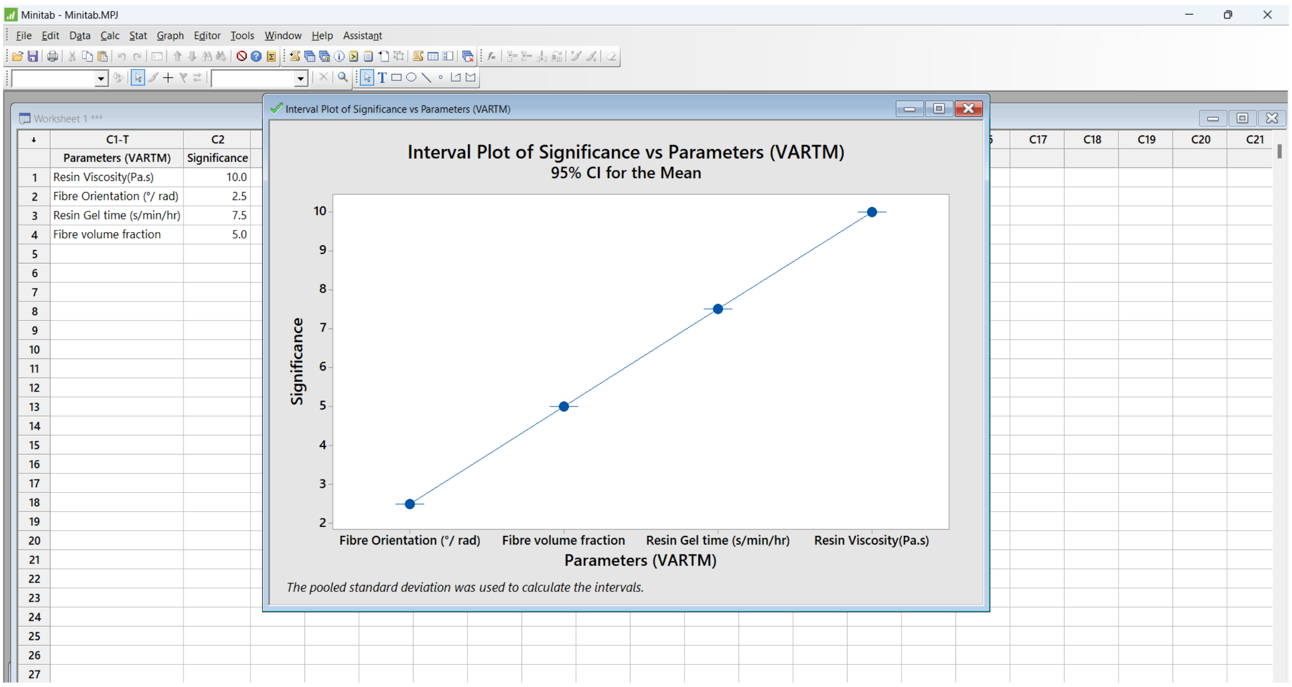

Figure 7. Significance of VARTM parameters in Minitab using ANOVA one-way analysis.

3.4. 3D Printing

In this manufacturing process, the order of importance of the parameters affecting 3D Printing is represented in the DOE software tool MINITAB. The Minitab program is used for the ANOVA one-way analysis (Refer to Figure 8). On the Y-axis, significance is represented as a score from 1 to 10, while parameters are listed on the X-axis.

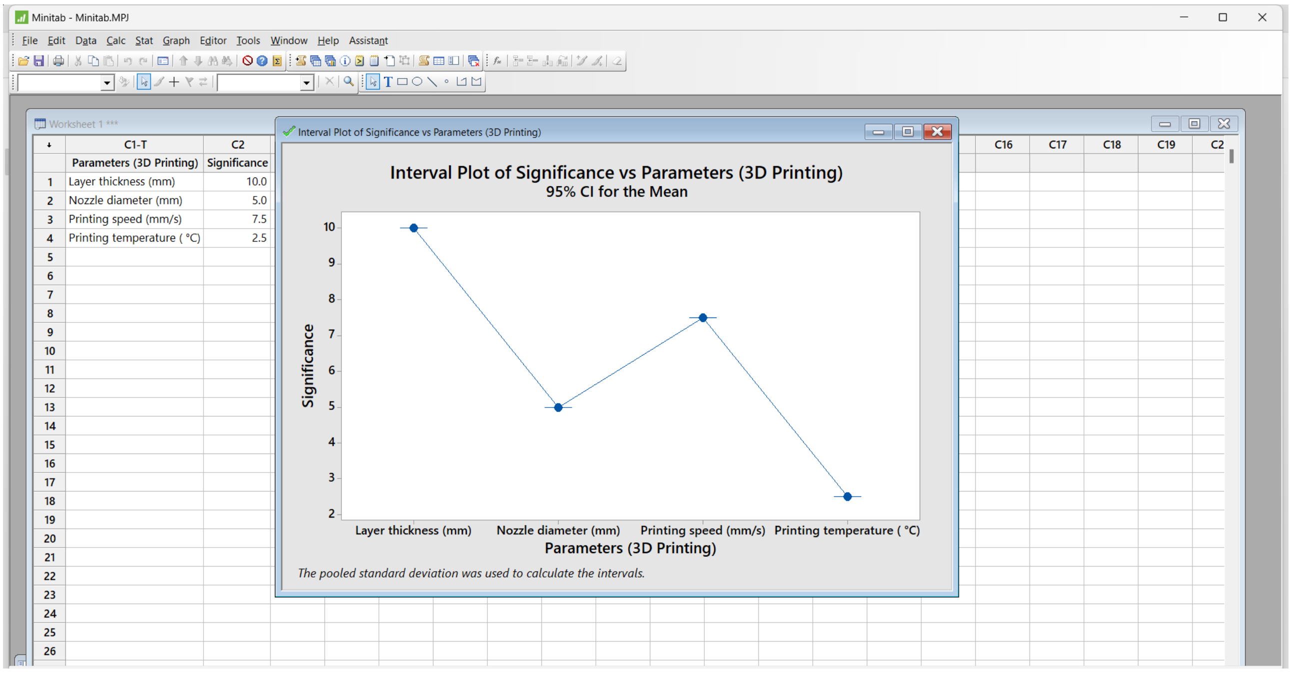

Figure 8. Significance of 3D Printing parameters in Minitab using ANOVA one-way analysis.

4. Evaluation

When Stat → ANOVA → One-way ANOVA analysis is opened in Minitab, the "Response" dialogue box shows significance. Process parameters were provided via the "factor" dialogue box. The Interval Plots of Data Plots are employed in the ANOVA One-way analysis to examine the importance of each manufacturing process.

1) In the injection molding process, four input parameters and four output parameters are taken into account. Based on the findings of the investigation, the following are the order of importance of these input parameters influencing the injection molding process when these four output components are combined:

Injection Speed: This means that changes in injection speed have the most significant impact on the process.

Melt Temperature: Changes in melt temperature are the second most significant factor affecting the process.

Mold Temperature: The temperature of the mold comes next in terms of significance.

Holding Pressure: Holding pressure has the least significant impact among the four input parameters.

An important point is that the order of significance can change under different circumstances or when the output parameters change. This means that in some specific cases or for different types of products, the impact of these input parameters on the process may vary. Therefore, it's crucial for manufacturers to consider the specific requirements of their products and adjust these parameters accordingly to achieve the desired results.

2) The four input parameters and the four output parameters are used in the

extrusion process.

The order of relevance of these input parameters impacting the extrusion process when these four output components are combined is as follows based on the analysis results:

Extrusion Temperature: This is considered the most significant factor affecting the extrusion process, meaning it has the greatest impact on the process.

Screw RPM: The speed of the screw comes next in significance.

Feed Rate: The rate at which material is fed into the machine is the third most significant factor.

L/D Ratio: The length-to-diameter ratio of the extruder screw is the least significant among the input parameters.

The order of significance can change when the output parameters change. In other words, depending on the specific desired characteristics of the extruded product or the material being used, the relative importance of these input parameters may shift. This highlights the importance of considering the specific requirements of a given extrusion process and adjusting the input parameters accordingly to achieve the desired output.

3) The VARTM method takes into consideration four input variables and four output variables. According to the findings of the research, when all four output parameters are evaluated together, the order of significance for the VARTM process appears to be as follows: resin viscosity, resin gel time, fibre volume fraction, fibre orientation.

However, it's important to note that the order of significance can change under different conditions or when the output parameters are adjusted. In other words, if you change the specific goals or requirements of the VARTM process or the desired properties of the final product, the relative importance of these input parameters may shift. This underscores the need for flexibility and adaptability in manufacturing processes to achieve the desired outcomes.

4) The 3D printing method employs four input variables and four output variables. When these four output parameters are added together, the following order of significance influences the 3D printing process: Layer thickness, printing speed, nozzle diameter, printing temperature.

5. Conclusions

The order of relevance of the features impacting the processes in each of these four manufacturing processes is determined through the assessment of the specific output parameters. As a result, the following inferences can be drawn:

The statistical analysis using Minitab's one-way ANOVA indicates that there is a significant influence of the input parameters on the manufacturing processes. The rating scale of 1-10 likely reflects the impact or performance of these processes under different parameter settings. The significance observed in the analysis implies that variations in input parameters have a notable effect on the outcomes, potentially affecting product quality, efficiency, or other relevant factors.

This conclusion suggests that careful consideration and optimization of the input parameters in each manufacturing process are crucial for achieving the desired results. Further investigation and experimentation may be needed to fine-tune these parameters and identify the optimal conditions for each process, leading to improvements in overall manufacturing performance.

In practical terms, this information is crucial for process optimization and quality control. Identifying significant input parameters allows manufacturers to focus on controlling and adjusting those specific factors to enhance the overall manufacturing process. It concludes by noting that the order of significance may change if the output parameters or other conditions change. In other words, depending on different factors or goals (such as different materials, object sizes, or desired qualities), the importance of these input parameters may vary. However, the combination of the parameters of each of the manufacturing processes has a greater impact on the processes.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Gibson, I., Rosen, D. and Stucker, B. (2010) Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. Springer, Berlin, 1-18. https://doi.org/10.1007/978-1-4419-1120-9

[2] Montgomery, D.C. (2017) Design and Analysis of Experiments. John Wiley & Sons, Hoboken, 1-7.

[3] Fisher, R.A. (1935) The Design of Experiments. Oliver and Boyd, London, 11-25.

[4] Box, G.E.P., Hunter, J.S. and Hunter, W.G. (2005) Statistics for Experimenters: Design, Innovation, and Discovery. John Wiley & Sons, Hoboken.

[5] Lee, C.S., Kang, M.K. and Kim, H.S. (2019) Study on Optimization of Injection Molding Process for Reduction of Weld Line in Thin Shell Parts. *Materials Today Communications*, **20**, Article ID: 100566.

[6] Materon, E.M., Karkhanis, S.S. and Pilla, S. (2020) Sustainable Injection Molding: A Review. *Journal of Manufacturing Processes*, **49**, 204-229.

[7] Xiong, H., Lai, X. and Liu, Y. (2017) Recent Advances in Nanocomposites Based on Melt Processable Poly (Lactic Acid). *RSC Advances*, **7**, 25076-25098.

[8] Meng, L., Wang, Y. and Li, L. (2021) Smart Injection Molding: A Comprehensive Review of Research and Applications. *Journal of Manufacturing Processes*, **67**, 856-878.

[9] Tao, W., Kusiak, A. and Li, Y. (2018) A Data-Driven Approach to Energy Efficiency in Injection Molding Processes. *Journal of Manufacturing Science and Engineering*, **140**, Article ID: 071012.

[10] Gao, H., Zhang, Y., Zhou, X., *et al.* (2018) Intelligent Methods for the Process Parameter Determination of Plastic Injection Molding. *Frontiers of Mechanical Engineering*, **13**, 85-95. https://doi.org/10.1007/s11465-018-0491-0

[11] Ferris, T. and Young, B. (2018) Effect of Mold Temperature on Mechanical and Physical Properties. 2018 *Society of Plastics Engineers Annual Technical Conference, ANTEC* 2018, Orlando, 7-10 May 2018.

[12] Chen, W.-C. and Nguyen, M.-H. (2016) Optimization of the Plastic Injection Molding Process Using the Taguchi Method, RSM, and Hybrid GA-PSO. *The International Journal of Advanced Manufacturing Technology*, **83**, 1873-1886. https://doi.org/10.1007/s00170-015-7683-0

[13] Farotti, E. and Natalini, M. (2018) Injection Molding. Influence of Process Parameters on Mechanical Properties of Polypropylene Polymer. A First Study. *Procedia Structural Integrity*, **8**, 256-264. https://doi.org/10.1016/j.prostr.2017.12.027

[14] Stan, D., *et al.* (2008) Influence Factors on the Dimensional Accuracy of the Plastic Parts. *Materiale Plastice*, **45**, 119-124.

[15] Liao, S.J., Hsieh, W.H., Wang, J.T. and Su, Y.C. (2004) Shrinkage and Warpage Prediction of Injection-Molded Thin-Wall Parts Using Artificial Neural Networks. *Polymer Engineering and Science*, **44**, 2029-2040. https://doi.org/10.1002/pen.20206

[16] Kale, H.P. and Hambire, U.V. (2015) Review on Optimization of Injection Molding Process Parameter for Reducing Shrinkage of High Density Polyethylene (HDPE) Material. *International Journal of Science and Research*, **4**, 2847-2850.

[17] Singh, G., Pradhan, M.K. and Verma, A. (2018) Multi Response Optimization of Injection Moulding Process Parameters to Reduce Cycle Time and Warpage. *Materials Today: Proceedings*, **5**, 8398-8405. https://doi.org/10.1016/j.matpr.2017.11.534

[18] Lakshmi, K., Manamalli, D. and Rafiq, M. (2014) Design of Multimodel Based MPC and IMC Control Schemes Applied to Injection Molding Machine. *International Journal of Engineering & Technology*, **3**, 82-92. https://doi.org/10.14419/ijet.v3i2.1844

[19] Karimi-Maleh, H. and Malekfar, R. (2020) Extrusion as a Green and Sustainable Technology for the Production of Bio-Based Materials. *Polymers*, **12**, Article No. 2701.

[20] Kalyon, D., Lu, G., Yilgor, I. and Yilgor, E. (2003) Rheology and Extrusion of Medical-Grade Thermoplastic Polyurethane. *Polymer and Engineering Science*, **43**, 1863-1877.

[21] Boparai, K.S., Singh, R. and Singh, H. (2016) Modeling and Optimization of Extrusion Process Parameters for the Development of Nylon6-Al-Al_2O_3 Alternative FDM Filament. *Progress in Additive Manufacturing*, **1**, 115-128. https://doi.org/10.1007/s40964-016-0011-x

[22] Shenzhen Rapid Direct Co., Ltd. (2004) What Is Plastic Extrusion: A Definitive Process Guide. https://www.rapiddirect.com/blog/plastic-extrusion-process/

[23] Yang, T.-C. (2018) Effect of Extrusion Temperature on the Physi-Co-Mechanical Properties of Unidirectional Wood Fiber-Reinforced Polylactic Acid Composite (WFRPC) Components Using Fused Deposition Modeling. *Polymers*, **10**, Article No. 976. https://doi.org/10.3390/polym10090976

[24] Jones, R. (2002) Design and Analysis of Experiments (Fifth Edition), Douglas Montgomery, John Wiley and Sons, 2001, 684 Pages, £33.95. *Quality and Reliability Engineering International*, **18**, 163. https://doi.org/10.1002/qre.458

[25] GÁLvez, J., *et al.* (2020) Effect of Extrusion Screw Speed and Plasticizer Proportions on the Rheological, Thermal, Mechanical, Morphological and Superficial Properties of PLA. *Polymers*, **12**, Article No. 2111. https://doi.org/10.3390/polym12092111

[26] Bhattacharya, S. and Choudhury, G.S. (1994) Twin-Screw Extrusion of Rice Flour: Effect of Extruder Length-to-Diameter Ratio and Barrel Temperature on Extrusion Parameters and Product Characteristics. *Journal of Food Processing and Preservation*, **18**, 389-406. https://doi.org/10.1111/j.1745-4549.1994.tb00261.x

[27] Ai, J.-R., Peng, F., Joo, P. and Vogt, B.D. (2021) Enhanced Dimensional Accuracy of

Material Extrusion 3D-Printed Plastics through Filament Architecture. *ACS Applied Polymer Materials*, **3**, 2518-2528. https://doi.org/10.1021/acsapm.1c00110

[28] Pan, H. and Sun, X.S. (2003) Effects of Moisture Content and Extrusion Parameters on Tensile Strength of Starch and Poly(Lactic Acid) Blends. *Applied Engineering in Agriculture*, **19**, 573-579. https://doi.org/10.13031/2013.15307

[29] Toshimitsu, M., Okubo, H., Yao, S. and Matsukuma, Y. (2023) Analysing the Relationship between Mechanical Properties and Inner Structure of LLDPE Virgin Film for Optimizing Extrusion Condition. *Journal of Chemical Engineering of Japan*, **56**, Article ID: 2172979. https://doi.org/10.1080/00219592.2023.2172979

[30] Qamar, S.Z., Pervez, T. and Chekotu, J.C. (2018) Die Defects and Die Corrections in Metal Extrusion. *Metals*, **8**, Article No. 380. https://doi.org/10.3390/met8060380

[31] Kumar, A. and Kumar, D. (2022) Vacuum Assisted Resin Transfer Moulding Process Review and Variability Analysis Using Taguchi Optimization Technique. *Materials Today: Proceedings*, **50**, 1472-1479. https://doi.org/10.1016/j.matpr.2021.09.055

[32] Hsiao, K. and Heider, D. (2012) Vacuum Assisted Resin Transfer Molding (VARTM) in Polymer Matrix Composites. In: Advani, S.G. and Hsiao, K.-T., Eds., *Manufacturing Techniques for Polymer Matrix Composites* (*PMCs*), Elsevier, Berlin, 310-347. https://doi.org/10.1533/9780857096258.3.310

[33] Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T.Q. and Hui, D. (2018) Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges. *Composites Part B: Engineering*, **143**, 172-196. https://doi.org/10.1016/j.compositesb.2018.02.012

[34] Lyu, L.-H., Liu, W.-D., Guo, J., Wei, C.-Y., Zhao, Y.-P., *et al.* (2019) Compression Properties of Three-Dimensional I-Shaped Woven Composites with Basalt Fiber Filament Tows. *Journal of Engineered Fibers and Fabrics*, **14**, Article 1558925019884683. https://doi.org/10.1177/1558925019884683

[35] Gibson, R.F. (2016) Principles of Composite Material Mechanics. CRC Press, Boca Raton. https://doi.org/10.1201/b19626

[36] Mazumdar, S.K. (2002) Composites Manufacturing: Materials, Product, and Process Engineering. CRC Press, Boca Raton. https://doi.org/10.1201/9781420041989

[37] Mallick, P.K. (2007) Fiber-Reinforced Composites: Materials, Manufacturing, and Design. 3rd Edition, CRC Press, Boca Raton. https://doi.org/10.1201/9781420005981

[38] Tsai, S.W. (1992) Theory of Composites Design. Think Composites, Dayton.

[39] Flower, H. (1997) An Introduction to Composite Materials—Second Edition D. Hull and T.W. Clyne Cambridge University Press, the Pitt Building, Trumpington Street, Cambridge CB2 IRP. 1996. 326 pp. Illustrated. £19.95. *Journal of the Royal Aeronautical Society*, **101**, 228. https://doi.org/10.1017/S0001924000066410

[40] Thakur, V.K., Thakur, M.K. and Gupta, R.K. (2017) Hybrid Polymer Composite Materials: Processing. Woodhead Publishing, Sawston.

[41] Gibson, R.F. (2007) Principles of Composite Material Mechanics. CRC Press, Boca Raton. https://doi.org/10.1201/9781420014242

[42] KubÁČ, L. and Kodym, O. (2017) The Impact of 3D Printing Technology on Supply Chain. *MATEC Web of Conferences*, **134**, Article No. 00027. https://doi.org/10.1051/matecconf/201713400027

[43] Shaik, Y.P., Schuster, J., Katherapalli, H.R. and Shaik, A. (2022) 3D Printing under High Ambient Pressures and Improvement of Mechanical Properties of Printed Parts. *Journal of Composites Science*, **6**, Article No. 16. https://doi.org/10.3390/jcs6010016

[44] Pipalla, R., Schuster, J. and Shaik, Y.P. (2021) Experimental Analysis on 3D Printed Onyx Specimens with Honeycomb Infill Structure. *Journal of Advanced Material Science Engineering*, **1**, 1-10. https://doi.org/10.33425/2771-666X.1003

[45] Shaik, Y.P., Schuster, J. and Shaik, A. (2021) A Scientific Review on Various Pellet Extruders Used in 3D Printing FDM Processes. *Open Access Library Journal*, **8**, 1-19. https://doi.org/10.4236/oalib.1107698

[46] Shaik, Y.P., Schuster, J. and Chowdary, R. (2020) Impact of 3D Printing Patterns and Post-Consolidation Pressure on Mechanical Properties of FDM Printed Samples. *American Research Journal of Materials Science*, **2**, 1-10.

[47] Gibson, I., Rosen, D. and Stucker, B. (2015) Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Springer, Berlin. https://doi.org/10.1007/978-1-4939-2113-3

[48] Tofail, S.A.M., *et al.* (2018) Additive Manufacturing: Scientific and Technological Challenges, Market Uptake and Opportunities. *Materials Today*, **21**, 22-37. https://doi.org/10.1016/j.mattod.2017.07.001

[49] Ambade, V.V., Rajurkar, S.W. and Awari, G.K. (2023) Optimization of Process Parameters Affecting Performance of Part Characteristics in Fused Deposition Modeling (FDM) 3D Printing: A Critical Review. *AIP Conference Proceedings*, **2800**, Article ID: 020072. https://doi.org/10.1063/5.0162925

[50] Hopkinson, N., Hague, R. and Dickens, P. (2006) Introduction to Rapid Manufacturing. In: Hopkinson, N., Hague, R.J.M. and Dickens, P.M., Eds., *Rapid Manufacturing: An Industrial Revolution for the Digital Age*, John Wiley & Sons Ltd., Hoboken, 1-4. https://doi.org/10.1002/0470033991.ch1

[51] Bourell, D., Kruth, J.P., Leu, M., Levy, G., Rosen, D., Beese, A.M. and Clare, A. (2017) Materials for Additive Manufacturing. *CIRP Annals*, **66**, 659-681. https://doi.org/10.1016/j.cirp.2017.05.009

[52] Al-Ahmari, A., *et al.* (2019) Evaluation of Additive Manufacturing Technologies for Dimensional and Geometric Accuracy. *International Journal of Materials and Product Technology*, **58**, 129-154. https://doi.org/10.1504/IJMPT.2019.10018139

[53] Ahn, S., Montero, M., Odell, D., Roundy, S. and Wright, P.K. (2002) Anisotropic Material Properties of Fused Deposition Modeling ABS. *Rapid Prototyping Journal*, **8**, 248-257. https://doi.org/10.1108/13552540210441166

[54] Zhang, Y., Chou, K., Wu, S. and Zhang, D. (2018) Optimal Process Planning for Reducing 3D Printing Time. *Procedia CIRP*, **68**, 23-28.

[55] Ali, M.H., Abilgaziyev, A. and Adair, D. (2019) 4D Printing: A Critical Review of Current Developments, and Future Prospects. *The International Journal of Advanced Manufacturing Technology*, **105**, 701-717. https://doi.org/10.1007/s00170-019-04258-0

[56] Myers, R.H. and Montgomery, D.C. (2002) Response Surface Methodology: Process and Product Optimization Using Designed Experiments. John Wiley & Sons, Hoboken.

[57] Ryan, T.P. (2017) Modern Experimental Design with Applications Using Minitab. John Wiley & Sons, Hoboken.

[58] Surace, R., *et al.* (2014) Dimensional Accuracy Investigation of Injection Moulded Micro Features. *Proceeding of ICOMM*, 26-28. https://www.researchgate.net/profile/gianluca-trotta-4/publication/265913422_dimension-al_accuracy_investigation_of_injection_moulded_micro_features/links/59dbd144aca2728e201830c2/dimensional-accuracy-investigation-of-injection-moulded-micro-features.pdf

[59] Ravikiran, B., Pradhan, D.K., Jeet, S., Bagal, D.K., Barua, A. and Nayak, S. (2021) Parametric Optimization of Plastic Injection Moulding for FMCG Polymer Moulding (PMMA) Using Hybrid Taguchi-WASPAS-Ant Lion Optimization Algorithm. *Materials Today*: *Proceedings*, **56**, 2411-2420. https://www.sciencedirect.com/science/article/abs/pii/s221478532105642x https://doi.org/10.1016/j.matpr.2021.08.204

[60] Zamani, H., *et al*. (2013) Warpage Characterization of Thin and Centrally-Gated Injection Molded Part by Applying Cavity Pressure Measurement. *Applied Mechanics and Materials*, **446**-**447**, 1099-1103. https://www.scientific.net/amm.446-447.1099 https://doi.org/10.4028/www.scientific.net/AMM.446-447.1099

[61] Hyie, K.M., Budin, S. and Wahab, M. (2019) Effect of Injection Moulding Parameters in Reducing the Shrinkage of Polypropylene Product Using Taguchi Analysis. *IOP Conference Series*: *Materials Science and Engineering*, **505**, Article ID: 012060. https://iopscience.iop.org/article/10.1088/1757-899x/505/1/012060/meta https://doi.org/10.1088/1757-899X/505/1/012060

[62] Thiry, J., Krier, F. and Evrard, B. (2015) A Review of Pharmaceutical Extrusion: Critical Process Parameters and Scaling-Up. *International Journal of Pharmaceutics*, **479**, 227-240. https://doi.org/10.1016/j.ijpharm.2014.12.036

[63] Modugu, S.C.R., Schuster, J. and Shaik, Y.P. (2022) Synthesis and Characterization of Carbon Fiber Nanocomposite Using Titanium Dioxide and Silicon Carbide Nanomaterials. *Journal of Composites Science*, **6**, Article No. 312. https://doi.org/10.3390/jcs6100312

[64] Antony, J. (2023) Design of Experiments for Engineers and Scientists. Elsevier, Amsterdam.

[65] Shaik, Y.P., Schuster, J. and Naidu, N.K. (2023) High-Pressure FDM 3D Printing in Nitrogen [Inert Gas] and Improved Mechanical Performance of Printed Components. *Journal of Composites Science*, **7**, Article No. 153. https://doi.org/10.3390/jcs7040153

[66] Stewardson, D. (2001) Design and Analysis of Experiments Design and Analysis of Experiments 5th Ed by Douglas C Montgomery 2001, John Wiley, New York. Hard-Bound, 684 pp ISBN 0471316490. *MSOR Connections*, **1**, 15-16. https://doi.org/10.11120/msor.2001.01010015a

[67] Shaik, Y.P., Schuster, J., Seemala, S. and Naidu, N.K. (2022) 3D Printing in High Ambient Pressure and Analysis of Parts Printed with Minimum or No Base Support. *SSRG International Journal of Polymer and Textile Engineering*, **9**, 17-24. https://doi.org/10.14445/23942592/IJPTE-V9I2P103

[68] Murugan, R., Mitilesh, R.N. and Singamneni, S. (2019) Influence of Process Parameters on the Mechanical Behaviour and Processing Time of 3D Printing. *The International Journal of Modern Manufacturing Technologies*, **1**, 21-27.

[69] Wang, Y.Q., *et al*. (2021) Mechanical Properties of Fused Filament Fabricated PEEK for Biomedical Applications Depending on Additive Manufacturing Parameters. *Journal of the Mechanical Behavior of Biomedical Materials*, **115**, Article ID: 104250. https://doi.org/10.1016/j.jmbbm.2020.104250 https://www.sciencedirect.com/science/article/abs/pii/s175161612030789x

[70] El Magri, A., *et al*. (2020) Optimization of Printing Parameters for Improvement of Mechanical and Thermal Performances of 3D Printed Poly(Ether Ether Ketone) Parts. *Journal of Applied Polymer Science*, **137**, 49087. https://doi.org/10.1002/app.49087

[71] Strano, M., Rane, K., Herve, G. and Tosi, A. (2019) Determination of Process-Induced

Dimensional Variations of Ceramic Parts, 3D Printed by Extrusion of a Powder-Binder Feedstock. *Procedia Manufacturing*, **34**, 560-565. https://www.sciencedirect.com/science/article/pii/s2351978919309503 https://doi.org/10.1016/j.promfg.2019.06.220

[72] Alsoufi, M.S. and Elsayed, A.E. (2018) Surface Roughness Quality and Dimensional Accuracy—A Comprehensive Analysis of 100% Infill Printed Parts Fabricated by a Personal/Desktop Cost-Effective FDM 3D Printer. *Materials Sciences and Applications*, **9**, 11-40. https://doi.org/10.4236/msa.2018.91002

[73] Salem, I.H. (2022) Multi-Objective Optimization on Dimensional Accuracy, Edge and Surface Quality of 3D-Printed Parts by Fused Deposition Modelling. Master's Thesis, The American University, Cairo. https://fount.aucegypt.edu/etds/1881/

[74] Elkaseer, A., Schneider, S. and Scholz, S.G. (2020) Experiment-Based Process Modeling and Optimization for High-Quality and Resource-Efficient FFF 3D Printing. *Applied Sciences*, **10**, Article No. 2899. https://www.mdpi.com/2076-3417/10/8/2899 https://doi.org/10.3390/app10082899

[75] Smith, D.M., *et al.* (2018) Pharmaceutical 3D Printing: Design and Qualification of a Single Step Print and Fill Capsule. *International Journal of Pharmaceutics*, **544**, 21-30. https://www.sciencedirect.com/science/article/abs/pii/s0378517318302035 https://doi.org/10.1016/j.ijpharm.2018.03.056

[76] Sonsalla, T., *et al.* (2018) 3-D Printer Settings Effects on the Thermal Conductivity of Acrylonitrile Butadiene Styrene (ABS). *Polymer Testing*, **70**, 389-395. https://www.sciencedirect.com/science/article/abs/pii/s0142941818305919 https://doi.org/10.1016/j.polymertesting.2018.07.018

[77] Singh, J., Goyal, K.K., Kumar, R. and Gupta, V. (2022) Influence of Process Parameters on Mechanical Strength, Build Time, and Material Consumption of 3D Printed Polylactic Acid Parts. *Polymer Composites*, **43**, 5908-5928. https://doi.org/10.1002/pc.26849