CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 3D PRINTING

3D printing, also known as additive manufacturing, is a process that creates three-dimensional physical objects from a digital design by building them layer by layer from materials such as plastics, metals, or resins. Unlike traditional manufacturing, which typically removes material from a solid block (subtractive manufacturing), 3D printing adds material only where needed, allowing for the efficient creation of complex and intricate shapes

There are several types of 3D printing technologies, including **Fused Deposition Modeling (FDM)**, **Stereolithography (SLA)**, and **Selective Laser Sintering (SLS)**, each with its unique materials and applications. FDM is the most accessible and is commonly used for plastics, making it popular in education, hobbyist, and prototype development settings. SLA offers high precision and smooth surface finishes using liquid resins, while SLS is ideal for industrial-grade parts, using powdered materials and lasers for fusion.

The impact of 3D printing spans across industries from healthcare, where it enables custom prosthetics and bioprinting, to aerospace and automotive sectors, where it supports lightweight, functional parts with rapid prototyping. Sustainability is also a growing focus, as 3D printing can reduce material waste and promote local, on-demand production. As the technology evolves, innovations in materials, speed, and multi-material printing continue to expand its potential in both commercial and creative fields.

Fig 1.1: 3D Printing Machine

1.2 CLASSIFICATION OF 3D PRINTING:

1.2.1. Polymer-Based 3D Printing

Materials Used:

- **Thermoplastics**: Polymers that become soft and pliable when heated and harden upon cooling.
- **Photopolymers**: Liquids that harden when exposed to light (usually UV).

Methods:

- **Fused Deposition Modeling (FDM) / Fused Filament Fabrication (FFF)**
  - **Materials**: Thermoplastic filaments
  - **Examples**: PLA, ABS, PETG, TPU, Nylon, PC
- **Stereolithography (SLA)**
  - **Materials**: Photopolymer resins (UV-cured)
  - **Examples**: Standard resins, tough resins, flexible resins, castable resins
- **Digital Light Processing (DLP)**
  - **Materials**: Photopolymer resins (UV-cured)
  - **Examples**: Various UV-curable resins (standard, flexible, and dental resins)
- **Selective Laser Sintering (SLS)**
  - **Materials**: Thermoplastic powders
  - **Examples**: Nylon (PA 12), TPU, polyamide
- **Material Jetting (MJ)**
  - **Materials**: Photopolymer resin (liquid form)
  - **Examples**: UV-curable resins

1.2.2. Metal-Based 3D Printing

Materials Used:

- **Metal Powders**: Materials in fine powder form, including stainless steel, titanium, aluminium, etc.
- **Metal Wire**: A feedstock material used in some methods.

Methods:

- **Selective Laser Melting (SLM) / Direct Metal Laser Sintering (DMLS)**
  - **Materials**: Metal powders
  - **Examples**: Titanium, stainless steel, Inconel, aluminum
- **Electron Beam Melting (EBM)**
  - **Materials**: Metal powders

    - **Examples**: Titanium alloys (Ti6Al4V), cobalt-chrome alloys
- **Binder Jetting (Metal)**
    - **Materials**: Metal powder and binding agent
    - **Examples**: Stainless steel, bronze, aluminium
- **Directed Energy Deposition (DED)**
    - **Materials**: Metal powder or wire
    - **Examples**: Titanium, stainless steel, Inconel

1.2.3. Ceramic-Based 3D Printing

Materials Used:

- **Ceramic Powder**: Fine ceramic materials, such as alumina, zirconia, and porcelain.
- **Ceramic Slurry**: A mixture of ceramic powders and liquids used for printing.

Methods:

- **Binder Jetting (Ceramic)**
    - **Materials**: Ceramic powder mixed with a binder
    - **Examples**: Alumina, zirconia, porcelain
- **Stereolithography (SLA) with Ceramic Materials**
    - **Materials**: Ceramic-filled photopolymer resins
    - **Examples**: Alumina, zirconia

1.2.4. Composite and Hybrid Materials 3D Printing

Materials Used:

- **Reinforced Polymers**: Polymers mixed with fibres (e.g., carbon fibre, glass fibre) or particles (e.g., metal, ceramic).

Methods:

- **FDM with Composite Filaments**
    - **Materials**: Polymers reinforced with fibres or particles
    - **Examples**: Carbon Fiber-infused PLA, Nylon, Glass Fiber, Wood-filled PLA
- **Continuous Fiber Fabrication (CFF)**
    - **Materials**: Polymers combined with continuous reinforcement fibres
    - **Examples**: Carbon Fiber, Kevlar, Glass Fiber

1.2.5. Bio-Based & Food 3D Printing

Materials Used:

- **Bioinks**: Composed of living cells, hydrogels, and biomaterials for medical and bioprinting applications.

- **Edible Materials**: Food-based materials like chocolate, dough, and cheese.

Methods:

- **Bioprinting**
  - **Materials**: Bioinks (living cells, bio-materials)
  - **Examples**: Hydrogels, living cells, extracellular matrix
- **Food 3D Printing**
  - **Materials**: Edible substances
  - **Examples**: Chocolate, dough, pureed foods, cheese, sugar

1.2.6 Applications Of 3d Printing

a) Manufacturing and Prototyping
b) Medical and Healthcare
c) Automotive and Aerospace
d) Consumer Products and Fashion
e) Architecture and Construction
f) Education and Research
g) Art, Entertainment, and Gaming
h) Robotics and Electronics
i) Environmental and Humanitarian

1.3 FUSED DEPEOSITION MODELING [FDM]

Fused Deposition Modelling (FDM) is one of the most popular and widely used 3D printing technologies. It is part of the material extrusion category of additive manufacturing processes. It works by extruding a thermoplastic filament through a heated nozzle, layer by layer, to build an object from the bottom up.

The process begins with a **3D digital model** of the object, typically created using computer-aided design (CAD) software. This model is then sliced into thin horizontal layers, and the printer uses this data to construct the object layer by layer. The FDM printer uses a heated **extruder** to melt a thermoplastic filament, such as PLA, ABS, PETG, or TPU. The filament is then extruded through a small nozzle, which precisely deposits the melted material onto the **build platform** or print bed.

As the material cools and solidifies, it forms a layer, and the printer moves the extruder along the specified path, creating the next layer. This process is repeated continuously until the part is fully built. The material used in FDM printing comes in the form of spooled filament, which is available in various diameters, typically 1.75 mm or 2.85 mm, and a wide range of colours and material types. The printer's movement is controlled by motors and precise software algorithms that ensure high accuracy in layer deposition and alignment. The **print bed** may be heated to improve adhesion and reduce warping, particularly when printing with materials like ABS that tend to shrink as they cool.

FDM offers significant flexibility in terms of customization, with the ability to adjust print settings such as **layer height**, **infill density**, **print speed**, and **temperature** to achieve the desired balance between strength, speed, and surface quality. The infill density affects the internal structure and strength of the part, while the layer height controls the print resolution—thinner layers result in finer details, but longer print times. One of the key advantages of FDM is its ability to produce functional prototypes, complex geometries, and end-use parts, making it a preferred choice for industries such as automotive, aerospace, and medical devices. While it may not achieve the same level of surface smoothness as some other methods like SLA, the practicality and versatility of FDM make it an indispensable tool in modern manufacturing and prototyping.

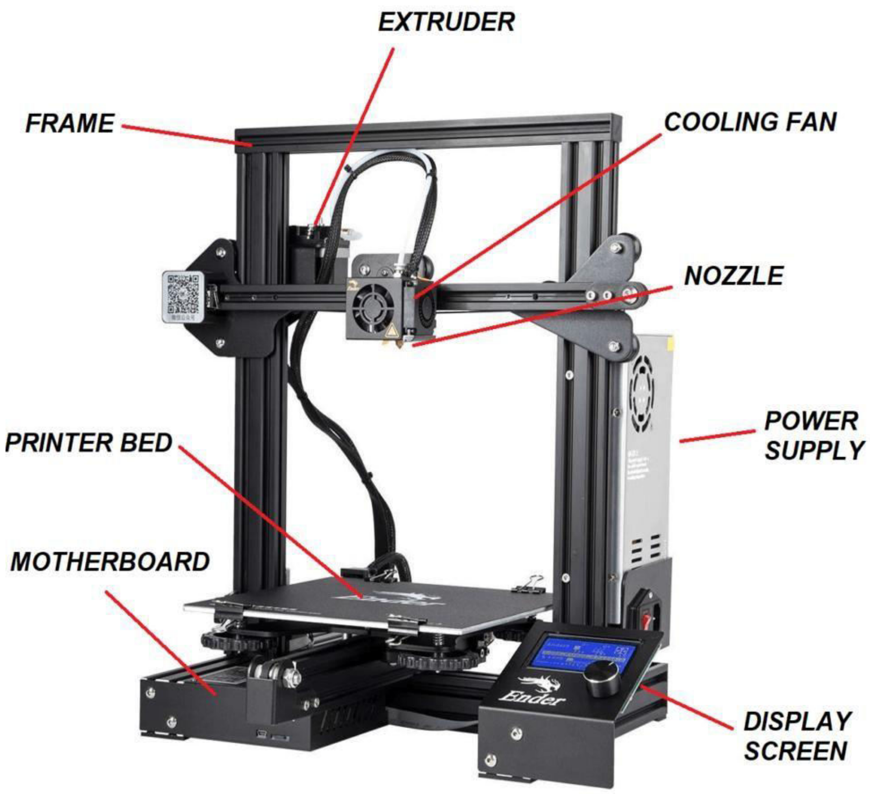

Fig 1.2: FDM 3D Printer

optimizing key FDM 3D printing parameters specifically infill density, print speed, and layer thickness—to understand how they affect the final properties of printed parts. To do this efficiently and scientifically, Design of Experiments (DoE) provides the perfect framework.

Instead of changing one variable at a time and running countless print trials, DoE allows you to study all the parameters together, analyze their individual and combined effects, and determine the optimal settings all with fewer experiments and more powerful insights.

1.3.1 Advantages of FDM Process

a) Cost-Effective
b) Easy to Use
c) Wide Range of Materials
d) Environmentally Friendly Options
e) Customizable and Scalable
f) Low Material Waste
g) Ideal for Rapid Prototyping

1.3.2 Disadvantages of FDM Process

a) Surface Finish and Resolution
b) Lower Dimensional Accuracy
c) Mechanical Weakness in Z-Direction
d) Slower Printing Speed
e) Limited Material Properties
f) Support Structures May Be Needed

1.3.3 Applications of FDM Process:

a) Prototyping
b) Educational Models
c) Custom Jigs and Fixtures
d) Medical Application
e) Consumer Products
f) Automotive and Aerospace
g) Architecture and Design

1.4 DESIGN OF EXPERIMENTS

Design of Experiments (DoE) is a systematic and statistical approach used to plan, conduct, and analyze experiments in order to understand the relationship between input factors (also called independent variables) and the resulting output or response (dependent variables). The goal of DoE is to identify which factors influence the outcome of a process or product, how they interact, and what combination of settings leads to optimal performance.

Detailed Explanation of DoE:

In any process whether it's in manufacturing, engineering, agriculture, or science there are usually several variables that can affect the final result. For example, in a 3D printing process, parameters like print speed, layer thickness, and infill density can all influence the quality of the printed part. DoE helps investigate how each of these parameters affects the outcome, both individually and in combination with others.

Unlike traditional methods where one variable is changed at a time (known as "one-factor-at-a-time" or OFAT), DoE allows multiple variables to be changed together in a structured way. This makes the process more efficient and provides much more information about how the system behaves. It also helps identify **interactions** cases where the effect of one variable depends on the level of another.

The **Taguchi L9 orthogonal array method** is a specialized technique **within the broader framework of Design of Experiments (DoE)**. While DoE refers to a wide range of systematic approaches used to plan, conduct, and analyze experiments to understand the influence of multiple variables on a given outcome, the Taguchi method provides a **simplified and structured way to apply DoE**, especially when resources are limited.

1.5 TAGUCHI L9 ORTHOGONAL ARRAY METHOD

The **Taguchi Method** is a statistical approach developed by **Dr. Genichi Taguchi** to improve the quality of manufactured goods through robust design. It focuses on:

- Reducing variation and defects
- Making the process/product less sensitive to noise (uncontrollable factors)
- Optimizing performance with minimal resources

- The **L9 orthogonal array** is one of the most commonly used Taguchi designs. It allows to study **3 factors** at **3 levels each** with just **9 experiments**, instead of 27 required in a full factorial design.

How to Use the L9 Array in an Experiment:

- **Assign real values** to each level of each factor (as shown above).
- **Conduct 9 experiments** according to the L9 table.
- **Measure the response** (e.g., tensile strength, flexural strength).
- **Analyze the data** using:
  - **Signal-to-Noise (S/N) Ratio**: To measure performance stability and identify optimal levels.
  - **Main Effects Plots**: To visualize which levels give the best results.
- **Determine the optimal factor levels** for the best performance with minimum variation.

1.5.1 Applications of Taguchi L9 Orthogonal Array Method

- Product Design Optimization
- Manufacturing Process Optimization
- Chemical and Process Engineering
- Electronics and Semiconductor Manufacturing
- Quality Control & Six Sigma Projects
- Material Science & Mechanical Testing
- Software & System Performance Tuning

The **Taguchi L9 Orthogonal Array** is a practical and efficient method in DoE, especially useful for optimizing processes like 3D printing. By using just 9 well-planned experiments, you can uncover the optimal combination of parameters, reduce variation, and improve quality—all without the need for complex statistics or large resources.

CHAPTER 2

LITERATURE REVIEW

2.1 Summary

An innovation in any field requires a proper study of existing. This helps in understanding various current technologies, the precision, the advantages and disadvantages. The following are the list of relevant published, patented and unpublished research around the world.

Yash Magdum, et all (2019) [1], Fused Deposition Modeling (FDM) is an efficient 3D printing method used to create solid parts with less time and human effort. Key parameters like layer thickness, shell thickness, and fill density significantly affect the mechanical properties of printed parts, such as surface roughness, hardness, and tensile strength. This paper focuses on optimizing these parameters to improve both manufacturing time and part quality. A clear methodology is provided, and experimental results show that proper adjustment of these settings leads to better performance and efficiency in 3D printing.

Patrich Ferretti, et all (2021) [2], Research on 3D printing, particularly Fused Deposition Modeling (FDM), highlights the need to better understand how printing parameters like speed, temperature, and layer height affect quality and defect rates, as current studies often treat these factors separately. The goal is to optimize these parameters to make FDM reliable for industrial manufacturing, not just prototyping. Similarly, Sara Valvez et al. (2021) worked on optimizing the printing conditions for PETG and its fibre-reinforced composites (with carbon and aramid fibres) using the Taguchi method and ANOVA. They found that specific extrusion temperatures, printing speeds, layer heights, and a 100% infill density significantly improved the bending strength of printed parts, showing how precise control of printing settings can enhance material performance and expand their industrial use.

Manav Doshi, et all (2022) [3], Additive Manufacturing, especially Fused Deposition Modelling (FDM), plays a key role in the fourth industrial revolution due to its wide use and flexibility. With a focus on sustainability, this article reviews how key printing parameters—like layer thickness, infill density and pattern, printing speed, build orientation, and raster angle—affect the mechanical properties of FDM parts, including tensile strength, stress, and

Young's modulus. It also provides detailed insights into the materials used in FDM and how different settings influence strength and performance.

S. Raja, et all (2022) [4], The main objective of this research study is to optimize the printing parameters that can be used in the FDM (fusion deposition modeling) production method to obtain the lowest production time and best printing parameter of PLA (polylactic acid) ‹lament with the tensile test.-e printing parameter that can be used in FDM machines such as extruder temperature, bed temperature, layer height, printing speed, travel speed, infill, and shell count is taken into account for optimization. In addition, the tensile specimens from ASTM (American Society for Testing and Materials) D638 standard were manufactured by PLA filament with the above modified printing parameters. The best printing parameters for PLA products were found by the time recorded during production and tensile test results after production. Thus, through this research, one can find the best PLA filament printing parameters and their timing.

Sara Valvez, et all (2022) [5], Fused filament fabrication (FFF) is a widely used 3D printing method that produces complex parts with minimal waste. Polyethylene terephthalate glycol (PETG) is increasingly popular due to its chemical resistance and mechanical strength, and when reinforced with fibres like carbon (CF) or aramid (KF), its applications broaden further. To ensure and enhance the performance of PETG and its composites, this study focused on optimizing key printing parameters—nozzle temperature, printing speed, layer height, and infill density—using the Taguchi method and an L16 orthogonal array. Bending properties were evaluated through ANOVA at a 95% confidence level. Results showed the best bending performance for PETG, PETG+CF, and PETG+KF was achieved at nozzle temperatures of 265°C, 195°C, and 265°C; printing speeds of 20, 60, and 20 mm/s; layer heights of 0.4, 0.53, and 0.35 mm; and 100% infill density for all materials.

M. Mani, et all (2022) [6], 3D printing and rapid prototyping are significantly shaping modern manufacturing by offering affordable and accessible solutions. With growing industry demand, there is a need to optimize key printing parameters for mass production. This study focuses on adjusting layer thickness (0.15–0.35 mm), nozzle temperature (210–220°C), and infill density (55–65%) using PLA material, printed via Fused Deposition Modeling (FDM). Specimens are designed following ASTM standards and printed using a Taguchi Orthogonal Array to systematically vary the parameters. Surface roughness, tensile strength, and hardness tests are then conducted to identify the optimal printing settings.

Nor Aiman Sukindar, et all (2024) [7], This study investigates how printing parameters—layer thickness, infill density, and printing speed—affect the tensile and structural properties of PETG carbon fibre parts made by FDM. Using an L9 (3^3) orthogonal array, nine sets of prints were produced, with three samples each for accuracy. Tensile tests and SEM analysis were performed, followed by ANOVA to identify key factors. Results showed that infill density had the greatest impact on tensile strength, with 80% infill giving the best results by minimizing air gaps and enhancing structural solidity. The optimal printing settings were a 0.4 mm layer thickness, 80% infill density, and a 30 mm/s printing speed.

Sabrine Chahdoura, et all (2024) [8], This study explores the optimization of mechanical properties in PLA parts printed using FDM/FFF technology by analyzing key parameters—layer thickness, infill density, raster angle, and printing speed. Using response surface methodology and gray relational analysis, the research minimizes experimental runs while identifying the impact of each parameter on tensile strength, flexural strength, and Young's modulus. Results show raster angle and infill density are the most influential. The optimal settings found were 0.1 mm layer thickness, 100% infill density, 0° raster angle, and 40 mm/s speed. Validation confirmed the effectiveness of these settings, showing comparable performance to industrial mold-injected parts, with potential for broader application in additive manufacturing.

Valentina Vendittoli, Wilma Polini & Michael S. J. Walter (2025) [9], This study presents a method using Response Surface Methodology and composite desirability to optimize both dimensional accuracy and mechanical strength in 3D-printed parts. Focusing on PLA components made with Fused Filament Fabrication, the optimized settings 80 mm/s print speed, 0.2 mm layer height, 50% fan speed, and 210°C extrusion temperature achieved a tensile strength of 53.27 MPa and dimensional errors under 5%. Experimental results closely matched predictions, proving the method's reliability. The research highlights the importance of multi-response optimization for improving quality and efficiency in industrial 3D printing applications like gear manufacturing.

CHAPTER 3
PROBLEM DEFINITION

Fused Deposition Modeling (FDM) is a popular additive manufacturing technique known for its affordability, simplicity, and material versatility. However, the quality of printed parts can often be inconsistent, affecting surface finish, dimensional accuracy, and mechanical strength. This variability is largely influenced by three key process parameters: infill density, print speed, and layer thickness. Despite the widespread use of materials like PLA and ABS many users rely on trial-and-error or default printer settings, which don't consider the unique properties of each material or how different parameters interact with one another. As a result, the findings of past research, which often focus on individual parameters, are not always applicable across different materials.

To address these challenges, a more systematic, data-driven approach is needed. This approach would optimize the FDM process parameters for each material type, ensuring consistent print quality, minimizing material waste, and reducing print time. The goal of this study is to determine the optimal settings for PLA and ABS through experimental analysis and statistical tools.

The project will focus on optimizing FDM process parameters using the Taguchi L9 Orthogonal Array, which considers parameters such as infill density, layer thickness, and print speed. By systematically adjusting these variables for different materials, the optimization process will minimize the number of tests needed and help achieve the best possible results for each material type and application. This approach aims to enhance print quality, reduce material waste, and streamline the overall printing process.

Objectives:

1. To investigate the individual effects of layer thickness, infill density, and printing speed on the mechanical properties (e.g., tensile strength and flexural strength) of FDM-printed parts.
2. To identify the optimal combination of the four parameters for maximizing part strength while minimizing material usage and print time.
3. To maximize the production rate and mechanical properties.

CHAPTER 4

METHODOLOGY

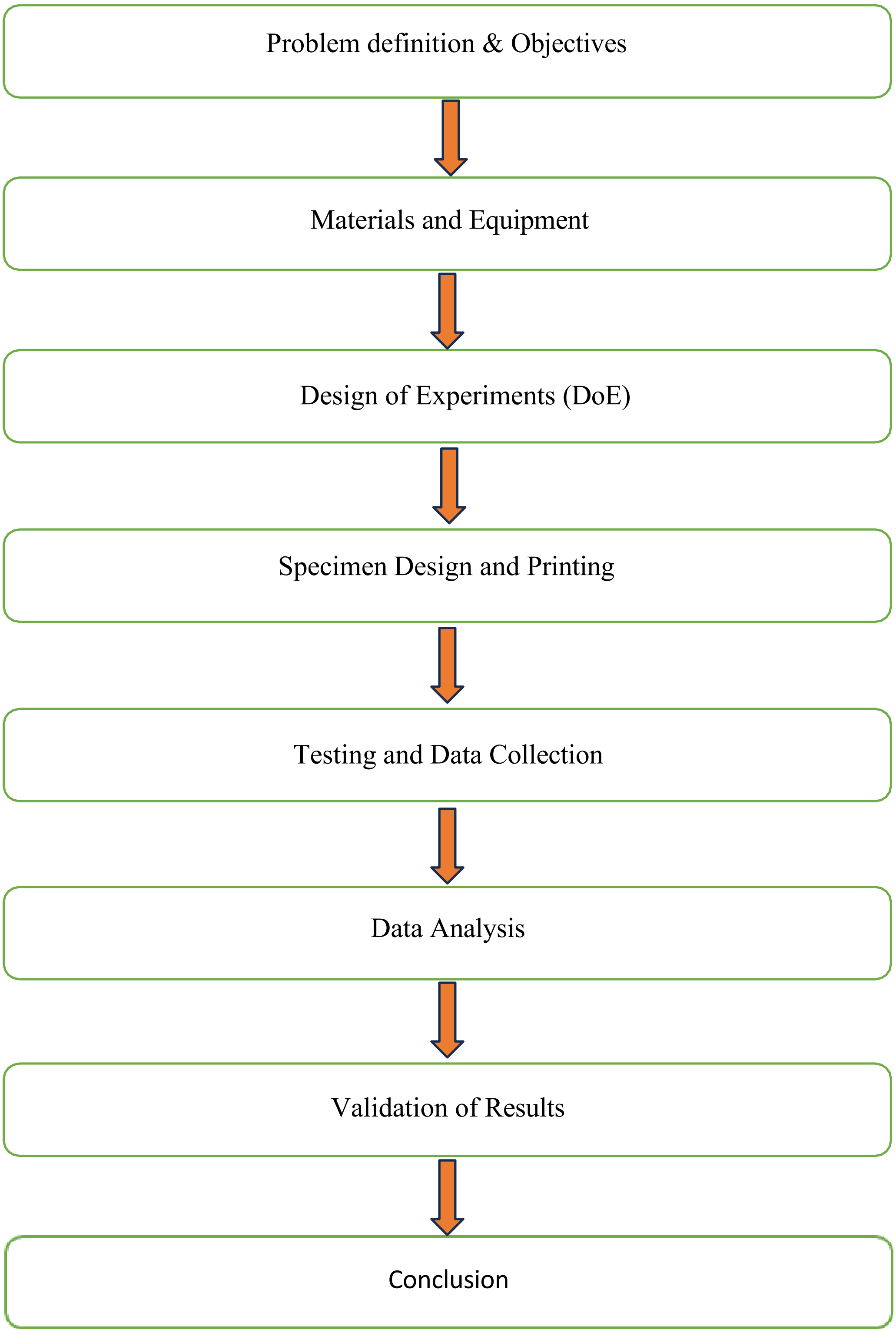

Fig.4.1. Methodology Chart

CHAPTER 5
MATERIALS AND METHODS

The experiment was designed to evaluate the mechanical properties (Tensile Strength and Flexural Strength) of 3D printed parts using PLA and ABS materials. The setup was configured to optimize FDM (Fused Deposition Modeling) process parameters, namely layer thickness, infill density, and printing speed. Here’s a quick breakdown of the experimental setup:

5.1 MATERIALS USED

5.1.1 PLA (Polylactic Acid)

PLA is a biodegradable thermoplastic made from renewable resources like cornstarch or sugarcane. It’s one of the most commonly used materials in FDM (Fused Deposition Modeling) 3D printing due to its ease of use, environmental friendliness, and relatively low cost. **PLA** (Polylactic Acid) is a biodegradable, eco-friendly thermoplastic made from renewable resources such as cornstarch or sugarcane, making it one of the most popular materials for 3D printing. The image of PLA material, where shown in figure 5.1.

Fig 5.1: PLA FILAMENT

5.1.2 ABS (Acrylonitrile Butadiene Styrene)

ABS is a petroleum-based thermoplastic widely used in industrial and commercial 3D printing applications. It is known for its strength, durability, and heat resistance compared to PLA, making it suitable for more demanding engineering parts.

ABS (Acrylonitrile Butadiene Styrene) is a versatile, petroleum-based thermoplastic known for its excellent mechanical properties, including high **impact resistance**, **strength**, and **durability**. It is commonly used in 3D printing for parts that require toughness and resistance to physical stress, making it ideal for applications like **automotive components**, **electronic housings**, **toys (such as LEGO bricks)**, and **functional prototypes**. The image of PLA material, where shown in figure 5.2. The properties of the PLA & ABS, where shown in Table 5.1.

Fig:5.2: ABS FILAMENT

Table.5.1 The properties of PLA and ABS materials

Property	PLA	ABS
Tensile Strength	Moderate (40-70 MPa)	Higher (40-60 MPa)
Flexural Strength	Good (60-100 MPa)	Very good (80-100 MPa)
Impact Resistance	Low (brittle)	High (tough and resilient)
Melting Point	180°C - 220°C	220°C - 250°C
Glass Transition Temp (Tg)	50°C - 60°C	105°C
Environmental Impact	Biodegradable, eco-friendly	Not biodegradable, less eco-friendly
Ease of Printing	Easy, no heated bed needed	Difficult, requires heated bed
Applications	Decorative items, prototypes	Functional parts, automotive, tools

5.2. MACHINES USED:

5.2.1. BAMBU LAB A1 (FDM-based 3D printer).

In this study, the BAMBOO LAB A1 (FDM-based 3D printer) was used to produce the experimental components using PLA and ABS materials. Figure 5.3 shows the BAMBOO LAB A1 machine.

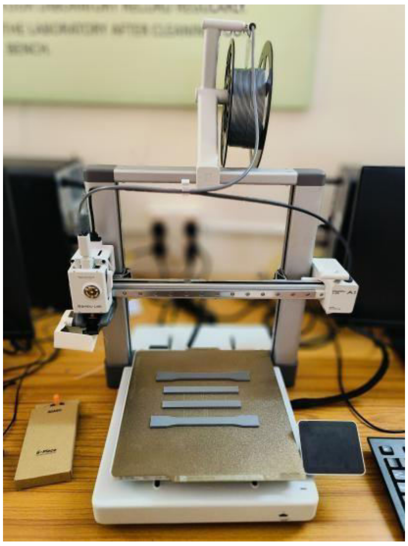

Fig.5.3. BAMBU LAB A1 (3D Printer)

5.2.2. Tensile and Flexural strength measurements:

A Universal Testing Machine (UTM) was employed to perform both tensile and flexural strength tests on the 3D-printed components. The specific model of the testing machine was the ZY2075A, which has a maximum load capacity of 100 KN is shown in figure 5.4. This machine facilitated precise measurement of the mechanical properties of the samples fabricated using PLA and ABS materials. After printing, the samples were subjected to mechanical testing:

- Tensile Strength Test: The samples were stretched to measure their resistance to pulling forces (according to ASTM D638). The test specimen where, shown in Figure 5.5.
- Flexural Strength Test: The samples were bent to determine their ability to resist deformation under bending loads (according to ASTM D790). The test specimen where, shown in Figure 5.6.

Fig.5.4.100 KN UTM (Model: ZY2075A)

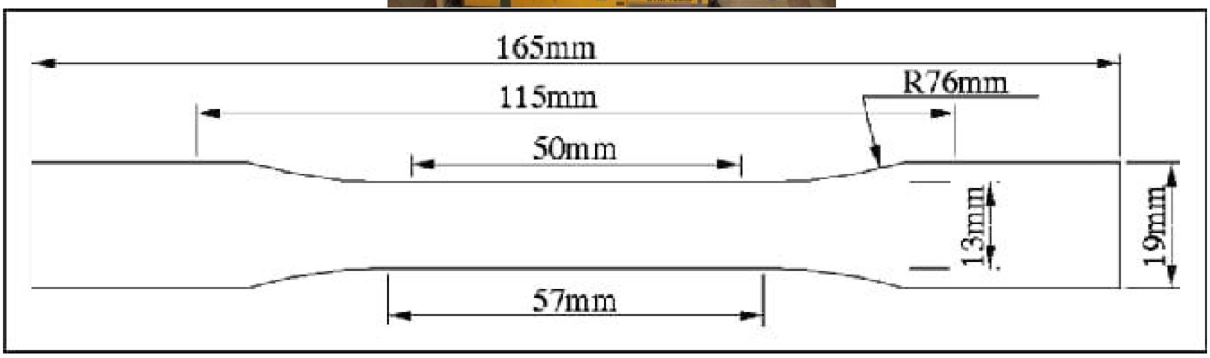

Fig.5.5. Dog Bone Structure for Tensile testing. (ASTM D638)

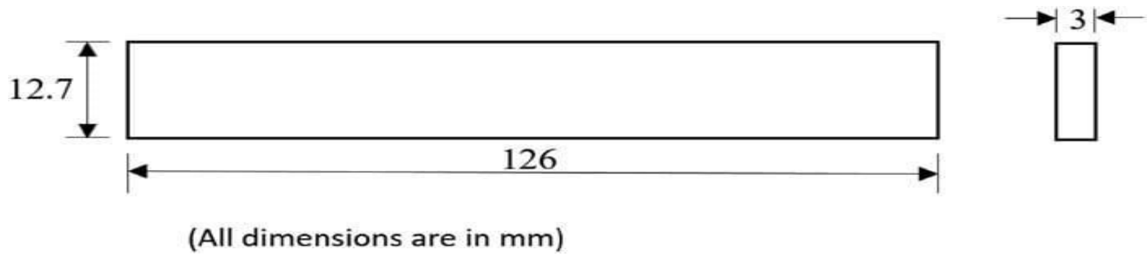

Fig.5.6. Simple Rectangular Piece for flexural Strength (ASTM D790)

5.3. DESIGN OF EXPERIMENTATION:

In this experiment, to enhance the tensile and flexural strengths of 3D printed PLA and ABS parts by adjusting the layer thickness, infill density, printing speed and Infill pattern. The above input parameters are selected each at three levels as shown in table 5.2. According to the Taguchi quality design L9 orthogonal array table was created and subsequent analysis, the best parameter combinations were determined, significantly improving the mechanical properties while maintaining efficient printing processes. By using Design Expert, software the Taguchi quality design L9 orthogonal array was created and are shown in table 5.3.

Table.5.2. Process parameters and their control factor levels used in the experiments.

Factor	Level 1	Level 2	Level 3
Layer Thickness	0.15 mm	0.20 mm	0.25 mm
Infill Density	20%	50%	80%
Printing Speed	30 mm/s	60 mm/s	90 mm/s
Infill Pattern	Rectilinear	Triangle	Honeycomb

Table 5.3: Taguchi's L9 Orthogonal Array

Standard order	Run order	Layer thickness (mm)	Infill density (%)	Printing speed(mm/s)	Infill pattern
5	1	0.2	50	90	Rectilinear
2	2	0.15	50	60	Triangle
6	3	0.2	80	30	Triangle
3	4	0.15	80	90	Honeycomb
9	5	0.25	80	60	Rectilinear
1	6	0.15	20	30	Rectilinear
4	7	0.2	20	60	Honeycomb
7	8	0.25	20	90	Triangle
8	9	0.25	50	30	Honeycomb

5.4. Statistical Analysis

The statistical analysis conducted in this study includes Analysis of Variance (ANOVA) and Taguchi multi-objective optimization technique (Desirability function method). These methods were employed to identify the optimal set of Fused Deposition Modeling (FDM) process parameters—namely, layer thickness, infill density, printing speed, and infill pattern—that significantly influence the mechanical properties (tensile and flexural strength) of the 3D-printed components.

CHAPTER 6

RESULTS AND DISCUSSION

This section presents the findings from the mechanical testing and statistical analysis performed on the 3D-printed components fabricated using the BAMBOO LAB A1 FDM printer with PLA and ABS materials.

6.1 MECHANICAL TESTING RESULTS

Tensile and flexural tests were conducted using the ZY2075A Universal Testing Machine with a maximum capacity of 100 kN. The results indicated that both material type and printing parameters significantly affected the mechanical strength of the printed samples.

6.1.1. Tensile and Flexural tests of PLA:

The PLA test specimens before and after tensile and flexural test, where shown in figure 6.1. (a) & (b). and the test results are tabulated in table 6.1.

Table. 6.1: Tensile and Flexural strengths of PLA

Standard order	Run order	Layer thickness (mm)	Infill density (%)	Printing speed(mm/s)	Infill pattern	Tensile Strength MPa	Flexural Strength MPa
5	1	0.2	50	90	Rectilinear	26.48	48.41
2	2	0.15	50	60	Triangle	22.57	34.33
6	3	0.2	80	30	Triangle	28.98	60.71
3	4	0.15	80	90	Honeycomb	31.65	54.16
9	5	0.25	80	60	Rectilinear	28.55	59.28
1	6	0.15	20	30	Rectilinear	21.09	42.07
4	7	0.2	20	60	Honeycomb	22.79	61.20
7	8	0.25	20	90	Triangle	24.14	61.89
8	9	0.25	50	30	Honeycomb	26.12	56.00

Fig.6.1. (a) PLA Test specimens before tensile and flexural test

Fig.6.1. (b) PLA Test specimens after tensile and flexural test

6.1.2. Tensile and Flexural tests of ABS:

The ABS test specimens before and after tensile and flexural test, where shown in figure 6.2. (a) & (b). and the test results are tabulated in table 6.2.

Table. 6.2: Tensile and Flexural strengths of ABS

Standard order	Run order	Layer thickness (mm)	Infill density (%)	Printing speed(mm/s)	Infill pattern	Tensile Strength MPa	Flexural Strength MPa
5	1	0.2	50	90	Rectilinear	34.03	22.57
2	2	0.15	50	60	Triangle	39.41	21.53
6	3	0.2	80	30	Triangle	39.07	23.22
3	4	0.15	80	90	Honeycomb	46.9	26.11
9	5	0.25	80	60	Rectilinear	41.02	26.43
1	6	0.15	20	30	Rectilinear	34.92	18.43
4	7	0.2	20	60	Honeycomb	40.80	16.75
7	8	0.25	20	90	Triangle	40.76	21.34
8	9	0.25	50	30	Honeycomb	48.30	23.24

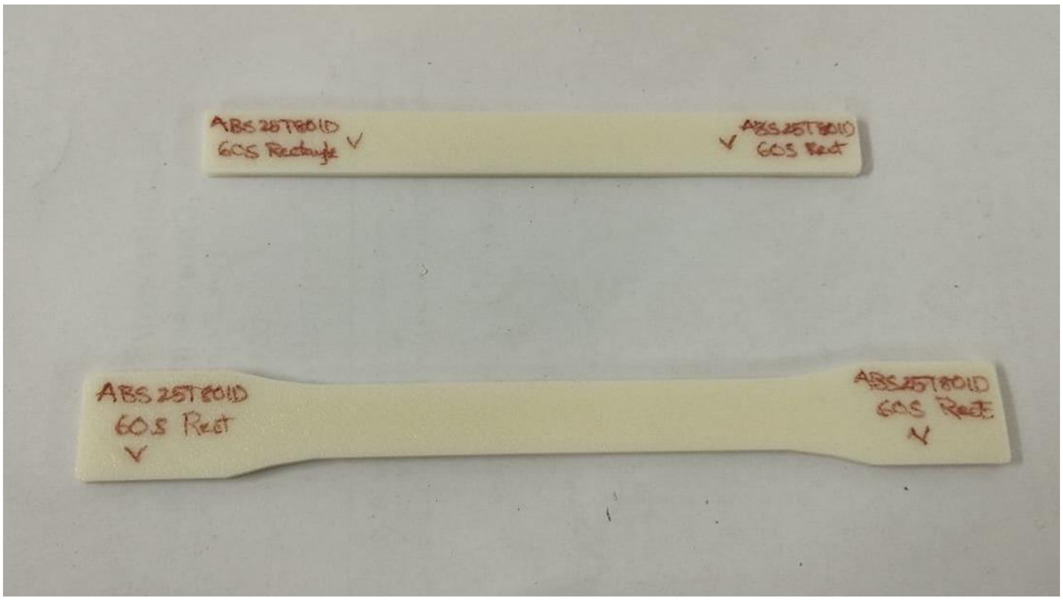

Fig.6.2. (a) ABS Test specimens before tensile and flexural test

Fig.6.2. (b) ABS Test specimens after tensile and flexural test

6.2. STATISTICAL ANALYSIS

In generally, Statistical analysis is the process of collecting, organizing, analyzing, interpreting, and presenting data. It helps to extract meaningful insights from the experimental data, identify patterns, relationships, and optimize outcomes.

6.2.1. Statistical Analysis of PLA test specimen.

In statistical analysis of experiments (e.g., materials testing), responses refer to the measured output variables you are interested in studying or optimizing. In the present study: R1 (Tensile Strength) and R2 (Flexural Strength) are the responses. Each response is typically analyzed for its variation, sensitivity to input factors, and correlation with process parameters

Table.6.3. Responses from the PLA testing results

Response	**Name**	**Units**	**Observations**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**	**Ratio**
R1	Tensile Strength	MPa	9.00	21.09	31.65	25.82	3.48	1.50
R2	Flexural Strength	MPa	9.00	34.33	61.89	53.12	9.65	1.80

The table 6.3. summarizes the statistical analysis of two mechanical property responses. The **average** tensile strength is **25.82 MPa**. The **standard deviation** is **3.48 MPa**, showing moderate variability. The **max/min ratio** is **1.50**, indicating the maximum value is 1.5 times the minimum. The average flexural strength is 53.12 MPa. The standard deviation is 9.65 MPa, which is higher than that of tensile strength, indicating greater variability. The max/min ratio is 1.80, showing a wider range of values compared to tensile strength.

6.2.2. Analysis of Tensile Strength test results of PLA

Table 6.4. ANOVA (Analysis of Variance) of tensile strength (PLA)

Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Model	89.69	4	22.42	12.45	0.0158	**significant**
B-Infill Density	77.24	2	38.62	21.45	0.0073	**significant**
C-Printing Speed	12.45	2	6.23	3.46	0.1343	**Not significant**
Residual	7.20	4	1.80			
Cor Total	96.89	8				

The table 6.4 is the result of an ANOVA (Analysis of Variance) applied to PLA test results (tensile strength), likely from a designed experiment investigating how input factors affect the output responses. Model represents the combined effect of all considered factors. F = 12.45 with a P = 0.0158 indicates the overall model is statistically significant, meaning at least one factor has a real effect on the response. The infill density P = 0.0073, which is $< 0.05 \rightarrow$ statistically significant. Interpretation effect of infill density has a strong influence on the PLA test results (tensile strength). Printing speed has P = 0.1343, which is $> 0.05 \rightarrow$ not statistically significant. Suggests printing speed, layer thickens and infill pattern does not have a strong or consistent effect on the output within the tested range.

Table 6.5. Fit Statistics of PLA test results (tensile strength)

Std. Dev.	0.3069	**R^2**	0.9989
Mean	40.58	**Adjusted R^2**	0.9958

C.V. %	0.7563	**Predicted R^2**	0.9786
		Adeq Precision	51.9867

From the table 6.5 predicted R^2 of 0.6237 is not as close to the Adjusted R^2 of 0.8513 as one might normally expect; i.e. the difference is more than 0.2. This may indicate a large block effect or a possible problem with model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 9.838 indicates an adequate signal. This model can be used to navigate the design space.

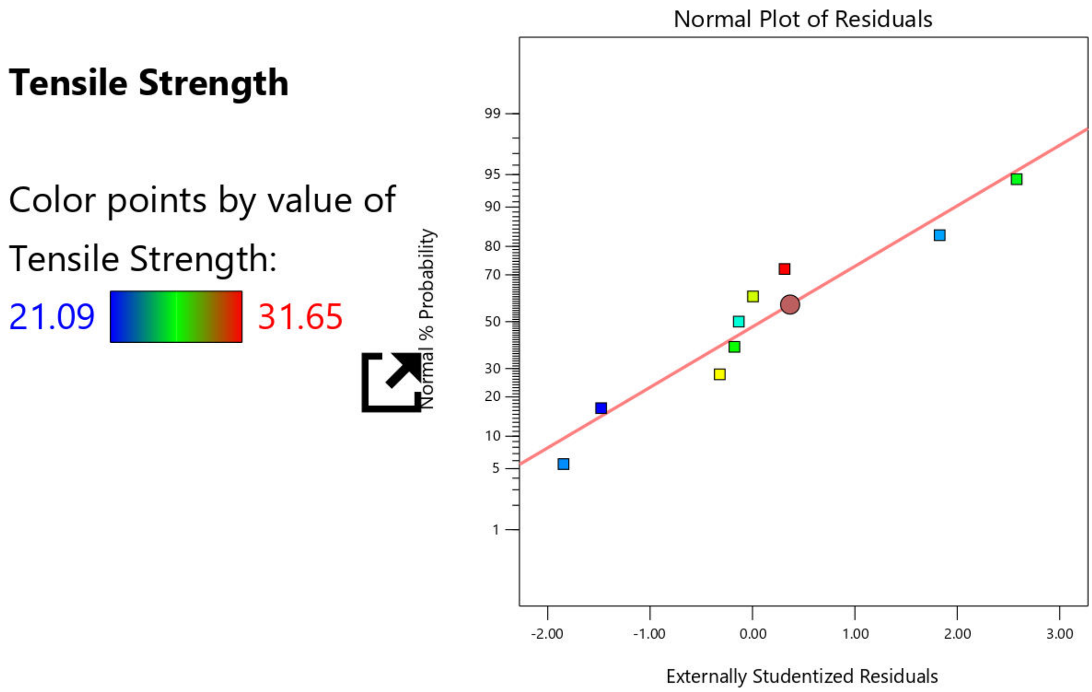

Fig.6.3. Normal Plots of residuals

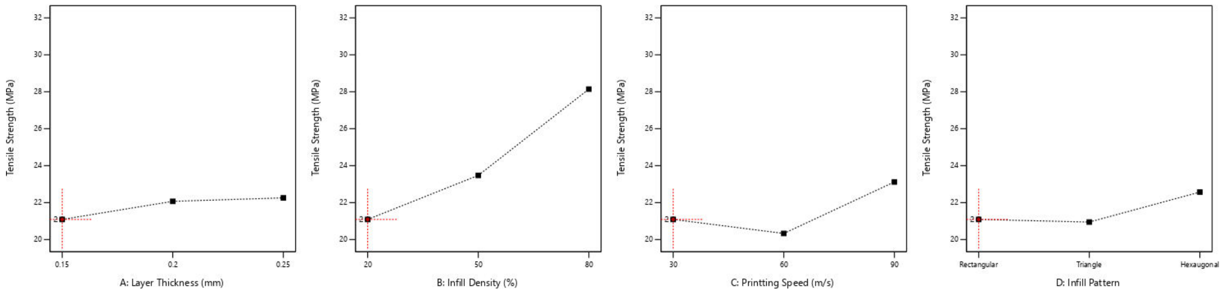

Fig.6.4. Tensile Strength design points of PLA test specimens (Tensile strength)

6.2.3 Analysis of Flexural Strength test results of PLA

Table 6.6. ANOVA (Analysis of Variance) of Flexural strength (PLA)

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	**Significance**
Model	648.11	4	162.03	6.73	0.0459	Ssignificant
A-Layer Thickness	422.25	2	211.13	8.76	0.0345	Significant
B-Infill Density	225.86	2	112.93	4.69	0.0894	Not significant
Residual	96.37	4	24.09			
Cor Total	744.48	8				

From the table 6.6 the **Model F-value** of 6.73 implies the model is significant. There is only a 4.59% chance that an F-value this large could occur due to noise. **P-values** less than 0.0500 indicate model terms are significant. In this case A is a significant model term. The layer thickness P = 0.0345, which is < 0.05 → statistically significant. Interpretation effect of layer thickness has a strong influence on the PLA test results (flexural strength). Infill density has P = 0.0894, which is > 0.05 → moderately statistically significant. Suggests printing speed, and infill pattern does not have a strong or consistent effect on the output within the tested range.

Table 6.7. Fit Statistics of PLA test results (Flexural strength)

Std. Dev.	4.91	**R^2**	0.8706
Mean	53.12	**Adjusted R^2**	0.7411
C.V. %	9.24	**Predicted R^2**	0.3447
		Adeq Precision	7.4729

From the table 6.7. **Predicted R^2** of 0.3447 is not as close to the **Adjusted R^2** of 0.7411 as one might normally expect; i.e. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. **Adeq Precision** measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 7.473 indicates an adequate signal. This model can be used to navigate the design space.

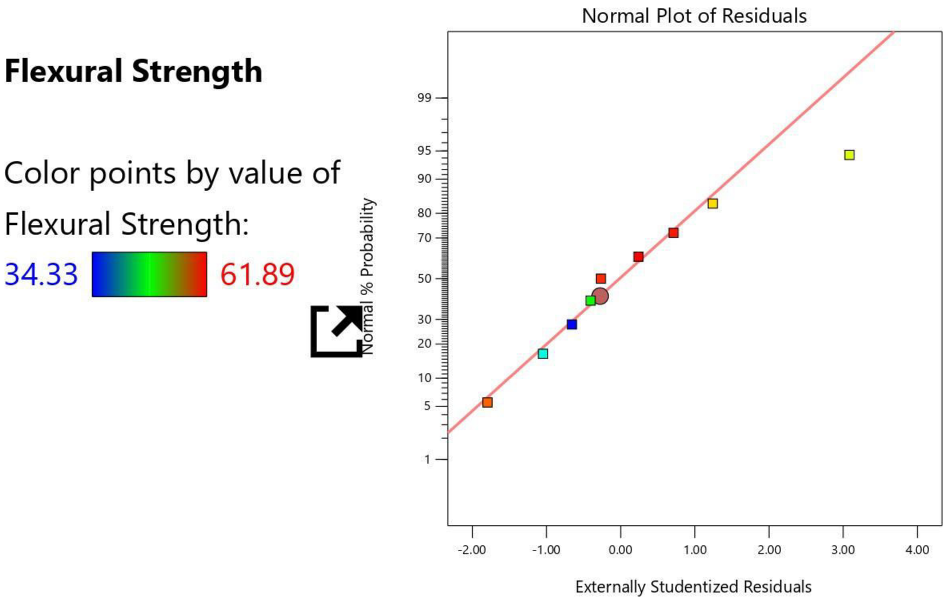

Fig.6.5. Normal Plots of residuals

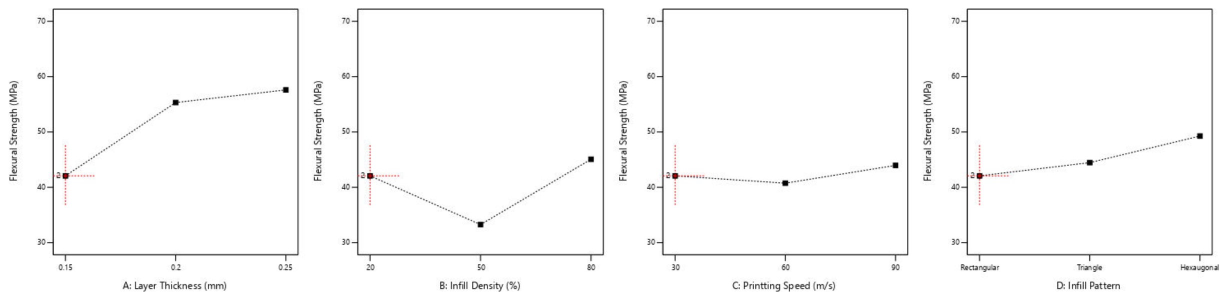

Fig.6.6. Flexural Strength design points of PLA test specimens

6.2.4. Statistical Analysis of ABS test specimen.

Table.6.8. Responses from the ABS testing results

Response	Name	Units	Observations	Minimum	Maximum	Mean	Std. Dev.	Ratio
R1	Tensile Strength	MPa	9.00	16.75	26.43	22.18	3.17	1.58
R2	Flexural Strength	MPa	9.00	34.03	48.3	40.58	4.72	1.42

The table 6.8. summarizes the statistical analysis of two mechanical property responses. The **average** tensile strength is **22.18 MPa**. The **standard deviation** is **3.17 MPa**, showing moderate variability. The **max/min ratio** is **1.58**, indicating the maximum value is 1.58 times the minimum. The average flexural strength is 40.58 MPa. The standard deviation is 4.75 MPa, which is higher than that of tensile strength, indicating greater variability. The max/min ratio is 1.42, showing a smaller range of values compared to tensile strength.

6.2.5. Analysis of Tensile Strength test results of ABS

Table 6.9. ANOVA (Analysis of Variance) of tensile strength (ABS)

Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance

Model	74.03	4	18.51	11.50	0.0182	significant
A-Layer Thickness	12.07	2	6.04	3.75	0.1210	Not significant
B-Infill Density	61.95	2	30.98	19.25	0.0089	significant
Residual	6.44	4	1.61			
Cor Total	80.46	8				

The table 6.9 is the result of an ANOVA (Analysis of Variance) applied to ABS test results (tensile strength), likely from a designed experiment investigating how input factors affect the output responses. The **Model F-value** of 11.50 implies the model is significant. There is only a 1.82% chance that an F-value this large could occur due to noise. The infill density P = 0.0089, which is < 0.05 → statistically significant. Interpretation effect of infill density has a strong influence on the PLA test results (tensile strength). layer thickness has P = 0.1210, which is > 0.05 → not statistically significant. Suggests printing speed, layer thickens and infill pattern does not have a strong or consistent effect on the output within the tested range. Same where shown in figures 6.7 and 6.8.

Table 6.10. Fit Statistics of ABS test results (tensile strength)

Std. Dev.	1.27	**R^2**	0.9200
Mean	22.18	**Adjusted R^2**	0.8400
C.V. %	5.72	**Predicted R^2**	0.5950
		Adeq Precision	9.7657

From the table 6.5 predicted R^2 of 0.5950 is not as close to the **Adjusted R^2** of 0.8400 as one might normally expect; i.e. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. **Adeq Precision** measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 9.766 indicates an adequate signal. This model can be used to navigate the design space.

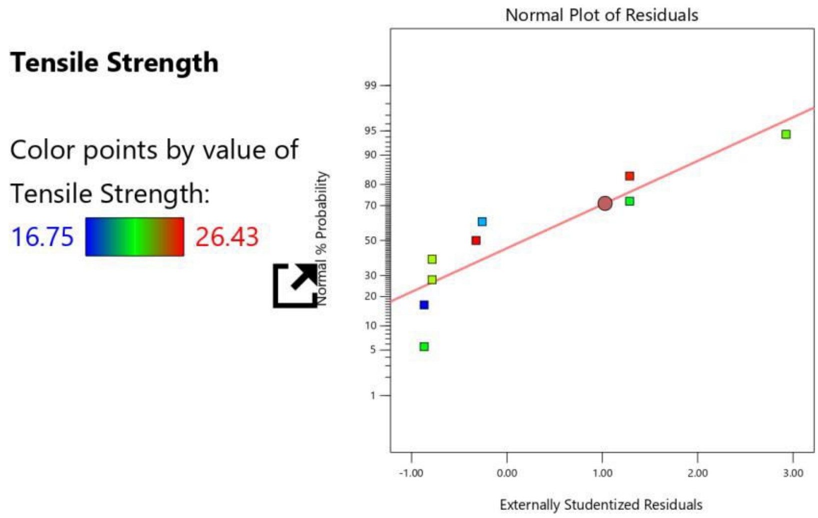

Fig.6.7 Normal Plots of residuals

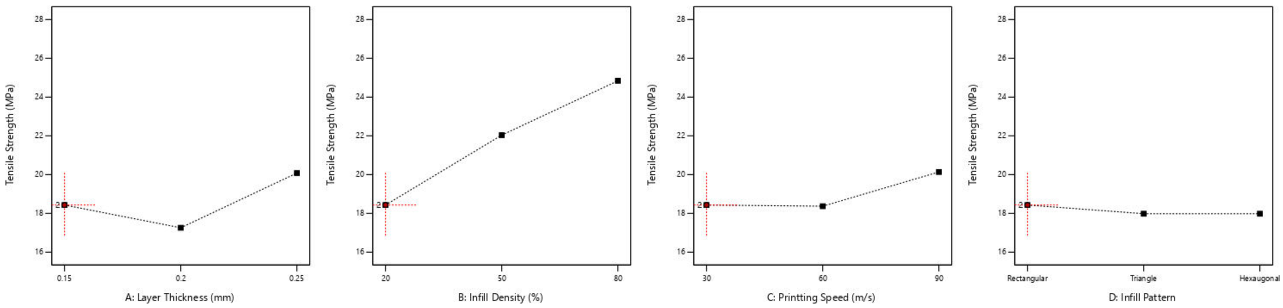

Fig.6.8 Tensile Strength design points of ABS test specimens (Tensile strength)

6.2.6. Analysis of Flexural Strength test results of ABS

Table 6.11. ANOVA (Analysis of Variance) of Flexural strength (ABS)

Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Model	178.21	6	29.70	315.39	0.0032	Significant

A-Layer Thickness	43.76	2	21.88	232.33	0.0043	significant
B-Infill Density	18.41	2	9.21	97.74	0.0101	Significant
D-Infill Pattern	116.04	2	58.02	616.09	0.0016	Significant
Residual	0.1884	2	0.0942			
Cor Total	178.40	8				

From the table 6.11 the **Model F-value** of 315.39 implies the model is significant. There is only a 0.32% chance that an F-value this large could occur due to noise. **P-values** less than 0.0500 indicate model terms are significant. In this case Layer Thickness, Fill density and Infill pattern are significant model terms. Same where shown in figures 6.9 and 6.10.

Table 6.12. Fit Statistics of ABS test results (Flexural strength)

Std. Dev.	0.3069	**R^2**	0.9989
Mean	40.58	**Adjusted R^2**	0.9958
C.V. %	0.7563	**Predicted R^2**	0.9786
		Adeq Precision	51.9867

From the table 6.12. the **Predicted R^2** of 0.9786 is in reasonable agreement with the **Adjusted R^2** of 0.9958; i.e. the difference is less than 0.2. **Adeq Precision** measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 51.987 indicates an adequate signal. This model can be used to navigate the design space.

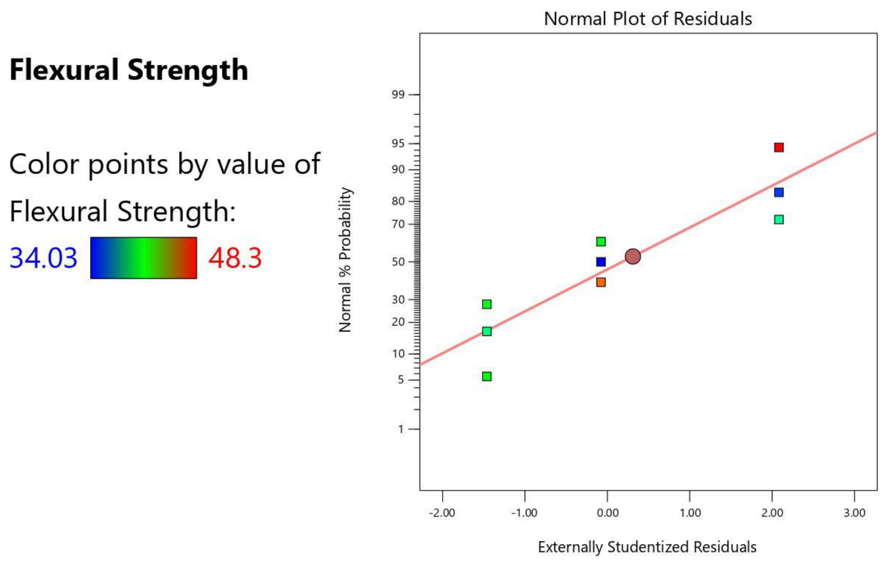

Fig.6.9 Normal Plots of residuals

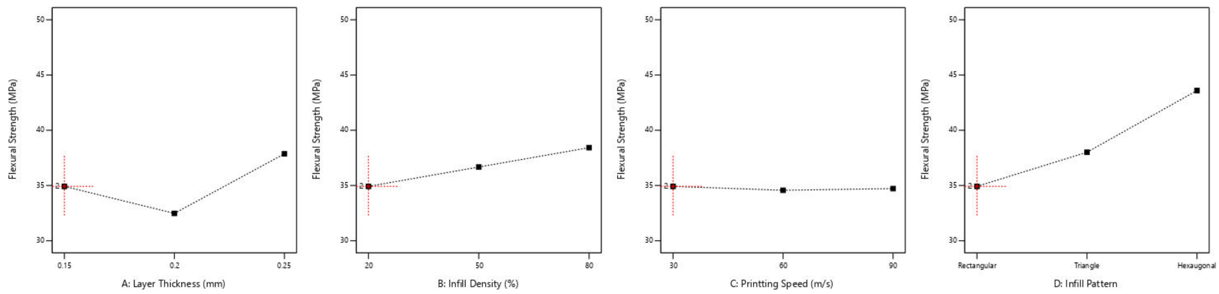

Fig.6.10 Flexural Strength design points of ABS test specimens

6.3 Taguchi-Based Multi-Objective Optimization using the Desirability Function Method:

The Taguchi-Based Multi-Objective Optimization using the Desirability Function Method is an advanced approach that combines:

- The Taguchi method (for efficient experimental design and robust analysis),
- With the desirability function approach (for handling multiple response variables).

This hybrid technique is widely used in manufacturing, materials science, and engineering to optimize multiple conflicting quality characteristics in a structured, data-efficient way. In the present study maximization of tensile strength and flexural strength was the multi-objective function.

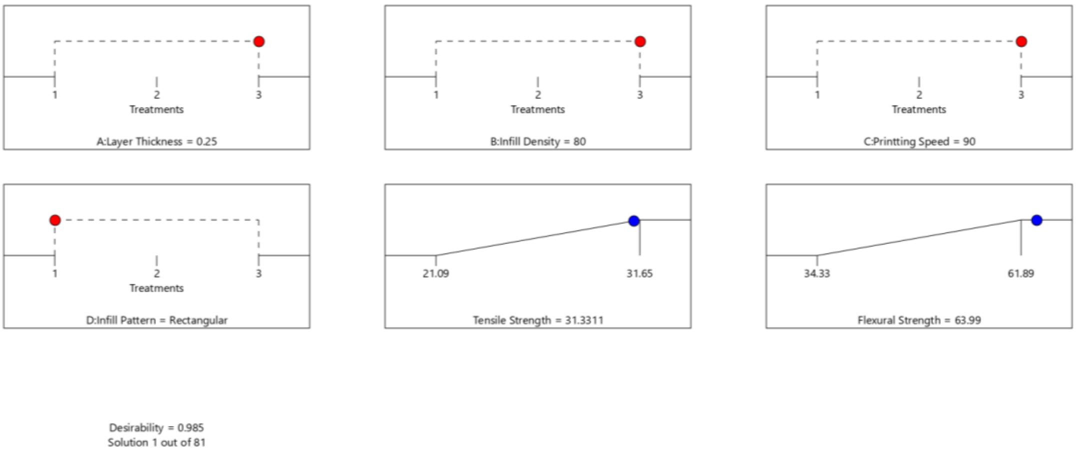

Fig.6.11. Taguchi-Based Multi-Objective optimization (Desirability function method) for PLA test specimens

Based on Figure 6.11, the predicted optimal tensile and flexural strengths of the PLA test specimens are 31.3311 MPa and 63.99 MPa, respectively, corresponding to a layer thickness of 0.25 mm, an infill density of 80%, a printing speed of 90 mm/s, and a rectangular infill pattern. Among the 81 predicted solutions, the one with a desirability factor of 0.985 was selected as the optimal, corresponding to the above parameter combination. The optimal solutions are tabulated in table 6.13.

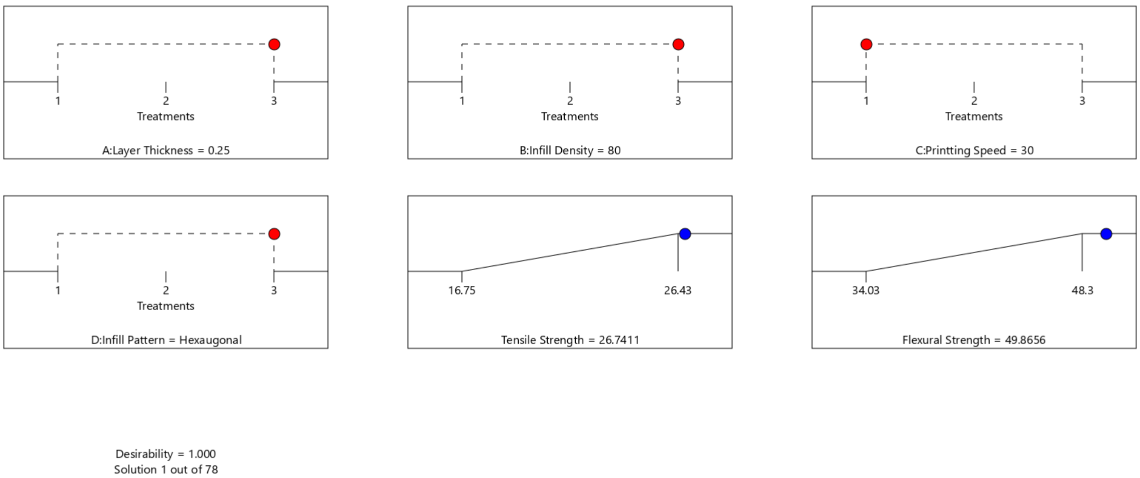

Fig.6.12. Taguchi-Based Multi-Objective optimization (Desirability function method) for ABS test specimens

Based on Figure 6.11, the predicted optimal tensile and flexural strengths of the ABS test specimens are 26.7411 MPa and 49.8656 MPa, respectively, corresponding to a layer thickness of 0.25 mm, an infill density of 80%, a printing speed of 30 mm/s, and a hexagonal infill pattern. Among the 78 predicted solutions, the one with a desirability factor of 1.000

was selected as the optimal, corresponding to the above parameter combination. The optimal solutions are tabulated in table 6.14.

Table 6.13. Optimal solutions for PLA

	Optimal process condition			
	Layer thickness (mm)	**Infill Density (%)**	**Printing speed (mm/s)**	**Infill pattern**
Factor level	0.25	80	90	Rectangular
Maximum Tensile Strength (MPa)	31.3311			
Maximum Flexural Strength (MPa)	63.99			

Table 6.14. Optimal solutions for ABS

	Optimal process condition			
	Layer thickness (mm)	**Infill Density (%)**	**Printing speed (mm/s)**	**Infill pattern**
Factor level	0.25	80	30	Hexagonal
Maximum Tensile Strength (MPa)	26.7411			
Maximum Flexural Strength (MPa)	49.8656			

CHAPTER 7

ADVANTAGES, DISADVANTAGES AND APPLICATIONS

7.1 Advantages of Optimization of FDM 3D Printing (Materials: PLA & ABS)

- Improved mechanical properties
- Better print quality
- Material and Time Efficiency
- Cost reduction
- Customized properties
- Process reliability

7.2 Disadvantages

- Time-Consuming Experimentation
- Complex Data Analysis
- Potential for Overfitting
- Limited to Specific Machines/Conditions
- Material Behaviour Variance

7.3 Applications

- Functional Prototypes
- Custom Tooling and Jigs
- Medical Devices & Orthotics
- Automotive & Aerospace
- Educational Models
- Consumer Products
- Structural Testing Models

CHAPTER 8
CONCLUSION

The present study investigated the mechanical performance of FDM 3D-printed components using PLA and ABS materials, focusing on tensile and flexural strengths as key response parameters. The study involved experimental testing, statistical analysis, and multi-objective optimization using the Taguchi method integrated with the desirability function approach. The major conclusions are summarized below:

1. Material Performance Comparison: ABS exhibited higher tensile strength than PLA, with a maximum of 48.30 MPa for ABS compared to 31.65 MPa for PLA. PLA demonstrated better flexural strength in some combinations, reaching up to 61.89 MPa, while ABS reached a maximum of 49.87 MPa. This suggests PLA may offer higher bending resistance, whereas ABS offers superior tensile performance.

2. Influence of Printing Parameters: For PLA, tensile strength was significantly influenced by infill density ($p = 0.0073$), while flexural strength was significantly influenced by layer thickness ($p = 0.0345$). For ABS, both tensile and flexural strengths were strongly influenced by infill density, layer thickness, and infill pattern, as indicated by their statistically significant p-values ($p < 0.05$). Printing speed had no significant effect on either material within the tested range.

3. Statistical Model Validity: ANOVA results confirmed that the proposed models were statistically significant with F-values indicating strong model fit. The Adequate Precision ratios (>4 for all cases) confirmed that the signal-to-noise ratio was acceptable, indicating the models were suitable for navigating the design space. While some predicted R^2 values showed a deviation from adjusted R^2, the overall models still provided reasonable predictive capability.

4. Optimization Using Desirability Function Method:

For PLA, the optimal parameter combination was: Layer thickness = 0.25 mm, Infill density = 80%, Printing speed = 90 mm/s, Infill pattern = Rectilinear, achieving a predicted tensile strength of 31.33 MPa and flexural strength of 63.99 MPa, with a desirability factor of 0.985.

For ABS, the optimal combination was: Layer thickness = 0.25 mm, Infill density = 80%, Printing speed = 30 mm/s, Infill pattern = Hexagonal, yielding a predicted tensile strength of 26.74 MPa and flexural strength of 49.87 MPa, with a perfect desirability factor of 1.000.

Overall Conclusion:

- The integration of mechanical testing with statistical and multi-objective optimization techniques provided comprehensive insights into how process parameters influence the mechanical behavior of FDM-printed parts.
- The desirability-based optimization framework proved effective in identifying robust combinations of parameters for achieving high strength in both PLA and ABS prints.
- These findings are valuable for industries and researchers aiming to optimize FDM parameters for specific strength requirements in functional components.