DESIGN A LABORATORY 3D FILAMENT EXTRUDER

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Entitled:

Design a Laboratory 3D Filament Extruder

Task description:

Design of a small "desktop" polymer extruder for the production of filamentous feedstock for testing purposes. 3D CAD modeling, manufacturing technology design and raw material price calculation. The result is a finished production plan.

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1 Introduction

The ability to print complex geometric shapes into one piece without assembly has sparked widespread interest in additive manufacturing (AM), commonly known as 3D printing, over the past 30 years (Thompson et al., 2016). In 1984, Charles Hull patented stereolithography (SLA), a process that uses ultraviolet (UV) light to cure a liquid-polymer resin to create any complex three-dimensional building or design. From the advent of filament deposition modelling (FDM) in the 1990s to the widespread distribution and testing of metal 3D printers as a billion-dollar business by 2020, this patent cleared the way for several innovative technical advances over the next few decades (Whitaker, 2014).

FDM technology has evolved rapidly, creating many machines using the same primary construction method layer by layer (Fico et al., 2022). **See Figure 1.**

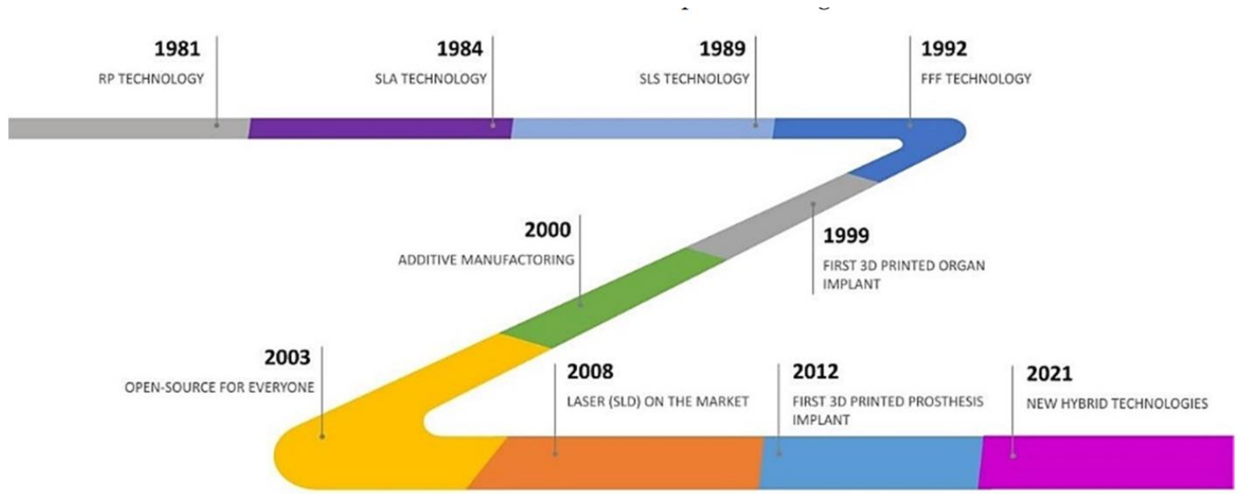


Figure 1. Time evolution of AM technologies (Fico et al., 2022).

It was in 2011 that the German government launched a program called Industry 4.0 as part of its high-tech policy to digitalize the industry intelligently (Kagermann, 2015). Cyber machines and ubiquitous connection, cloud storage, autonomous control, and additive manufacturing are all examples of intelligent systems used in modern industrial facilities.

The capacity to deal with a wide variety of materials and the steady improvement of related technology have contributed to the expansion of additive manufacturing. Shorter product development cycles, more emphasis on sustainability, decreased production costs and decreased lead times are only a few of the results of this technical advancement (Thompson et al., 2016).

The market for traditional manufacturing technology is saturated, and production technology today requires speed and flexibility. The need to stay competitive has resulted in a shortened manufacturing cycle and quicker growth of the product ecosystem. Industry 4.0 encourages the adoption of AM technology due to its digital speed, increased product accuracy, and reduced capital costs. All of these are key to a philosophy focused on manufacturing process technology. AM is indicative of all three characteristics of a revolutionary idea: applicability, efficiency, and generality (Bandyopadhyay & Heer, 2018). It is also an essential enabling technology for several industries, including the aerospace, medicinal, automotive, and turbomachinery fields (Stansbury & Idacavage, 2016).

AM is a method of manufacturing that puts thinking into its output and can be controlled by an intelligent system without losing its adaptability. The term "smart factory" refers to a notion in the Fourth Industrial Revolution. With the support of cyber-physical systems, machines may perform their basic operations without being physically connected. With AM and Industry 4.0, the consumer may also play the designer role, and anyone can turn their house into an intelligent factory or a network of many smart ones. Another point demonstrating AM's importance in Industry 4.0 is its contribution to sustainability through decentralization.

Material extrusion, material jetting, binder jetting, sheet lamination, vat photopolymerization, powder bed fusion, and directed energy deposition are the seven process categories specified by ISO/ASTM 52900:2015 for AM systems (Wu et al., 2020).

For its low cost and widespread use, Fused Deposition Modelling (FDM) 3D printing stands out among the other methods listed above (Angelopoulos et al., 2019). In 1989, Crump founded Stratasys Corporation after patenting FDM the previous year (Vyavahare et al., 2020).

In order to create prototypes and functional parts from 3D CAD models, FDM printers use controlled thermoplastic extrusion in the form of filaments (Angelopoulos et al., 2019). The filaments become semiliquid at the nozzle during the part-building process. The materials are then extruded onto a construction platform in a layer-by-layer pattern before being fused and cured to produce the final product (Angelopoulos et al., 2019). Several aspects, including process parameter choice, material characteristics, and component geometry, affect the final product's functional qualities after FDM fabrication (Dey et al., 2021).

3D printers are a great example of how technology can take the smart factory idea forward, as they can do the work of many different machines while taking up much less space. With the addition of AM equipment, an Industry 4.0 facility may become a smart factory, saving money on both labour and materials. The potential economic effect of 3D printers soon is intriguing, and so are the business opportunities it may present.

In the industry 4.0 movement context, AM is seen as an enabling technology. In addition, high-quality, individualized goods can only be produced in modern, efficient, and cyber-physically integrated factories. Thus, it is crucial to create materials that can solve design and software-related issues to implement industry 4.0 (Dilberoglu et al., 2017).

While FDM is more affordable than some other AM techniques, it still has limitations in its widespread industrial applications due to a lack of suitable materials. Developing new filaments with improved mechanical, physical, electrical and magnetic properties is essential to meet the needs of additive manufacturing applications in various industries (Angelopoulos et al., 2019).

1.1 Problem statement.

Additive manufacturing is one of the sustainable enabling technologies essential to the industry 4.0 philosophy. Autonomous robotics, the IoT, additive manufacturing, cyber security, AI, big data analytics, cloud computing, vertical and horizontal system integration, and augmented reality are some of the technologies that make up Industry 4.0's architecture.

Further, intelligent factories with high efficiency and cyber-physical integration are required to properly implement industry 4.0, which necessitates the development of filament materials that can resolve design and software-related issues to produce customized, high-quality goods. (Dilberoglu et al., 2017).

Even though FDM is relatively inexpensive compared to other AM methods, the challenge lies in the limited availability of resources in the form of filaments to create components with the appropriate qualities. As a result, it is necessary to create new filaments with improved mechanical, physical, electrical, and magnetic qualities to fulfil the many needs of additive manufacturing in the industry (Angelopoulos et al., 2019).

Therefore, this research aims to develop a CAD 3D model of a desktop polymer filament extruder for testing Fused Deposition Modelling.

1.2 Justification.

Though the fused deposition model (FDM) is relatively inexpensive compared to other additive manufacturing (AM) technologies, the need for more available materials has limited its industrial use for producing functional parts (Ngo et al., 2018).

Main Objective.

- To design a 3D desktop polymer filament extruder for Fused Deposition Modelling testing purposes.

Specific Objectives.

- To design a 3D desktop polymer filament extruder for Fused Deposition Modelling testing purposes.
- To design a 3D CAD model of a desktop polymer filament extruder for Fused Deposition Modelling testing purposes.
- To carry out the raw material cost estimation.

2 Literature Review

The term "additive manufacturing" (AM) refers to a set of innovative manufacturing techniques used to create physical models of two- or three-dimensional designs from computer-aided design (CAD) files. These techniques commonly build three-dimensional objects by adding and bonding materials in successive layers. The term "layered manufacturing techniques" may also be used to describe AM technologies. The AM technique uses full 3D models, while conventional methods often only employ 2D drawings (Prakash et al., 2018). The 3D CAD file is broken down into layer data and built layer by layer on the computer (Prakash et al., 2018).

In its early stages, AM was known as Rapid Prototyping (RP), the practice of quickly developing a system or part representation before final release or commercialization.

AM is the process of combining materials to create objects using 3D CAD model data layer by layer. In comparison to more traditional manufacturing procedures such as subtractive and formative production. As a result, it is helpful for mass-producing components that have a long history of design revisions (Gibson et al., 2010, 2020). In addition, the layer-by-layer method enables the production of complex geometries and functional components with low waste rates and in a reasonable amount of time (González-Henríquez et al., 2019; Ivanova et al., 2013).

Additive manufacturing (AM) is also known as "3D printing." American Society for Testing and Materials developed the AM standards on the principle that a 3D CAD model can be used directly in manufacturing without additional process design. Using computer-aided design (CAD) files, atomic layer deposition (ALD) manufacturing makes it easier to build three-dimensional (3D) products (Gibson et al., 2020).

AM adds material in stages, each layer representing a narrow cross-section of the component drawn from the original CAD data. As a result, the thinner each layer, the more similar the finished item will be to the original.

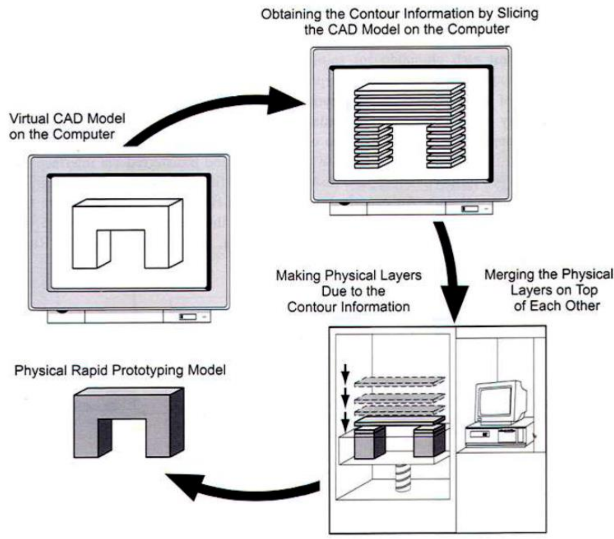


Figure 2. Rapid prototyping principle (Prakash et al., 2018).

One of the primary benefits of additive manufacturing is the ability to produce complex parts fast with minimal human interaction and cheaply (Prakash et al., 2018). AM systems may also generate models using 3D CAD data, CT and MRI images, and 3D digitizing technologies (Prakash et al., 2018).

AM varies significantly from traditional formative or subtractive manufacturing processes. It employs a 'bottom-up' manufacturing approach in which a structure is built into its planned shape 'layer by layer' rather than casting or shaping processes such as forging or machining. Because additive manufacturing is versatile, flexible, and highly customizable, it has the potential application in nearly any industrial production field (Tofail. S & Koumoulos. E, 2018). However, materials must be addressed as a fundamental enabling technology for AM to attain predictive and reproductive capabilities (Tofail. S & Koumoulos. E, 2018).

Additive manufacturing processes.

The international standard ISO/ASTM 52900 has identified seven processes: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization. In this discussion, the primary focus is on five essential AM methods, which are Fused Deposition Modelling (FDM), laminated object manufacturing (LOM), stereolithography (SLA), selective laser melting (SLM), and selective laser sintering (SLS) (Jin et al., 2018).

2.1 Fused Deposition Modelling (FDM)

FDM is an additive manufacturing process that uses a thin layer of thermoplastic wire (filament) as a raw material in a machine where a print head melts and thrusts it out in a thickness of 0.20 mm. The material is heated to approximately 2 degrees Celsius over its melting point, hardening virtually immediately after discharge, and cold welds to the last layers. This procedure may employ a wide range of materials, and FDM equipment has low maintenance costs.(Prakash, Nancharaih & Rao, 2018).

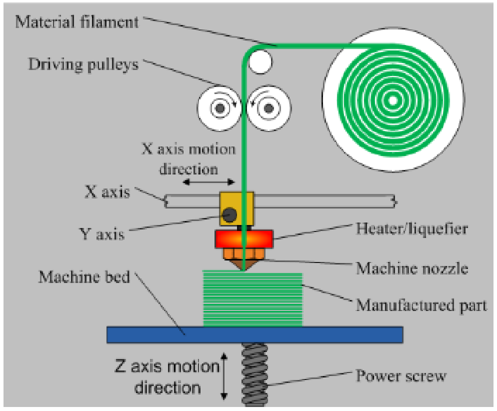


Figure 3. FDM process and its main components (Adel & Khalil, 2018).

2.2 Laminated Object Manufacturing (LOM)

Laminated Object Manufacturing (LOM) is a layer-by-layer technique that combines additive and subtractive processes. This process uses paper, composites, and metals as raw materials: pressure, heat, and a thermal adhesive covering bond the layers. Finally, a laser cuts the material to the shape defined by the 3D CAD and STL files. LOM offers several benefits, including minimal overhead, no post-processing, no support structures, and no warping or out-of-phase. LOM drawbacks include a poor surface polish, poor precision, and intricate interior chambers that are difficult to build (Prakash et al., 2018).

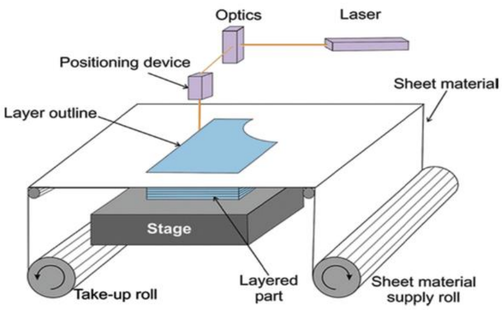


Figure 4. Laminated Object Manufacturing process scheme (Ahmad et al., 2019)

2.3 Selective Laser Melting (SLM).

The SLM procedure builds a component layer by layer by selectively melting metal powder with a laser beam. As a result, the mechanical qualities of items generated using SLM technology are more like those produced by traditional manufacturing procedures (Li et al., 2020). However, significant residual stresses and severe deformations in the manufactured components limit SLM industrial applicability. Furthermore, residual tensions contribute considerably to the production of thermal fractures, which create changes in the quality of the built parts. (Zaeh & Branner, 2010).

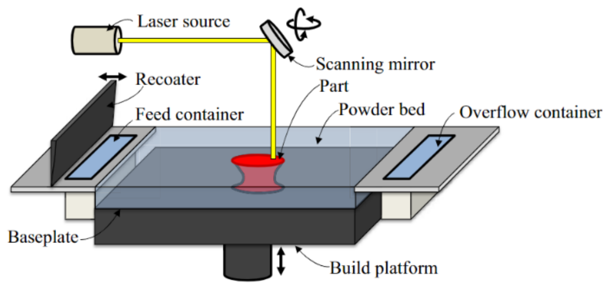


Figure 5. Selective Laser Melting process scheme (Yang et al., 2018).

2.4 Stereolithography (SLA)

In the SLA process, components are built layer by layer in a vat of liquid photopolymer resin. UV radiation cures the built item (Mathur, 2016). Support structures are necessary to connect the component to the construction platform. The building platform is lowered to coat the component during the process thoroughly. The component is then elevated to a level where a blade wipes the resin away, leaving exactly one layer above it. The component is then lowered by one layer and left until the liquid has settled to provide a flat surface before forming the next layer (Prakash et al., 2018).

The SLA process is suitable for producing a prototype object with a smooth surface finish. The primary limitation of SLA is that the product size is small, and the technique is expensive. Furthermore, as compared to other AM processes, the materials used in SLA are limited (Prakash et al., 2018).

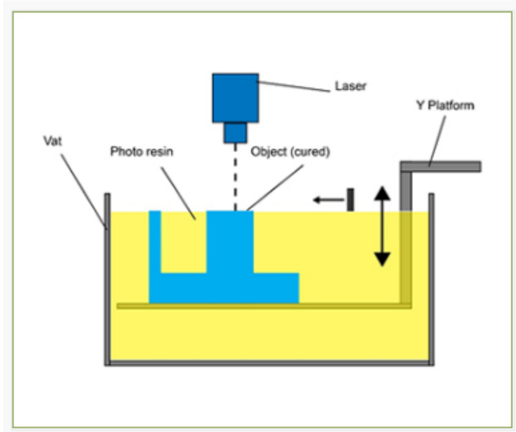


Figure 6. Stereolithography process scheme (Mathur, 2016).

2.5 Selective Laser Sintering (SLS)

In the SLS process, a powder is sintered using a Carbon dioxide laser beam. The chamber is heated close to the melting point of the material. Depending on the design, the laser attaches the powder to a specified position for each layer.

The SLS technique can use various materials, including plastics, metals, metal-metal combinations, metal-polymer combinations, and metal-ceramic combinations (Prakash et al., 2018).

SLS allows for the fast creation of complex components that are more robust and useable than other AM technologies; there is no post-curing required, and the build time is short.

The SLS method, on the other hand, is complex due to many design considerations. The print quality is inferior to SLA, and switching materials is a hassle.

The primary benefits of this method include the flexibility in materials used and the potential for recycling new powder. The material's particle size limits the process's accuracy; oxidation must be prevented by carrying it out in an inert gas atmosphere, and the operation calls for a stable temperature close to the melting point.

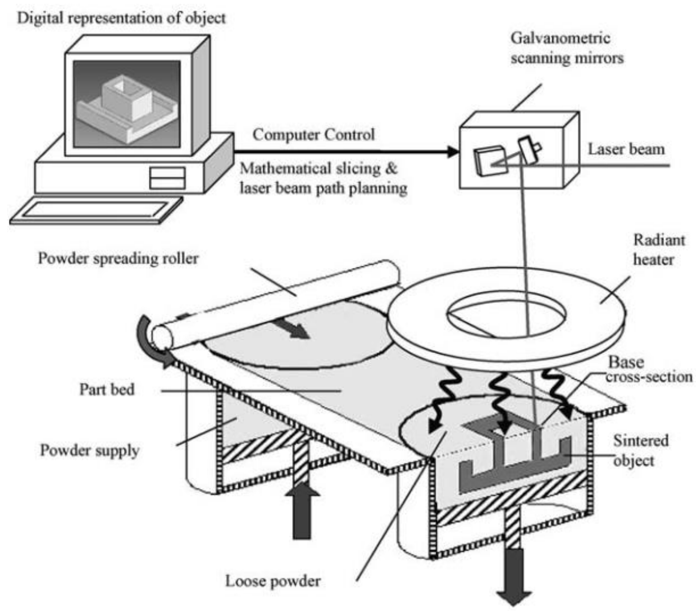


Figure 7. Selective laser sintering process scheme (Das, 2008).

One of the fundamental drawbacks of additive manufacturing is the lack of a broad materials selection portfolio. The bulk of materials used for AM is thermoplastics that have not been modified, which means that the printed components cannot be utilized for high-performance applications or where multifunctionality is sought.

Among the 3D printing methods mentioned, FDM is the most utilized additive manufacturing technology (Angelopoulos et al., 2019).

Therefore, the extent of this study is confined to developing a desktop extruder for polymer filaments that can be used in Fused Deposition Modelling (FDM) 3D Printing.

Conclusion.

AM is emerging as a significant future manufacturing method. Flexibility and robustness of the printing process are essential and promising advantages of 3D printing over traditional manufacturing processes. Despite existing limitations, there are, for example, slow print speeds and topological challenges for printed parts. For example, quickly building complex structures is a crucial advantage of additive manufacturing.

2.6 The Fused Deposition Modelling Technology

Fused Deposition Modelling (FDM) machines are another term for filament-based 3D printers. (Kloski & Kloski, 2021). FDM, one of the most widely used AM methods, uses thermoplastic filaments to create prototypes and working parts (Fu et al., 2021).

The fused deposition modelling method is the most widely utilized, low-cost, and extensively used AM approach (Angelopoulos et al., 2019). Crump invented FDM in 1988 and founded Stratasys Corporation in 1989 (Vyavahare et al., 2020).

2.7 FDM Working Principle.

The FDM process creates a three-dimensional geometric model from a digital project, often 3d CAD data. The FDM technique typically involves pressurizing and melting a polymer thermoplastic filament into a liquid state, followed by deposition on the construction platform through a nozzle.

A 3D CAD model is converted into a machine-readable format, such as a stereolithographic STL file or additive manufacturing format (AMF), for use in the AM process of generating components. The 3D CAD model is then divided into layers. The 3D model is subsequently constructed by adding layer after layer. To control the movement of the FDM extruder in the machine's XY plane, a programming language (G-code) is utilized. Most commercial FDM machines use specific software for slicing and generating G-code. STL files, on the other hand, may be transferred immediately to the FDM machine software. The FDM process construction parameters (print speed, build orientation, and infill density) are determined during machine setup (X. Gao et al., 2021).

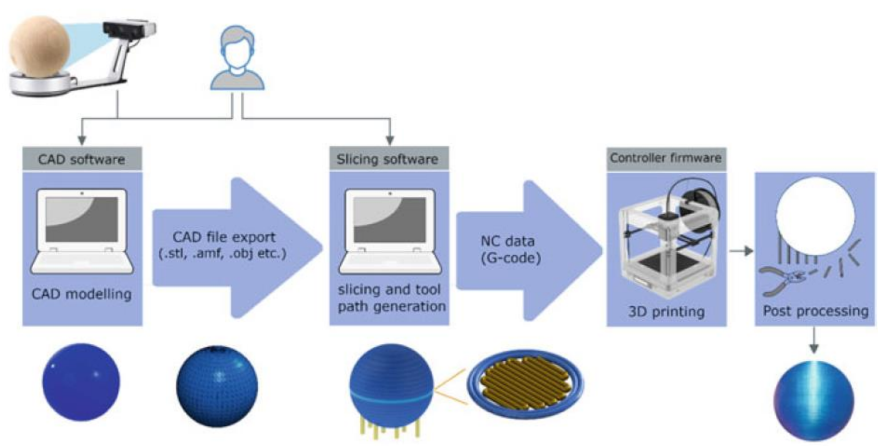


Figure 8. Fused Deposition Modelling working principal (Dave & Davim, 2021).

During printing, the extruder in most FDM machines moves in a horizontal plane, depositing the layer by following the tool path. The build platform glides lower in the z-direction after each layer is placed. The next layer is deposited over the previous ones, and the process is repeated until the model is completed. The bonding between two consecutive layers determines the strength of the built component. Adequate heat energy is required to activate the earlier deposited layer's surface and allow adhesion between the activated surface and the freshly deposited layer.

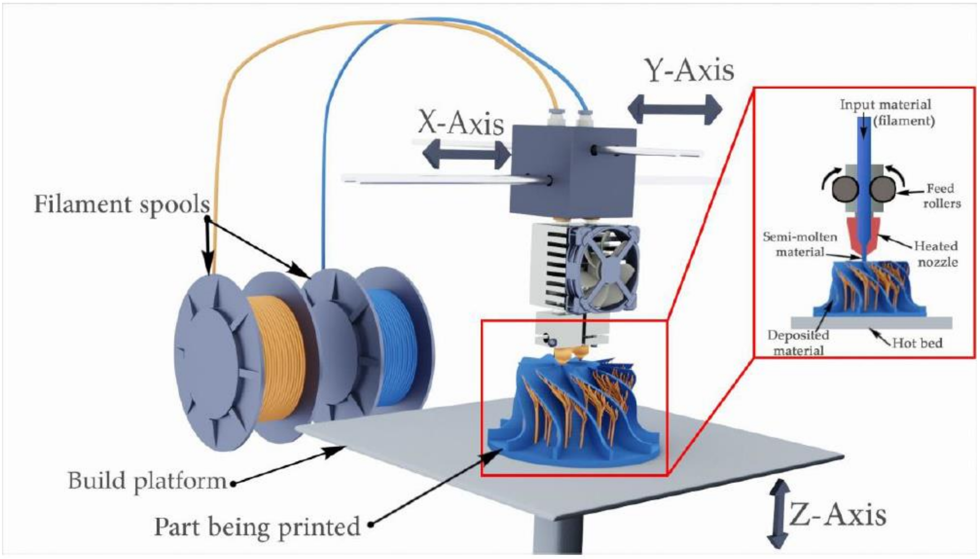


Figure 9. A diagram illustrating the FDM procedure (Elkaseer et al., 2020).

The FDM process parameters considerably influence the final characteristics, such as surface roughness, dimensional accuracy, and mechanical properties of the models generated (X. Gao et al., 2021).

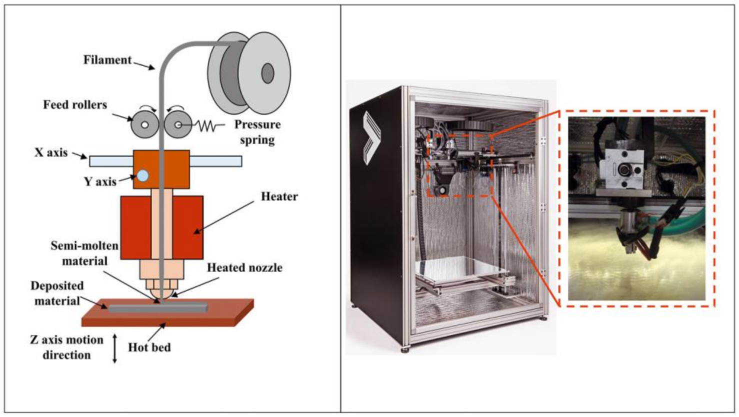


Figure 10. The FDM system's schematic view and actual representation (Zhang et al., 2019).

By allowing complex plastic products to be manufactured at home rather than in factories, desktop 3D printing allows users to create products directly from waste and promote a circular economy (Mikula et al., 2020).

Although FDM is a low-cost AM method, its industrial use for producing functional components is limited by raw materials (Ngo et al., 2018b).

FDM process factors such as tensile strength, compressive strength, flexural strength, dimensional accuracy, surface quality, hardness, yield strength, and ductility are well recognized in the literature to have a significant impact on the final qualities of the printed models.

The FDM process parameters determine production time and prices, which are crucial for manufacturers and customers. The quality of parts in terms of strength and accuracy produced through FDM techniques is still lower than parts manufactured using conventional processes, such as injection moulding.

Unlike FDM machines, traditional manufacturing processes cannot easily create complex geometries. Because of rising competition and technical breakthroughs, new feedstock materials for FDM filaments with better qualities for various industrial applications such as tissue engineering, automotive, aerospace, and medical sector are required (Mohan et al., 2017). The extrusion technique is utilized in fused filament fabrication, employing thermoplastics as pellet feedstocks. The foundation of FDM technology is a thermoplastic material coiled into a spool, often with a diameter of 1.75 mm, 2.85 mm, or 3.00 mm (Aguilar-Duque et al., 2018).

2.8 FDM Filament Extrusion Technology

2.9 Extruders.

The FDM process's applicability in various sectors can be hastened by expanding the availability of filament materials with various qualities (Dey et al., 2021). Filament extruders are used to produce thermoplastic and composite filaments for FDM.

The filament manufacturing technique uses thermoplastics and composites as raw materials as granulates or pellets that are gravity fed into the barrel through a hopper. The material is then extruded into filaments. After exiting the nozzle, the filament cools down via heat transfer between the heated filament and the surroundings before being used. **See Figure 11.**

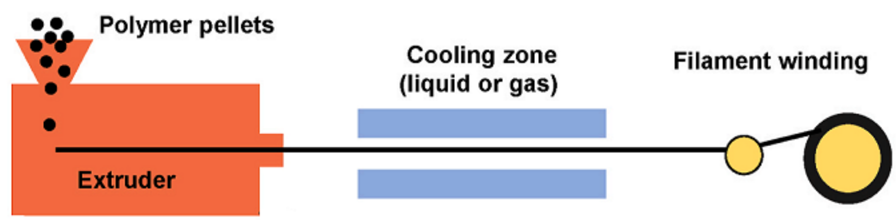


Figure 11. Feedstock filament fabrication process (Park & Fu, 2021).

The filament production method has three stages: hot-melt extrusion, cooling, and winding. The barrel, which serves as the housing, is divided into three zones: the feed zone, the transition zone, and the metering zone (Chaturvedi et al., 2017).

- The feed zone, which softens the input materials.
- The raw materials are plasticized in the transition zone.
- The raw materials are melted in the metering zone.

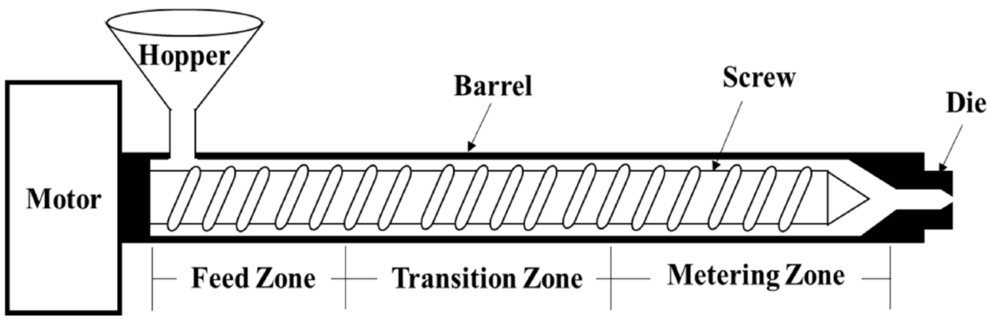


Figure 12. Shows a schematic layout representing barrel extrusion zones (Dey et al., 2021).

The input material properties of the different zones determine the temperature in each zone. Molten raw materials are forced out of the metering zone through the nozzle. The final required filament diameter determines the die diameter (Nassar et al., 2019). Hot-melt extrusion method for FDM polymer filament fabrication can dispense two or more solid components in a homogenous manner (Tan et al., 2018). Materials can be melted or made pliable by applying heat and pressure, while a die produces products with uniform shape and density. The material undergoes melting due to the heat, and as the screw turns, it blends the pellets and carries the softened substance toward the end of the barrel. To control the production of the filament, variables such as screw speed, feed rate, and temperature can be adjusted.

The hot end, where the physical state of the polymer changes, is critical to the filament production process. The temperature regulation on the hot end requires much attention. The hot end temperature must be high enough to maintain molten material but not so high that it deteriorates. (Gibson et al., 2010, 2020).

After extrusion, the filaments are cooled by fixing their form in the cooling process and coiled for the filament bundle in the winding stage. The nozzle diameter depends on the filament diameter requirements. Filaments are typically manufactured in two standard diameter sizes: 1.75mm and 2.85mm. A 3D printer can only utilize one diameter of the filament and cannot readily use a different size if it was not built to use it. On the other hand, a 1.75mm filament diameter is more common and preferable since it takes less force to melt and extrude (Kloski & Kloski, 2021). Typically, the printhead travels in the X and Y directions in FDM printers, whereas the work table moves in the Z direction. After the printhead applies a layer, the table descends, and the succeeding layer is deposited. This sequence is repeated until the object is entirely built. Figure 13. Shows; (a) FDM filament extrusion process, (b) FDM printing process.

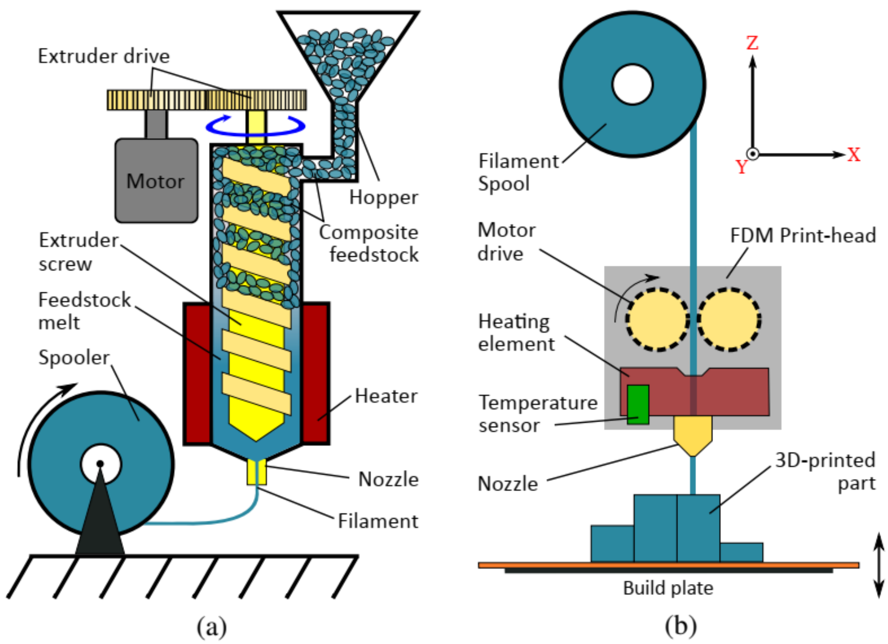


Figure 13. FDM filament fabrication and printing processes (Khatri et al., 2018).

2.10 Extruder machine for filament.

Extrusion is a thermomechanical technique that shapes plastic or dough-like materials by pushing them through a die or aperture. The die or orifice size primarily controls the extruded product's thickness, width, and shape. Extruders are high-temperature short-time (HT-ST) reactors capable of converting a wide range of raw materials into modified intermediate and final products. Extrusion offers infinite uses and continuous manufacturing capacity to meet new market challenges, making it appealing to various industrial operations (Rosato & Rosato, 2003).

A filament extruder forces raw polymer pellets into an extrusion head, where they are quickly heated and extruded. The polymer strand also acts as a piston, with the material in an unheated section, pressing against the material's heated section to propel the polymer out of the die.

There are typically two types of extruders used for hot-melt extrusion, distinguished by the number of screws.

2.11 Single-screw extruder.

This type of extruder machine has a single screw and is mainly used to produce homogenous polymers in a continuous form (Geus, 2016). When the screw turns, frictional forces are created between the moving screw and the barrel surface, resulting in high pressure that compresses the material and causes it to flow and advance to the die, producing a filament (Patil et al., 2016).

Because single-screw extruders lack shear deformation, agglomeration and poor mixing can occur. Hence, single-screw extruders are appropriate for manufacturing filaments made of a single polymer material. However, it is challenging to extrude polymer composite filaments of superior quality that involve mixing two or more components.

2.12 Twin-screw extruder.

This extruder machine comprises two screws that run parallel to the barrel. A twin-screw extruder, as opposed to a single-screw extruder, generates more shear stress not just between the screws and the barrel but also between the rotating screws, resulting in the uniform mixing of feedstock materials (Tan et al., 2018).

When the molten material is forced between the screws during extrusion, it strains and generates a viscous flow by dissipating heat. Consequently, the speed and heat produced by the screws operate separately, and reversing the direction of the two rotating screws can increase shear forces. There are two types of rotating screws: co-rotating screws that turn in the same direction and counter-rotating screws that turn in opposite directions.

The counter-rotating method is more effective for distributing fillers in the polymer matrix because it generates more substantial shear stresses when the materials are compressed between the screws (Crowley et al., 2007).

A twin-screw extruder is used to make polymer composite filaments because it is more efficient in homogeneously mixing two or more components.

Table 1. Comparison between Single-screw and Twin-screw Extruders (Geus, 2016).

Types of extrusion	Advantages	Disadvantages
Single-screw extrusion	Low cost, mechanical simplicity, low maintenance	Poor mixing, and not suitable for heat-sensitive materials
Twin-screw extrusion	High dispersing capacity, resulting in better mixing, better control of process parameters, easy material feeding, and high productivity and flexibility	Relatively high cost, high input energy, and not suitable for shear-sensitive materials

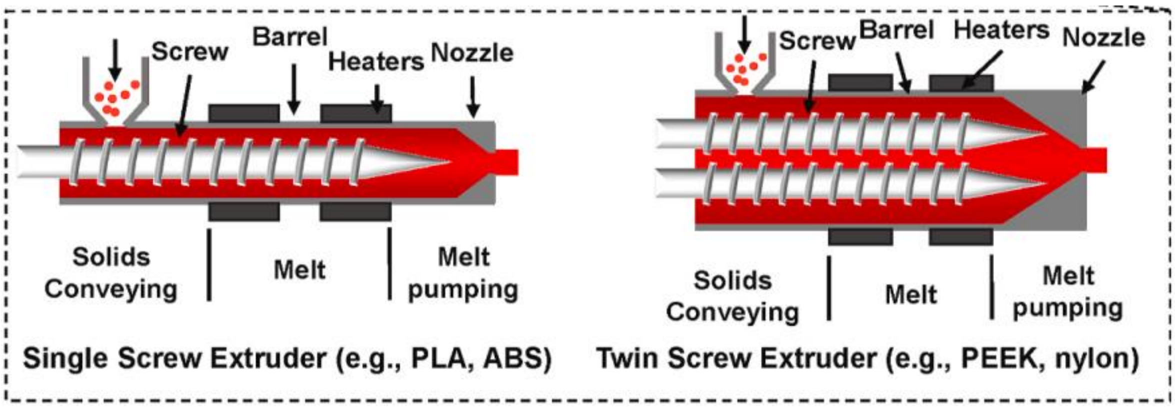


Figure 14. Schematic representation of Single and Twin-screw extruders (Park & Fu, 2021).

FDM Filament equipment.

Filament extruders convert FDM feedstock material pellets into 3D printable filaments by melting them and passing them through an output nozzle. The filament extruder contains many heating and cooling stages, sensors, and numerous more devices to guarantee that the filament is appropriately extruded.

Commercial filament extruders corporations use for bulk spool production cost tens of thousands of dollars and take up much space. However, additional consumer filament extruders have lately emerged, intending to reuse waste material or cut costs by producing their filament. These extruders are available in kits, pre-assembled machines, or open-source DIY (Do-It-Yourself) projects. The selection of an appropriate filament extruder is often based on the critical factors.

- **Type of assembly**. Filament extruder assembly determines how easily technical and non-technical persons may build the extruder.
- **Speed**. The speed specifies the capability of the filament extruder in a specific period. This metric may also be used to calculate the output power of a filament extruder.

- **Supporting materials**. Given the specific process characteristics, such as the extrusion temperature of the various commonly used filament feedstock materials, knowing the kind of extruder and material feedstock supported for extrusion is critical.

2.13 Commercially available Desktop filament extruders.

These include, but are not limited to, those briefly detailed below (All3DP, 2022; O'Connell, 2021).

2.14 Filabot EX2.

Source: https://www.filabot.com/

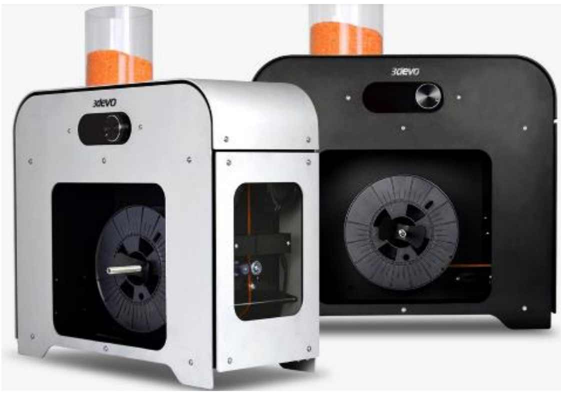
The Filabot EX2 has a three-stage extrusion screw that pressurizes polymers throughout the extrusion process, aiding in diameter control and increasing total production. Furthermore, the screw's mixing capacity applies shear stress between the polymer and the barrel wall. This extruder additionally incorporates an extrusion speed control board with an automated, variable voltage control module designed to adjust the precise RPM of the screw when extrusion forces fluctuate. The Filabot EX2 has a maximum temperature of 450 °C, can extrude a wide variety of feedstock materials, and comes pre-assembled. It features one heat zone, a PID controller, a speed of 35 rpm, and is simple to use. Physical dimensions of (45.75x17.78x22.86) cm. It can extrude polymers such as ABS, PLA, PC, HIPS, and PETG (Filabot, 2022).

2.15 Wellzoom desktop filament extruder.

Source: http://wellzoomextruder.com/

The extruder is in a well-designed casing with a small hopper. It has a maximum temperature of 300 ℃, a PID controller, is simple to operate, and is pre-assembled. Physical dimensions of (50.8x14.02x25.4) cm. It can extrude polymers like ABS, PLA, and PVA (Wellzoom, 2022).

2.16 3devo Precision 350.



Source: https://www.3devo.com/

This Precision and Composed extruder are for filament production and material testing. The extruder produces a filament with a diameter sensor with a precision of 43 microns using four heating zones. It is simple to operate, as the machine has a filament spool holder that spools the extruded filament. It features a maximum extrusion temperature of 350 °C, a rotational speed of 15 rpm, and a PID controller with USB connectivity. It is pre-assembled. Physical dimensions of (44.8x50.6x21.6) cm. It can extrude polymers such as ABS, PLA, PC, and PS (3devo, 2022).

2.17 ReDeTe ProtoCycler+.

Source: https://redetec.com/

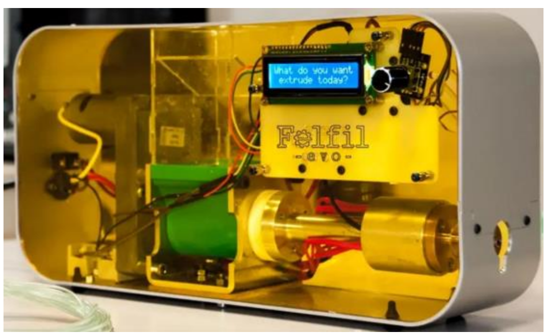
The ProtoCycler+ desktop extruder is the most sophisticated on the market. It has cutting-edge extrusion machinery and digitally controlled filament diameter. Furthermore, it has cutting-edge software that offers a new degree of extrusion control when working with polymers and additives. It has a maximum extrusion temperature of 250 °C, a PID controller, is simple to use, and is delivered pre-assembled. Physical dimensions of (38.1x35.56x22.86) cm. It can extrude polymers like ABS, PLA, PETG, HIPS, and PA. (ReDeTec, 2022).

2.18 Noztek Pro Desktop Extruder.

Source: https://noztek.com/

The Noztek team developed the Noztek FusionX extruder, one of the market's most advanced desktop single-screw filament extruders. The Noztek Pro combines a high-torque planetary motor with a custom-engineered screw to provide quick extrusion flexibility for virtually any pellet or powder-form polymer. Furthermore, this extruder is dependable, straightforward, and simple to operate. It is pre-assembled and has a maximum extrusion temperature of 300 °C. It can extrude polymers such as ABS, PLA, PET, HDPE, and PP (Noztek, 2022).

2.19 Felfil Evo (Kit).



Source: https://felfil.com/

The Evo is a filament extruder manufactured by Felfil, a business specializing in manufacturing machinery such as shredders and extruders. This extruder is available as a kit, which means it is complete or fully completed.

The extruder features three heating zones and two separate output extruder nozzles, allowing it to produce a filament with a diameter of 1.75 or 2.85 mm. It features a maximum extrusion temperature of 250 °C, 9 rpm, a PID controller, and an easy-medium usage difficulty. Physical dimensions of (35x18x10.8) cm. It can extrude polymers such as ABS, PLA, TPU, HIPS, and PA (Felfil, 2022).

2.20 Filastruder Kit.

Source: https://www.filastruder.com/

Filastruder has risen to prominence in the consumer filament extruder industry following the success of its Filastruder kit, which examined how consumers produce their filaments. The maximum extrusion temperature of the Filastruder is 260 °C, which limits the input material range. Furthermore, the assembly of this extruder necessitates intermediate electrical and mechanical abilities. It features one heat zone and a PID controller. Physical dimensions of (45.72x15.24x10.16) cm. It can extrude polymers such as ABS, PLA, PC, and PC (Filastruder, 2022).

2.21 FilaFab.


Source: https://www.filafab.co.uk/

A Filafab extruder is durable and can handle a wide range of materials. This extruder extrudes materials ranging from standard types to novel compounds and other innovative materials. It has also been extensively employed in materials laboratories and for novel material research and development. Furthermore, the mobility, low ownership cost, and quick deployment of the Filafab extruder system enabled the project to be completed on schedule. This extruder has a maximum extrusion temperature of 240 °C, four heat zones controlled by a PID controller, and is pre-assembled. It can extrude polymers such as ABS, PLA, PET, HDPE, and PP (Filafab, 2022).

2.22 Comparison of Desktop Filament Extruders on the Market

Table 2. Desktop Filament Extruders available on the market

Manufacturer				
	Filabot	Wellzoom	3devo	ProtoCycler+
Extrusion rate[kg/h]	0.9	0.1	0.1	0.5
Hopper capacity [ml]	28.8	400	2000	n. a
Diameter tolerance	±0.05	±0.05	±0.05	±0.05
Filament diameter [mm]	1.75 or 2.85	1.75 or 2.85	0.5-3	n. a
Maximum temperature [°C]	450	300	450	250
Heat Zones	1	n. a	4	n. a
Power [W]	500	120	1300	120
Price ($)	6,856	588	7500	3,999
Control Mechanism	PID controller	PID controller	PID controller	PID controller
Pre-assembled	Yes	Yes	Yes	Yes
Physical Dimension (cm)	45.75x17.78x22.86	50.8x14.02x25.4	44.8x50.6x21.6	38.1x35.56x22.86
Material Used	ABS, PLA, PETG	ABS, PLA, PVA	ABS, PLA, PC,	ABS, PLA, PA
Difficulty of Use	Easy to use	Easy to use	Easy to use	Easy to use
References	(Filabot, 2022)	(Wellzoom, 2022)	(3devo, 2022)	(ReDeTec, 2022)

n.a: not available

Table 3. Continuation of Desktop Filament Extruders available on the market

		Manufacturer		
	Noztek Pro	Felfil Evo	Filastruder	FilaFab
Extrusion rate[kg/h]	*2.5	0.2	0.2	*1.2
Hopper capacity [ml]	n. a	1000	n. a	n. a
Diameter tolerance	±0.04	±0.07	±0.03	n. a
Filament diameter [mm]	1.75 or 2.85	1.75 or 2.85	1.75 or 3	1.75 or 2.85
Maximum temperature [°C]	300	250	260	240
Heat Zones	n. a	3	1	4
Power [W]	1100	180	60	350
Price ($)	2066.98	670.03	300	5587.96
Control Mechanism	Switch buttons	PID controller	PID controller	PID controller
Pre-assembled	Yes	Kit	Kit	Yes
Physical Dimension (cm)	n. a	35x18x10.8	45.72x15.24x10.16	n. a
Material Used	ABS, PLA, PET	ABS, PLA, TPU	ABS, PLA, PC, PC	ABS, PLA, PET
Difficulty of Use	Easy to use	Easy-medium	Medium	n. a
References	(Noztek, 2022)	(Felfil, 2022)	(Filastruder, 2022)	(Filafab, 2022)

*Extrusion rate (m/min)

How to Select the Best Desktop Extruder for FDM Filament Production on the Market Today.

Extruder selection in terms of ideal value based on the fundamentals of decision theory, with simple weighting for cost reduction (Temesi J, 2002). The weighing system combines many aspects in a weighting system where the total weight is 1. The choice with the highest sum of weighted values is chosen.

The chosen weighting system (W) for cost minimization.

W = (0.2,0.1,0.1,0.2,0.1,0.3) respectively.

From Table 3, the ideal value for extruder selection is calculated for the respective extruders fully documented and identified parameters.

Table 4. Chosen Parameters for Selected Commercial Extruders

Manufacturer	Extrusion rate[kg/h]	Hopper capacity [ml]	Maximum Extrusion temperature [°C]	Power [W]	Price ($)
Filabot	0.9	28.8	450	500	6,856
Wellzoom	0.1	400	300	120	588
3devo	1	2000	450	1300	7500
Felfil Evo	0.2	1000	250	180	670

Table 5. Data Modification for Cost minimization (Own Work)

Manufacturer	Extrusion rate[kg/h]	Hopper capacity [ml]	Maximum Extrusion temperature [°C]	Power [W]	Price ($)
Filabot	0.9	0.01	1.00	4.17	11.66
Wellzoom	0.1	0.20	0.67	1.00	1.00
3devo	1	1.00	1.00	10.83	12.76
Felfil Evo	0.2	0.50	0.56	1.50	1.14

Table 6. The Transformed Data (Own Work)

	[a]0.2	[b]0.1	[c]0.3	[d]0.2	[e]0.2
Manufacturer	Extrusion rate[kg/h]	Hopper capacity [ml]	Maximum extrusion temperature [°C]	Power [W]	Price ($)
Filabot	0.9	0.01	1.00	4.17	11.66
Wellzoom	0.1	0.20	0.67	1.00	1.00
3devo	1	1.00	1.00	10.83	12.76
Felfil Evo	0.2	0.50	0.56	1.50	1.14

[abcde]: Weighting system multipliers

Table 7. Final Data After Considering the Weighting System (Own Work)

Manufacturer	Extrusion rate[kg/h]	Hopper capacity [ml]	Maximum extrusion temperature [°C]	Power [W]	Price ($)	Total
Filabot	0.18	0.00	0.30	0.83	2.33	3.65
Wellzoom	0.02	0.02	0.20	0.20	0.20	0.64
3devo	0.20	0.10	0.30	2.17	2.55	*5.32
Felfil Evo	0.04	0.05	0.17	0.30	0.23	0.78

*Extruder with the greatest sum of the weighted values.

From the sum of the weighted values in Table 7, economically, the 3devo extruder is an ideal choice from the commercially available filament extruders.

2.23 Main Applications of FDM.

FDM has been utilized in various industries such as automotive, aviation, rail, defence, maritime, medical and dental, electronics, architecture, sports, art and design, the textile industry, the food industry, research and science, education, jewellery, and consumer goods (Jasiuk et al., 2018).

By 2026, it is anticipated that FDM's cumulative annual growth rate (CAGR) will increase between 18% and 32% in various sectors, including the medical, automotive, aerospace, and food industries. Polymers are mainly used for proof-of-concept, prototype applications, and industries like biomedical, dentistry, electronics, sports, consumer goods, and industrial products (Wickramasinghe et al., 2020).

2.24 Advantages and disadvantages of FDM

FDM technology is widely adopted in the fast-prototyping industry due to the following advantages:

- FDM technology may be used as an automation approach to substitute human labor, increasing productivity.
- FDM facilitates a low-cost transfer from traditional mass production to new customized product applications. Companies use FDM to provide their customers with better product choices, customized items, or shorter product life cycles over time.
- FDM enables material optimization by reducing the physical flow of materials, which has economic benefits; this leads to efficient resource utilization and customized products based on customer satisfaction, resulting in positive ecological effects.
- The rapid fabrication of parts and reduced material waste in proportion to the number of materials used in model construction.
- The ability to print elements made of high-strength thermoplastics with great strength and resilience to high temperatures and chemicals.
- Many materials are available, and produced parts are reasonably accurate.
- The ability to program any configuration of the constructed model, including filling density, layer height of the created item, and model wall thickness, leads to processing control and model parameter setting.
- The flexibility provided by FDM allows for the efficient generation of objects that would have been impossible to produce using previous technologies.

FDM's disadvantages.

- Printed products have a high anisotropy.
- The requirement to employ support structures.
- The model's surface is of inferior quality, with plainly visible and identifiable layers of the applied and solidified material. It requires some final touches. It adds to the comparatively high cost of making many things compared to other additive technologies, particularly those that process polymers.

2.25 Defects in FDM printing.

FDM technology has various limitations, from generating the GCODE file to optimizing the printing process and parameters. The most frequent FDM defects are summarized here.

- **Elephant feet.** The printed object's base has been somewhat expanded. The most common reason is an overheated constructed platform on which the item is created.
- **The printed object's edges are warped.** It is generated by excessive material shrinkage or quick cooling of the printed object.
- **Losses between the walls and the filling of the item.** The most common reason is the inappropriate configuration of the width values of the extruded material channels and inaccurate printing nozzle diameter selection.
- **Filling of the model is evident on the model's exterior walls.** This arises from incorrect wall thickness setting, i.e., too thin external wall.
- **Cracks on high objects.** It is caused by a lack of a hot printer chamber or by the produced object cooling too quickly.
- **Poor reproduction of small object details.** They are caused by a boiling head, a high-speed rate of delivering the batch material to the head, or an inappropriately adjusted fan speed for cooling the printed object.
- **Misalignment of the applied layers.** There is slack in the kinematics system because of poor tensioning of the axle drive belts.

Figure 15. Shift of the model layers (Sastri, 2022).

- **Losses in the layers of the model.** These are caused by an insufficient printing temperature or a partly blocked nozzle.

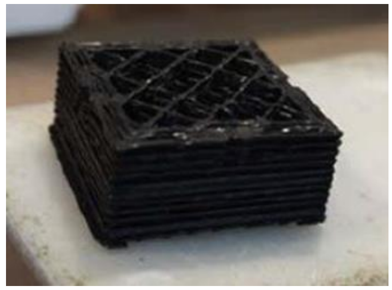


Figure 16. Losses in model layers (Sastri, 2022).

- **Visible undulation of the external surfaces of the object.** It is caused by incorrect timing belt tension on the printer's driving axes and poor head acceleration.

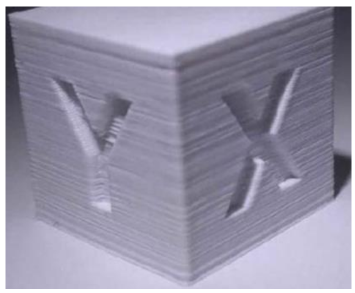


Figure 17. Visible waving of external surfaces of the model (Sastri, 2022).

- **Cobweb effect.** An incorrectly set parameter causes it for print head retraction, i.e., a parameter responsible for the retraction of the material at a suitable pace across a specified distance during idle head passes.

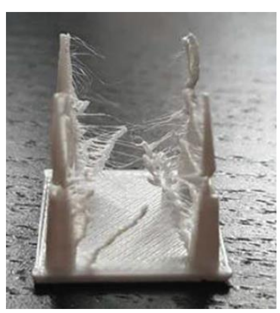


Figure 18. Cobweb effect (Sastri, 2022).

2.26 Significant challenges for FDM application.

The industry faces the following critical problems while implementing FDM technology:

- High material costs.

- Material or multi-material limitations in delivering physical and mechanical qualities required for the application while maintaining design correctness.

Conclusion.

FDM techniques are designed to process a specific category of ever-changing market materials to meet the most diversified demands of today's end-users. Although the industry is expanding and evolving rapidly to fulfil the needs of manufacturers and consumers, there are still certain limitations in the materials available to meet specific printing requirements.

Furthermore, as the price of desktop FDM technology declines, there is a growing need for thermoplastic filament type of material, which creates a fertile field for the expansion of various filament makers to replace or at least complement existing production processes.

Another requirement is for material development and FDM technology development per the goal of Sustainable Development Goals, hence the need for inexpensive and sustainable FDM polymer filaments.

2.27 Material for FDM Filaments

The thin strand, known as filament material, which is used to print an item layer by layer, is a critical component of an FDM printer.

Figure 19. Filament spool (Kloski & Kloski, 2021).

The excessive length of the homogeneous cross-section of a filament distinguishes it. The most popular filament diameter sizes are 1.75- and 2.85-mm. Multiple options are available when selecting materials, and fresh materials frequently come up in 3D Printing. As a result, single-screw extruders are appropriate for creating pure polymer filaments. However, it becomes challenging to extrude high-quality polymer composite filaments that demand to blend of two or more components. **See Figure 20.**

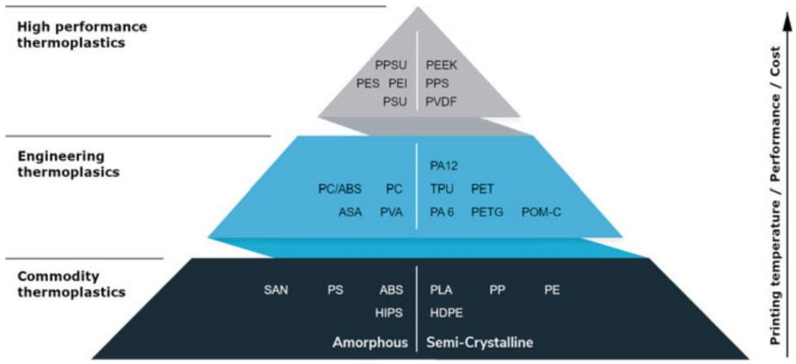


Figure 20. Thermoplastic material pyramid for FDM filament materials (Dave & Davim, 2021).

Polylactic acid (PLA), polycarbonate (PC), polyethylene terephthalate (PET), nylon (PA), and acrylonitrile-butadiene-styrene (ABS) are examples of standard and engineering thermoplastics that are widely used as FDM materials. Because of the variety of feedstocks available, it is critical to understand material qualities (physical and mechanical properties) and printability when selecting the suitable polymer for the finished part (Park & Fu, 2021).

FDM polymer filament is classified into pure polymer filament and composite filament according to its composition. Polymer raw materials for FDM are turned into continuous filaments after being processed into polymers and pellets (Park & Fu, 2021).

2.28 Thermoplastics for the manufacture of filaments

Because of their versatility, which allows for the printing of complex shapes, thermoplastic polymers are the most often utilized feedstock for the FDM process (Mohan et al., 2017). Furthermore, the heating element on most commercial FDM machines typically has a maximum working temperature of around 300℃, implying that materials with a low melting point may be utilized for FFF machines (Mohan et al., 2017).

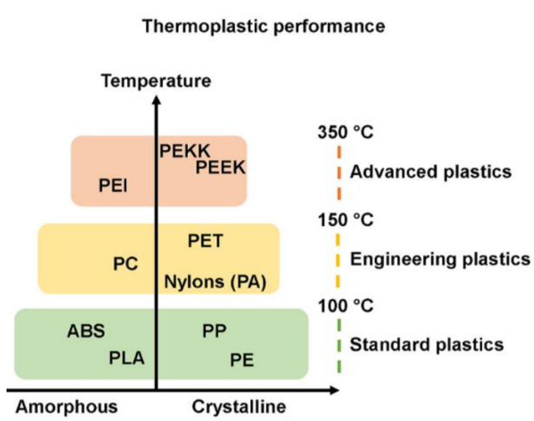


Figure 21. Typical thermoplastics are classified based on their performance (Park & Fu, 2021).

From **Figure 21**. Thermoplastics as FDM feedstock materials.

(a) **Standard plastics.** For ordinary parts that are subjected to mild stresses, acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polypropylene (PP), and polyethylene (PE) are preferred.

(b) **Engineering plastics.** (Polycarbonate (PC), polyethylene terephthalate (PET), and nylon (PA)) have superior wear resistance compared to ordinary plastics and are used in structural components.

(c) **Advanced plastics.** Polyethyleneimine (PEI) and polyether-ether-ketone (PEEK) have a strong temperature, wear, and chemical resistance.

Because the feedstock material directly influences the physical properties and printing behaviour of printed parts, material selection should be made prior to CAD modelling, taking into consideration heat resistance, impact resistance, and elongation break. The ease of printing refers to how simple it is to print a feedstock in terms of bed adhesion, maximum print speed, ease of feeding to the printer, and the frequency of print failures. In contrast, visual quality refers to how good the printed part looks, which is determined by surface quality, such as surface smoothness. These perspectives are significant while selecting materials for FDM (Park & Fu, 2021).

2.29 Thermoplastic materials for FDM Filaments in the market.

Polymer raw materials for FDM are converted into continuous filaments after being processed into polymers and pellets. According to the scientific literature, polymers have mechanical resistance in terms of tensile strength ranging between ranging between (1.5 – 150) MPa (Medellin-Castillo & Zaragoza-Siqueiros, 2019; Pervaiz et al., 2021).

The most used thermoplastics in FDM technology are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) (Algarni & Ghazali, 2021; Cao & Xie, 2017).

Due to their melting point and glass transition temperature, ABS and PLA possess thermal and rheological properties that enable them to be swiftly processed utilizing FDM technology (Mohan et al., 2017).

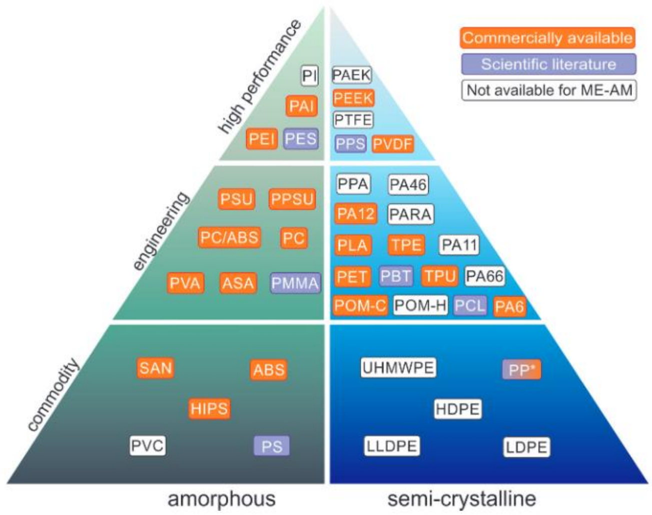


Figure 22. Polymeric material pyramid (He et al., 2014; Spoerk et al., 2020).

Table 8. Commercially Available Polymers for FDM Filaments, adapted from (Wu et al., 2020)

Polymer type	Material	Manufacturer
ABS	Acrylonitrile butadiene styrene (ABS)	Ultimaker, Makerbot, 3dxtech, etc.
	ABS-ESD7	Stratasys
	ABSi	Stratasys
	ABS-M30	Stratasys
	ABS-M30i	Stratasys
	ABSplus	Stratasys
	Agilus30	Stratasys
ASA	Acrylonitrile-styrene-acrylate (ASA)	Stratasys, 3dxtech, etc.
PE	High density polyethylene (HDPE)	Filaments.ca
PP	Polypropylene	Ultimaker, etc.
PS	High impact polystyrene (HIPS)	MatterHackers, etc.
Nylon	Nylon 6	Stratasys, 3dxtech etc.
	Nylon 12	Stratasys
	Nylon 12 CF	Stratasys
PC	Polycarbonate (PC)	Ultimaker, 3dxtech, etc.
	PC-ABS	Stratasys, 3dxtech, etc.
	PC-ISO	Stratasys
PLA	Polylactic acid (PLA)	Stratasys, Ultimaker, 3dxtech, etc.
PPSF/PPSU	Polyphenylsulfone	Stratasys, 3dxtech, etc.
TPE	Thermoplastic elastomer (TPE)	MatterHackers
TPU	Thermoplastic polyurethane (TPU)	Stratasys, Ultimaker etc.
ULTEM™	Polyethylenimine (PEI)	SABIC
PEEK	Polyether ether ketone	Solvay, Evonik, Victrex
PEKK	Polyether ketone ketone	Arkema

Thermoplastic filaments must possess varying characteristics, such as durability against chemicals, suitability for use in living systems, resistance to high temperatures, pliability, and robustness, to fulfil the specific needs of industrial applications and end products (Dey & Yodo, 2019).

The following thermoplastic polymer materials are commonly utilized in manufacturing FDM filaments for prototype development in 3D printing.

Nylon or polyamide (PA). Nylon has a low friction coefficient and is slightly flexible and slippery. When combined with the right colours, it may be vital. Because of its resilience and flexibility, Nylon has been regarded as a desirable thermoplastic for 3DP components with thin walls. Nylon is highly abrasion-resistant because of its high melting point and low coefficient of friction. It should be used when printing pieces with a lot of surface contact. The overall excellence of the printed components is linked to the fact that Nylon tends to absorb moisture (Terekhina et al., 2019).

Tools, working prototypes, or mechanical parts like hinges, buckles, or gears are examples of applications.

Polylactic acid (PLA). PLA is a type of polymer produced from plants and can be broken down naturally. It is created from a non-edible carbohydrate (sugar) derived from corn (Kloski & Kloski, 2021).

PLA is available in a variety of rigidity levels and colours. PLA is believed to be relatively easy to print compared to other polymer materials due to its low melting temperature. PLA is a thermoplastic aliphatic polyester utilized in FDM 3DP technology in products that necessitate biodegradable polymers. PLA is a biopolymer widely explored for renewable aliphatic and biodegradable polyester. It is described as capable of replacing traditional petrochemical-based polymers in biomedical applications requiring biomaterial characteristics (Gebler et al., 2014).

PLA is useful in the industrial packaging and biomedical fields due to its biocompatibility and strong mechanical qualities (relatively high strength and modulus) (DeStefano et al., 2020).

PLA prints nicely and is the preferred material for most consumer 3D printers for various reasons, including the fact that it produces less odour during printing. It is inexpensive, easy to find, and an excellent choice for beginners and educational settings (Kloski & Kloski, 2021).

Models, low-wear toys, prototype parts, and containers are typical applications.

Acrylonitrile butadiene styrene (ABS). ABS was introduced in the 1950s as a more stringent alternative to styrene–acrylonitrile (SAN) copolymers. ABS is a petroleum-based amorphous and thermoplastic polymer. It is not biodegradable and is extruded at high temperatures, around 220-280 degrees Celsius. ABS mechanical parameters reported in the literature include tensile strength ranging from 13.0 to 65.0 MPa, Young's modulus ranging from 1.00 to 2.65 GPa, and flexural strength of 66 MPa (Algarni & Ghazali, 2021; Rajendran Royan et al., 2021; Vidakis et al., 2020).

ABS is widely used in industry due to its impact resistance and hardness, for example, in the prototype and manufacturing of toys, boats, and car components (Algarni & Ghazali, 2021; Rett et al., 2021; Vidakis et al., 2020). On the other hand, ABS is a non-biodegradable substance with moderate toxicity (Mohan et al., 2017).

Phone covers, high-wear toys, tool handles, vehicle trim components, and electrical enclosures are typical applications.

Polyethene terephthalate glycol (PETG). PETG is a thermoplastic polymer developed from the terephthalate family of polyethene. PETG polymers are more robust, flexible, and softer than PLA and ABS. The temperature of PETG extrusion ranges from 220 to 250 C. PETG has a tensile strength of 49 MPa and a flexural strength of 70 MPa (Guessasma et al., 2019; Vidakis et al., 2020). PETG is widely used in medical implants and food packaging (Algarni & Ghazali, 2021).

Examples of typical applications are functional items that may be subjected to persistent or abrupt stress (such as mechanical parts), printer parts, and protective components.

High impact polystyrene (HIPS). HIPS is a type of thermoplastic that can naturally break down and decompose while having low durability and being easy to shape and manipulate. HIPS has good flow properties, is impact resistant, and is inexpensive (Kumar et al., 2018). However, HIPS has poor abrasion resistance and requires high printing temperatures and heated build platforms for component manufacturing (Ahn et al., 2002).

Parts that must withstand wear and tear and projects that require a finishing-friendly material to create the desired aesthetic are examples of typical applications.

Polypropylene (PP). PP is a polyolefin homopolymer and one of the most often used low-density and low-cost thermoplastic semi-crystals. Because of their physical and chemical qualities, PP filaments may be employed in various industrial applications, including military, domestic goods, automobiles, and construction. PP, on the other hand, has poor thermal, electrical, and mechanical properties (G. Gao et al., 2022; Herianto et al., 2020).

Hardy and light materials are typical applications.

Polycarbonate (PC). PC is a filament from the polycarbonate plastic group. Polycarbonates are polymers with good mechanical qualities used in CD and DVD casings. PC's strength comes in its impact resistance, heat resistance, toughness, and hardness. Polycarbonates are flame retardant and electrically insulating. Examples of typical applications are electrical, mechanical, or automotive components, lighting projects, displays, and other applications that need transparency.

Polyetherimide (PEI): PEI is a lightweight thermoplastic material with solid mechanical characteristics and is resistant to high temperatures and smoke. It has a high glass transition temperature and is also biocompatible. Unfortunately, PEI-based FFF products have poor surface polish and dimensional accuracy (Padovano et al., 2020).

Polyetheretherketone (PEEK): PEEK is a non-biodegradable thermoplastic biomaterial that possesses robust capabilities in terms of heat resistance, stability, and mechanical strength. When being extruded, its temperature range typically falls between 340 to 440℃. Furthermore, PEEK displays a tensile strength of 100 MPa and a flexural strength of 170 MPa (Algarni & Ghazali, 2021; Zanjanijam et al., 2020). PEEK is used to produce both aircraft components and medicinal applications that aid in reconstructing human bone tissues (Pervaiz et al., 2021; Rajendran Royan et al., 2021; Zanjanijam et al., 2020).

Other polymers used for FDM technology include Polycaprolactone (PCL), polymethyl methacrylate (PMMA), polystyrene (PS), and different variations of polyethylene (PE) like low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), and polyethylene terephthalate (PET) (Algarni & Ghazali, 2021; González-Henríquez et al., 2019; Vidakis et al., 2020; Vyavahare et al., 2020). Most of these substances are not eco-friendly, and their decomposition rate differs based on the surrounding environmental conditions (Dey et al., 2021).

When deciding which filament material to use for a specific purpose, it is crucial to consider both the quality and the desired characteristics of the final product. Depending on the application, PLA-based filaments can be helpful for things like food packaging and medical implants, while ABS and HIPS filaments are better suited for high-impact applications. It is crucial to thoroughly understand filament materials' mechanical and thermal properties, electrical resistance, and fatigue behaviour, as these can vary between manufacturers and customers. Any variations can be due to material quality, manufacturing processes, and test environments. Furthermore, the quality of the FFF equipment, the process settings, and the handling of materials by the user can also play a role in determining variability.

Table 9. General Properties of Thermoplastic Filament Materials, adapted from (Dey et al., 2021)

Material	Source	Advantages	Disadvantages	Printing Temperature Range
ABS	Petroleum	Good impact resistance, toughness, inexpensive	Prone to warp, produce unpleasant gases	210–250 °C
PLA	Plant starch	Biodegradable, does not warp, inexpensive	Poor mechanical properties, rough texture, brittle	190–230 °C
PC	Bisphenol	Strong and flexible, good optical properties	High print temperature, absorb moisture	260–310 °C
PEEK	Bisphenolate	Good rigidity and strength, light weight, heat and chemical resistance	High print temperatures, expensive, prone to warp	360–420 °C
PEI	Bisphenol-A dianhydride	Good heat resistance, chemical stability, good rigidity, and strength	High print temperatures, expensive, prone to warp, difficult to print	340–380 °C
Nylon	Crude oil	Good mechanical Properties, inexpensive, wear resistance, heat resistance	Prone to warp, high printing temperature	240–270 °C
HIPS	Petroleum	Dissolvability, high impact resistance, biodegradable	Prone to warp, heated build platform required, emits styrene while printing	220–250 °C

2.30 Pellets and Recycled materials.

Pellets.

In the extruder, resin pellets mould into filaments for FDM printing. The diameter and length of pellets are typically 1 to 3 mm (Whyman et al., 2018).

The polymers used in 3D printing in the form of pellets are equivalent to the polymers used in the form of filaments, primarily: PLA, ABS, HIPS, PET, and PETG (Woern & Pearce, 2018).

PLA pellets. PLA filament production begins with corn fermentation, condensation, and polymerization, after which the material is pelletized and extruded into filaments (Park & Fu, 2021). **See Figure 23.**

Figure 23. PLA filaments material processing, adapted from (Park & Fu, 2021).

Recycled materials.

As the feedstock for FDM filament production, virgin polymer pellets, and shredded recycled plastic waste may be utilized. This is consistent with the SDGs for Sustainable Development.

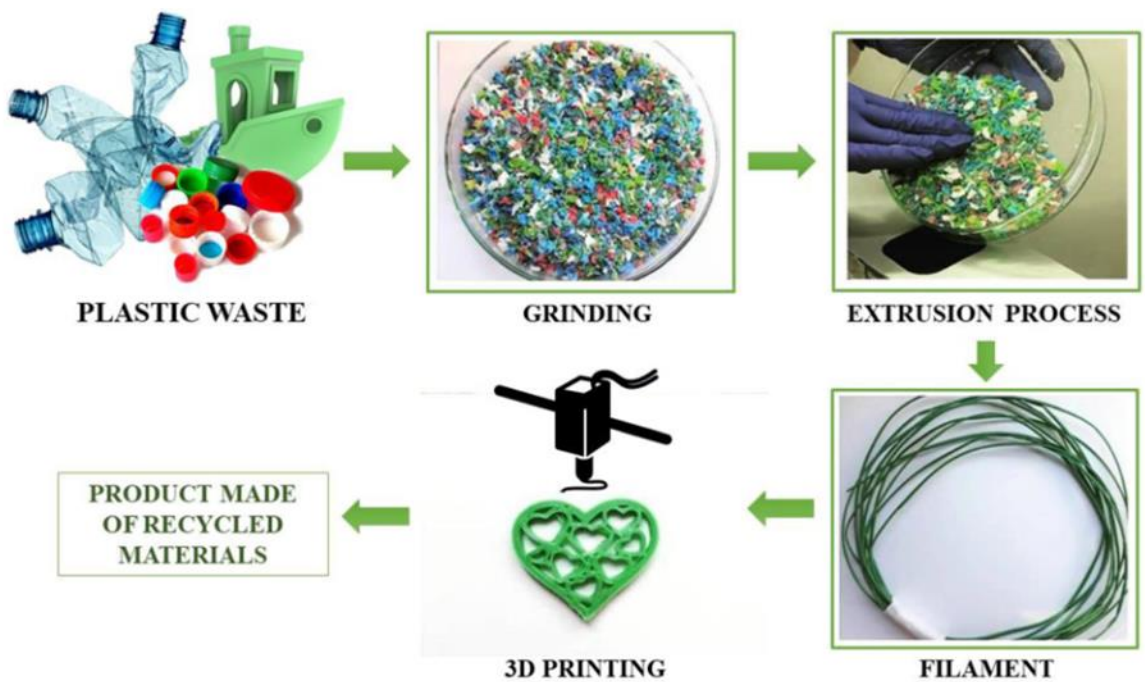


Figure 24. Material recycling system for filament fabrication (Mikula et al., 2020).

Table 10. Recycled Polymer Filaments for Commercial Use, adapted from (Mikula et al., 2020)

Manufacturer	Material	Source	Contnet of r-plastic (%)	Price (€)
B-PET	PET	PET bottles	100%	n.a.
Filamentive	PLA	Factory waste streams	55%	35.57
	ASA	n.a.	50%	36.82
	PETg	Plastic food containers and drinks bottles	99.5%	36.93
	PET	Plastic bottles	100%	37.62
	ABS	n.a.	64%	35.57
Fila-cycle	PLA	Yogurt pots	100%	n.a.
	ABS	Automotive waste	n.a.	
	PET	Bottle plastics		
	HIPS	Automotive Industrial Plastics, Home Electronics Industry		
Refil	HIPS	Refrigerators	100%	n.a.
	ABS	Car dashboards		
	PLA	Food packaging		
	PET	Blue bottles		
Innofil3D	PET	Recycled PET materials	100%	39.95
Fishy filaments Porthcurno	Nylon	Fishy nets	100%	34.21
Tridea	PET	PET food containers	100%	29.99
	PLA	n.a		27.99
CREAMELT	TPU	Recycled ski boots	100%	37.43

n.a. not available

2.31 Composite filament materials.

A composite filament comprises two or more components or phases, creating unique traits that are unattainable with a single element. Consequently, composites exhibit improved qualities when compared to pure polymers (Kabir et al., 2020; Penumakala et al., 2020; Rahim et al., 2019).

FDM printer filaments are available in a range of polymer materials and polymer-based composites that include fibre and particle reinforcement. Carbon fibre, glass fibre, Kevlar, wood, metal powder, and other reinforcing materials can be premixed with thermoplastic to create filament (Dave & Davim, 2021).

Certain thermoplastic filaments' limited strength and stiffness restrict their usage in the industry as the resulting printed products need to meet the necessary operational standards (Ahn et al., 2002). Various commercial and industrial applications can benefit from the superior qualities of FDM composite filament materials, including lightness, increased strength, and improved surface quality.

2.32 Composites of thermoplastic filaments.

Thermoplastic filament composites are formed mainly via mixing and extrusion (Valino et al., 2019). ABS, PLA, and PA are thermoplastic matrix materials that are commercially accessible.

Reinforced PLA filaments have improved structural and mechanical properties, as well as biocompatibility, for a variety of biological applications. For example, PLA/graphene oxide (GO) nanocomposite filament, used in the FDM 3D printing scaffolding method, has the potential for bone-forming application (Belaid et al., 2020).

ABS refers to a range of acrylonitrile blends, copolymers, butadiene-containing polymers, and styrene. Additionally, graphene oxide (GO) can be added to ABS composite filament to increase its tensile strength and Young's modulus, depending on the intended industrial application for 3D printing (Aumnate et al., 2018). Filler elements like fibers, particles, or nanoparticle-based compounds enhance strength. Reinforcement fibers come in two types: continuous and discontinuous. Continuous fibers require specialized printing equipment due to their high aspect ratio, and while they provide high strength, stiffness, and desired orientation, they are not widely used. Discontinuous fibers, on the other hand, are easy to use and cost-effective due to their low aspect ratio and random orientation. Necessary reinforcement materials include carbon fiber (CF), glass fiber (GF), and Kevlar (KF). In contrast, common matrix materials include polyether ether ketone (PEEK), acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and nylon (PA) (Wickramasinghe et al., 2020).

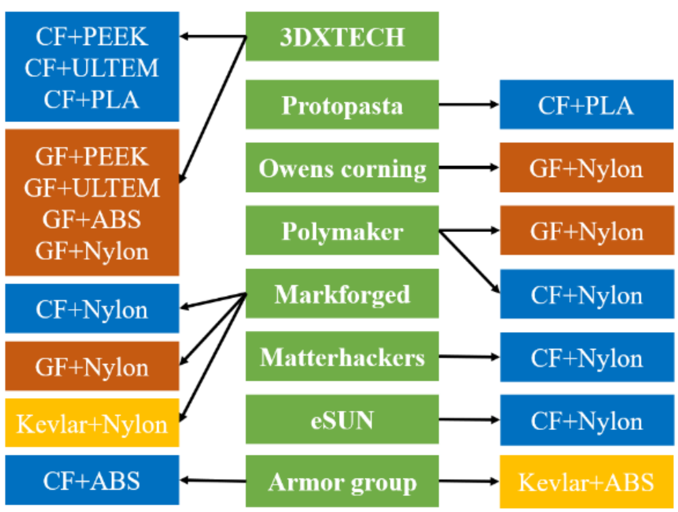


Figure 25. FDM fibre-reinforced composite filaments (Wickramasinghe et al., 2020).

Because of the advancement of various materials in AM technologies, the medical, aerospace, automotive, food, and engineering sectors have all begun to employ polymer composites for applications in functional devices (Peterson, 2019).

Table 11. Thermoplastic Applications in Various Industries Using FDM

3D printer type	Application	Manufacturer
Fused deposition modeling	CMM fixtures	Moog Aircraft
	3D demonstrator, optimizing zero-inventory supply chain	Stratasys
	Motorcycle rear fender support	Spring SRL-Italy
	Satellite development	Stratasys-NASA
	ABS injection mold components	Stratasys-TURCK
	Sports shoes	ADIDAS
	Automotive dashboard	Stratasys
	Design concept bike frames	Santa Cruz Bicycles
	Jigs and fixtures	Solaxis Ingenious Manufacturing
	Helmet prototype	Stratasys

Source: Courtesy: Team Stratasys white paper.

2.33 Biopolymers and hydrogels.

Biomedical 3D printing may make use of biopolymers and hydrogels. The biomedical industry significantly influences the growth of additive manufacturing and the introduction of novel materials (Ngo et al., 2018). AM technology is currently most used in bioprinting scaffolds and tissue engineering. However, the effort is also being made to develop prosthetic repair organs such as bionic ears and tissues (Lee et al., 2017).

Polyethylene glycol diacrylate (PEGDA), PLA, and polycaprolactone (PCL) are the most common polymers used in biomaterial 3D printing. Because these polymers are not photosensitive, they must be functionalized with methacrylate, diacrylate, or fumarate groups to form a photopolymer resin. PEGDA is used in the manufacture of hydrogels in scaffold printing. Polymeric materials, including hydroxyapatite and different polymers such as poly (ester urea), poly (propylene fumarate) or PCL, and PLA, are used to print 3D bone scaffolds (Laura et al., 2018).

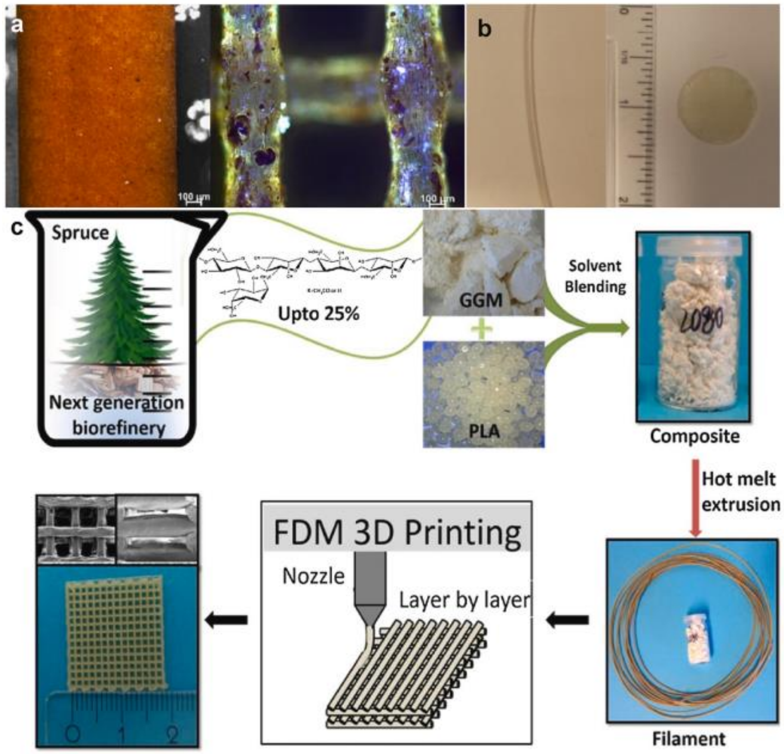


Figure 26. Biomaterial applications for composite filaments (Gkartzou et al., 2017; Liu et al., 2019; Murphy & Collins, 2018; Saleh Alghamdi et al., 2021).

Table 12. Filament Properties table of Commercially Available Polymers

	 ABS	 PLA	 HIPS	 PETG	 Nylon	 Polycarbonate
	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More
Compare Selected / Show All	☐	☐	☐	☐	☐	☐
Ultimate Strength	40 MPa	65 MPa	32 MPa	53 MPa	40 - 85 MPa	72 MPa
Stiffness	5 / 10	7.5 / 10	10 / 10	5 / 10	5 / 10	6 / 10
Durability	8 / 10	4 / 10	7 / 10	8 / 10	10 / 10	10 / 10
Maximum Service Temperature	98 °C	52 °C	100 °C	73 °C	80 - 95 °C	121 °C
Coefficient of Thermal Expansion	90 µm/m-°C	68 µm/m-°C	80 µm/m-°C	60 µm/m-°C	95 µm/m-°C	69 µm/m-°C
Density	1.04 g/cm^3	1.24 g/cm^3	1.03 - 1.04 g/cm^3	1.23 g/cm^3	1.06 - 1.14 g/cm^3	1.2 g/cm^3
Price (per kg)	\$10 - \$40	\$10 - \$40	\$24 - \$32	\$20 - \$60	\$25 - \$65	\$40 - \$75
Printability	8 / 10	9 / 10	6 / 10	9 / 10	8 / 10	6 / 10
Extruder Temperature	220 - 250 °C	190 - 220 °C	230 - 245 °C	230 - 250 °C	220 - 270 °C	260 - 310 °C
Bed temperature	95 - 110 °C	45 - 60 °C	100 - 115 °C	75 - 90 °C	70 - 90 °C	80 - 120 °C
Heated Bed	Required	Optional	Required	Required	Required	Required

Source: https://www.simplify3d.com/support/materials-guide/properties-table

2.34 Storage of filaments.

Proper filament storage for 3D printing is vital as it decreases the number of changing factors between prints so that the settings are successful each time. Furthermore, the filament must be kept such that it does not collect dust and debris, which might block the nozzle. The filament should be stored in a clean, temperature-controlled environment when not used.

Many FDM materials, such as PLA and nylon, are hygroscopic, meaning they collect moisture from the surrounding air. As a result, the filament must be maintained away from a humid environment. The filament should be stored in an airtight container, such as a desiccant canister. (Kloski & Kloski, 2021).

A *desiccant canister* is a reusable canister used to remove moisture from small regions, boxes, and containers. It protects up to three cubic feet of confined space per canister. When one of the canisters is filled with materials or valuables, water vapor is absorbed and kept within the desiccant material, maintaining a safe relative humidity. Metal desiccants can only be recharged in an oven, but plastic desiccants can be recharged in both an oven and a microwave.

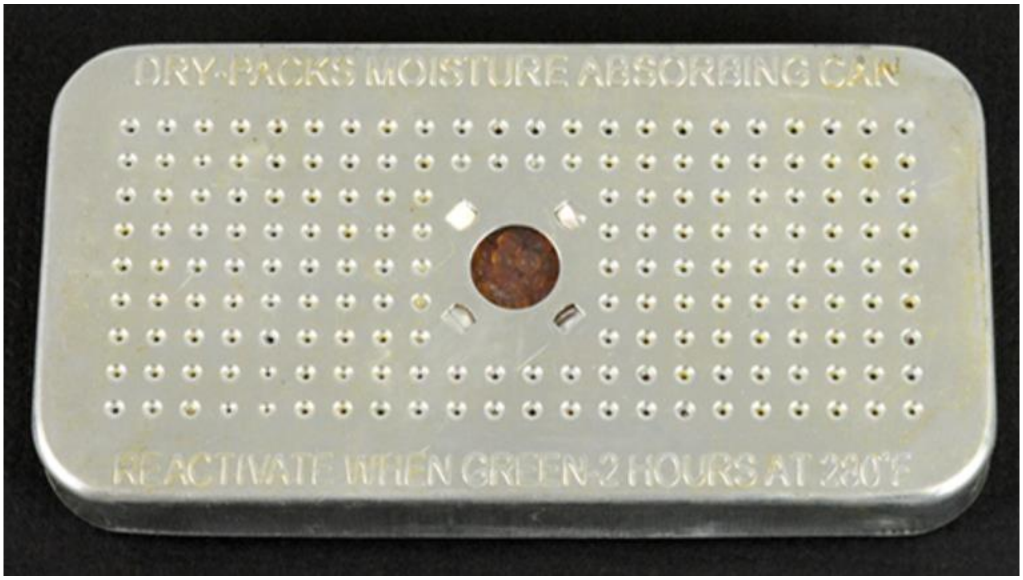


Figure 27. Desiccant for storing filament (Kloski & Kloski, 2021)

2.35 Polymer Material Selection for FDM Filament Fabrication.

Six significant features are chosen for the respective selected materials for comparison, as cited in the literature (ABS, PLA, PC, HIPS, PETG, and PA);

1. Extrusion temperature (^{0}C).
2. Bed temperature (^{0}C).
3. Ultimate strength (MPa).
4. Price ($).
5. Source of the material.
6. Biodegradability.

Table 13. Properties of Selected Materials for comparison (Own Work)

	Extrusion Temperature (℃)	Bed Temperature (℃)	Ultimate Strength (MPa)	Price ($)	Source	Biodegradability
ABS	220	95	40	10	Low	Poor
PLA	190	45	65	10	Very good	Very good
PC	260	80	72	40	Good	Poor
PA	220	70	85	25	Low	Poor
HIPS	230	100	32	24	Low	Poor
PETG	230	75	53	20	Good	Poor

Table 14. Quantification of the Qualitative Aspects (Own Work)

Poor	1 point
Low	3 points
Average	5 points
Good	7 points
Very good	9 points

Table 15. Modification of the Verbal Scale (Own Work)

	Extrusion Temperature (℃)	Bed temperature (℃)	Ultimate Strength (MPa)	Price ($)	Source	Biodegradability
ABS	220	95	40	10	3	1
PLA	190	45	65	10	9	9
PC	260	80	72	40	7	1
PA	220	70	85	25	3	1
HIPS	230	100	32	24	3	1
PETG	230	75	53	20	7	1

Table 16. Data Modification for Cost minimization (Own Work)

	Extrusion Temperature (℃)	Bed temperature (℃)	Ultimate Strength (MPa)	Price ($)	Source	Biodegradability
ABS	1.16	2.11	0.47	1	0.33	1
PLA	1	1	0.76	1	1	9
PC	1.37	1.78	0.85	4	0.78	1
PA	1.16	1.56	1	2.5	0.33	1
HIPS	1.21	2.22	0.38	2.4	0.33	1
PETG	1.21	1.67	0.62	2	0.78	1

Calculation of the ideal value based on the fundamentals of decision theory using simple weighting (Temesi J, 2002).

The weighing system combines many aspects in a weighting system where the total weight is 1. The choice with the highest sum of weighted values is chosen.

The chosen weighting system (W) for cost minimization.

W = (0.2,0.1,0.1,0.2,0.1,0.3) respectively

Table 17. The Transformed Data (Own Work)

	[a]0.2	[b]0.1	[c]0.1	[d]0.2	[e]0.1	[f]0.3
	Extrusion Temperature (℃)	Bed temperature (℃)	Ultimate Strength (MPa)	Price ($)	Source	Biodegradability
ABS	1.16	2.11	0.47	1	0.33	1
PLA	1	1	0.76	1	1	9
PC	1.37	1.78	0.85	4	0.78	1
PA	1.16	1.56	1	2.5	0.33	1
HIPS	1.21	2.22	0.38	2.4	0.33	1
PETG	1.21	1.67	0.62	2	0.78	1

abcdef: Weighting system multipliers

Table 18. Final Data After Considering the Weighting System (Own Work)

	0.2	0.1	0.1	0.2	0.1	0.3	
	Extrusion Temperature (℃)	Bed temperature (℃)	Ultimate Strength (MPa)	Price ($)	Source	Biodegradability	Total
ABS	0.23	0.21	0.05	0.2	0.03	0.3	1.02
PLA	0.2	0.1	0.08	0.2	0.1	2.7	*3.38
PC	0.27	0.18	0.08	0.8	0.08	0.3	1.71
PA	0.23	0.16	0.1	0.5	0.03	0.3	1.32
HIPS	0.24	0.22	0.04	0.48	0.03	0.3	1.32
PETG	0.24	0.17	0.06	0.4	0.08	0.3	1.25

∗Greatest sum of the weighted values.

PLA is chosen for filament fabrication based on the total of the weighted values.

PLA provides realistic attempts to solve environmental and economic challenges associated with the increased use of nondegradable polymer materials, which leads to the realization of Industry 4.0's objective of more sustainable production in the future.

3 Methodology

The flow chart in **Figure 28** illustrates the order of steps involved in designing a 3D filament extruder.

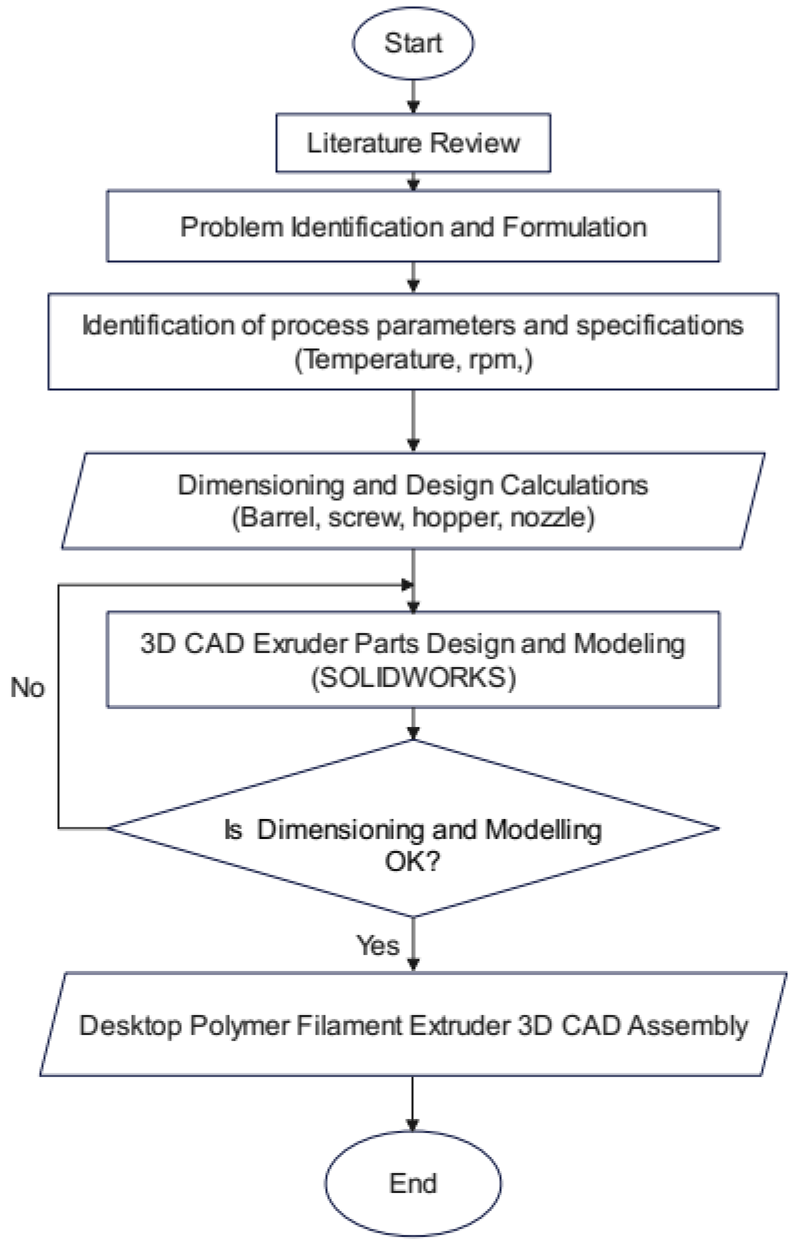


Figure 28. 3D CAD model Design Flow chart (Own Work)

3.1 FDM Desktop Polymer Filament Extruder.

Additive manufacturing technologies such as Fused Deposition Modelling (FDM) can produce high-performance materials with desired properties, which in turn can be used to construct complex industrial applications. FDM is a cost-effective method of additive manufacturing that is particularly suitable for creating intricate thermoplastic parts. The process involves extruding the filament through a heated nozzle above the polymer's glass transition temperature and then depositing it directly to construct a 3D component layer by layer (Gibson et al., 2010). The widespread use of FDM technology in industries is constrained by the limited availability of filament materials that possess the necessary functional properties required to construct components, even though FDM offers numerous advantages and can print a range of materials (Angelopoulos et al., 2019).

Amorphous thermoplastics such as polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS), and semi-crystalline polymers with low melting points, such as poly-lactic acid (PLA), are among the widely used materials in FDM technology (Drummer et al., 2012; Hill & Haghi, 2014; Turner et al., 2014).

This research is limited to the 3D CAD model design of a desktop polymer filament extruder for manufacturing polymer filaments at respective material extrusion temperatures with 1.75mm diameter.

3.2 Overview of Filament Extruder Construction

Extrusion is one of the essential plastics processing processes. It entails forcing a polymer melt through a specified shape die/nozzle to produce a plastic product with a continuous length and uniform cross-section (Crawford & Martin, 2019). For this study, a horizontal build extruder with a winding mechanism is being considered.

A *screw extruder* is a mechanical device consisting of a screw conveyor with a variable pitch and increasing core diameter rotating inside a heated cylindrical chamber (barrel). A single-screw extruder produces homogeneous polymers in a continuous shape and density.

The fundamental mechanism comprises a screw conveyor that mixes and transports raw plastic pellets from a hopper through a heating zone along the barrel (a metal pipe), where the plastic is dissolved and softened.

A motor rotates the screw. The motor's high speed is reduced to the low operating speed of the screw, using a gearbox and a transmission connecting the gearbox to the motor, increasing the drive torque. The drive torque is transmitted from the gearbox to the screw by a key-way geometry on the screw shank (Chan I. Chung, 2020).

The raw plastic pellets are gravity-fed from the hopper into the screw conveyor. When the screw rotates, frictional forces are generated between the rotating screw and the barrel surface, generating heat and changing the material viscosity, which makes it flow to the extrusion head. The extrusion head has a nozzle with the orifice shaped according to the required extrudate filament geometry.

3.3 Design Objectives

- To design a desktop polymer filament extruder for 3D printing for testing purposes.
- To carry out raw material cost estimation.

3.4 Filament Extruder Design considerations.

The aim is to create a low-priced small-scale screw extruder that enhances filament production, quality, and process consistency.

According to evaluations of earlier designs, pellets could flow straight into the barrel from the hopper directly fixed to the barrel without using a flow control device. **See Figure 29**

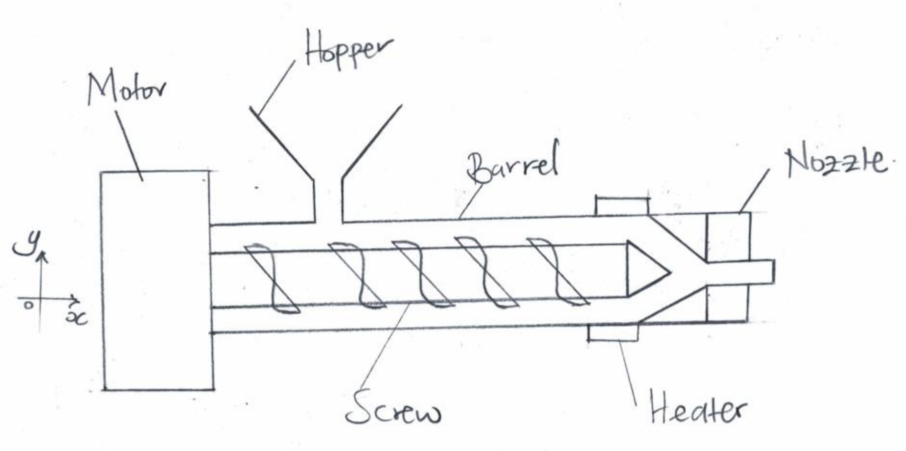


Figure 29. Horizontal layout of a filament extruder (Own Work)

An uncontrolled flow of pellets could present problems due to unexpected clogging or power outages that could cause the extrusion process to halt abruptly. **See Figure 30**

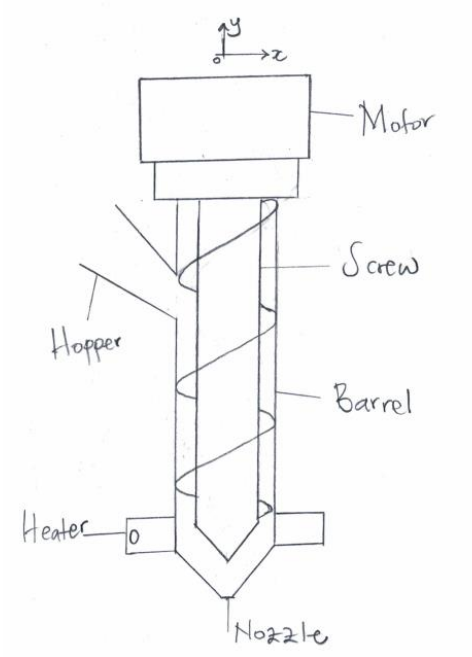


Figure 30. Vertical layout of a filament extruder (Own Work)

Table 19. The contrast between a filament screw extruder that is horizontally oriented and vertically oriented.

Orientation Type	Merits	Demerits
Horizontal	• Better Material Flow. • Ease of Maintenance. • Reduced Wear and Tear. • Better Cooling. • Better heat transfer.	• Limited throughput. • Increased wear and tear. • Limited material compatibility. • Difficult maintenance. • Higher energy consumption. • Limited flexibility.
Vertical	• Increased stability. • Improved filament feeding. • More compact design. • Easier maintenance. • Greater versatility.	• Reduced throughput. • Difficulty in handling certain materials. • Increased maintenance requirements. • Limited versatility. • Higher energy consumption.

Overall, the horizontal orientation of the filament screw extruder offers several advantages over the vertical orientation, making it a popular choice for many manufacturing applications.

A novel design idea resulted from evaluating the existing screw extrusion designs and orientation. **See Figure 31**

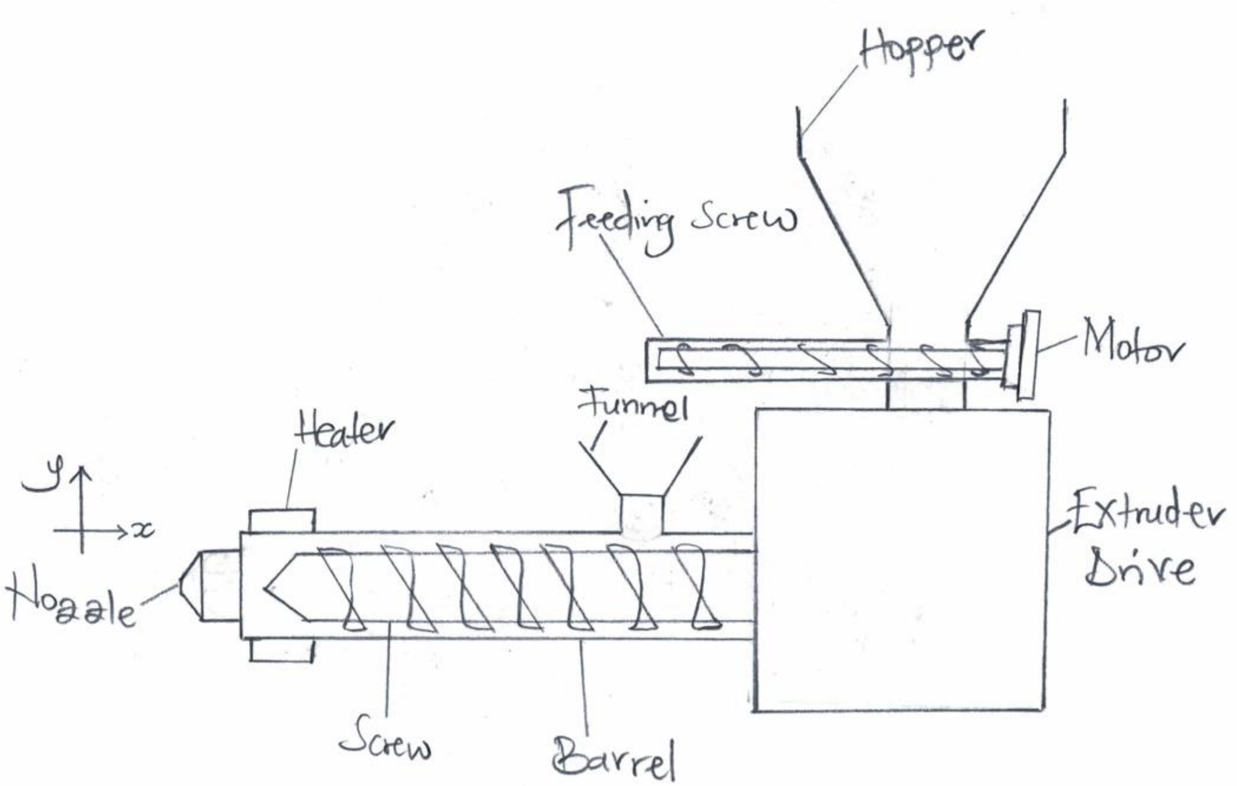


Figure 31. New design concept (Own Work)

The hopper and extrusion barrel are clearly separated in the new design, and pellet intake into the barrel is directed by a funnel. Pellet flow may be controlled, and the speed can be regulated to match the speed of the extrusion screw by using a feeding screw system with adjustable speed. The compact extruder design, combined with modified pellet feeding control, will help to produce better quality filaments for a broader range of materials.

In addition, the novel design proposes a filament winding spool whose speed can be adjusted to match the extrusion speed.

3.5 Equipment Description

3.6 Screw shaft.

The screw moves the pellets to the heating zone and forces the molten material out of the nozzle cross-section, resulting in a continuous filament used for printing. The material should be wear-resistant and hard enough to withstand high extrusion temperatures, and the screw shaft is of steel material. The purpose of the screw is to deliver the polymer to the heating zone and push the melted polymer through the extrusion die.

Carbon Steel is typically used in the manufacture of screws (Chan I. Chung, 2020). **See Figure 39**

3.7 Barrel

The barrel is made of Steel material as it can withstand high extrusion temperatures, just like the screw without deformation. **See Figure 32.**

Figure 32. 3D CAD model of the barrel (Own Work)

For barrel technical drawings (**See Appendix A**)

3.8 Nozzle

Typically, the nozzle is made of brass material. Brass is a good heat conductor, and it is relatively cheap. Nozzles usually come in standard sizes, depending on the diameter of the required filament (1.75, 2.85, or 3) mm. For this design, a 1.75 mm diameter is used. **See Figure 33.**

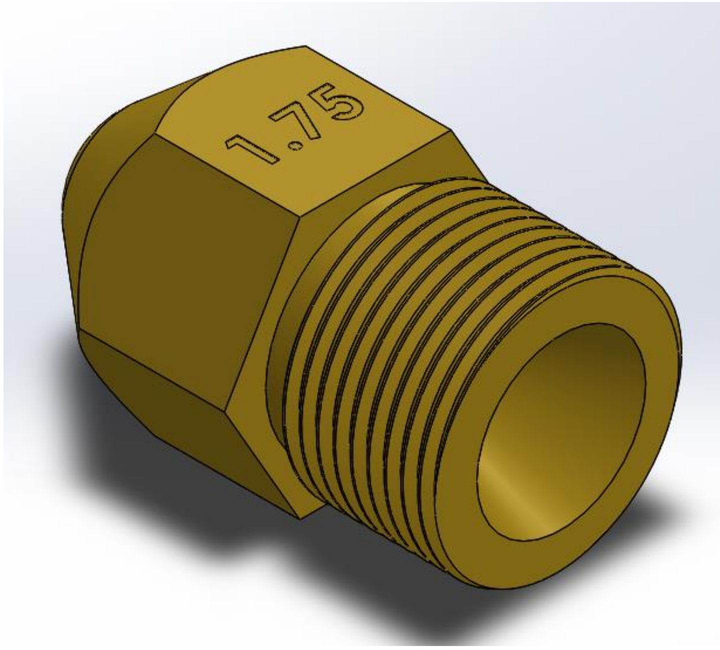


Figure 33. 1.75mm diameter nozzle (Own Work)

The nozzle can be bought online (Aliexpress, 2023).

3.9 Hopper

A supply screw delivers pellets contained in the hopper to the extruder via a funnel placed in the barrel's feed section through the feed throat and melts inside the extruder. The hopper has different geometries depending on the size of the pellet. With bulk materials of uniform pellet size, square feed hoppers are preferred (Rauwendaal, 2014). **See Figure 34.**

The supply screw is inserted in the hopper base and connected to the motor drive. The hopper is then bolted onto the hopper base. **See Figure 35**

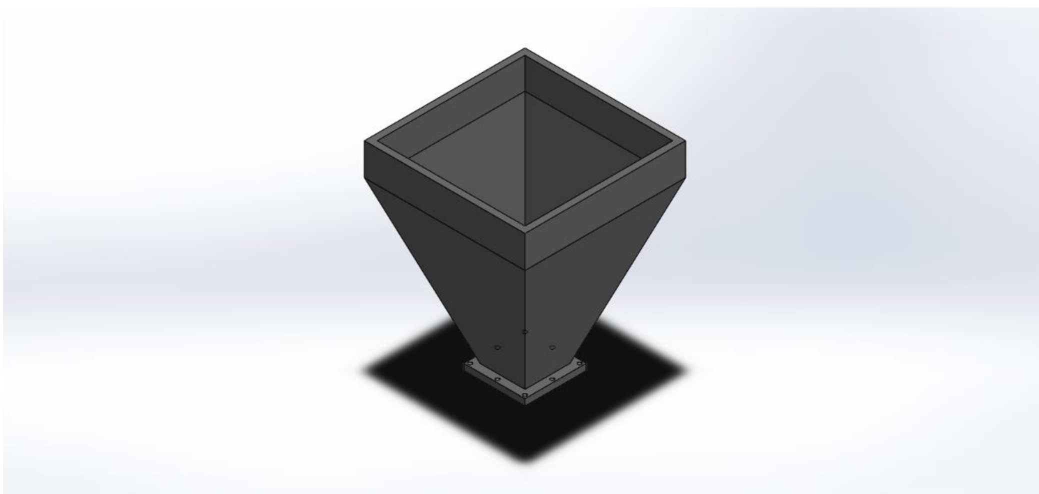


Figure 34. 3D CAD model of the hopper (Own Work)

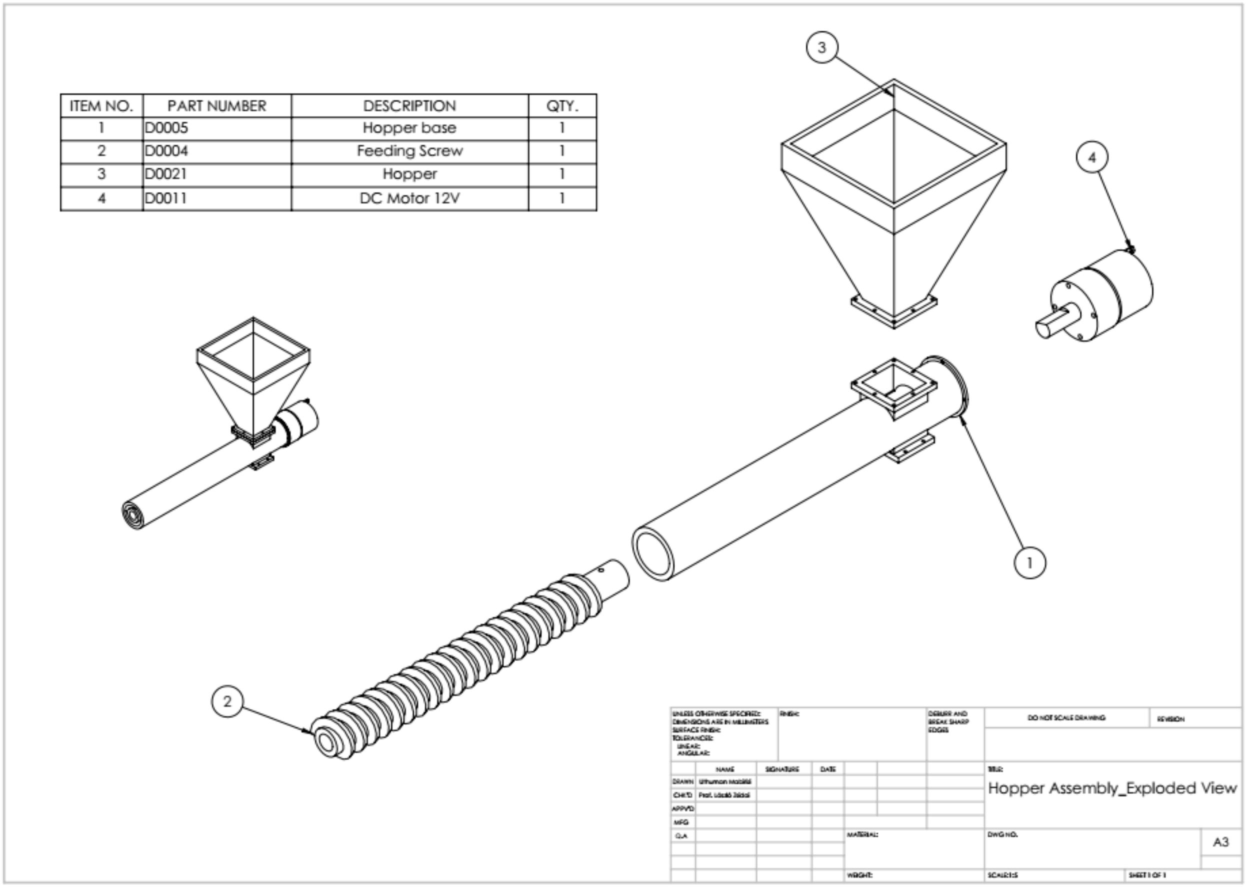


Figure 35. Hopper full Assembly exploded view (Own Work)

For hopper technical drawings (**See Appendices: B, C, and D**)

3.10 Heater

The heating is applied to the extruder to heat and melt the raw polymer pellets before extrusion, and it is monitored to maintain the set extrusion temperatures.

Band Heaters are efficient and economical solutions to the heating requirements of many applications. Band heaters can attain a maximum sheath temperature of up to 538°C but with different electrical termination styles, clamping mechanisms, and customizable. Mica band heaters have a wide range of industrial applications, particularly in the plastics sector.

Band Heaters utilize different types of top-grade mica. The thickness of each mica layer is carefully selected to balance the insulating characteristics of mica and the ease of heat transfer from the heating core to the barrel.

The resistance wire ribbon used in band heaters is not limited to the capabilities of nichrome wire. The internal winding of the wire ensures even heat distribution across the band heater.

The band heaters are appropriately rounded and moulded to optimize their grip to maximize surface-to-surface contact. The band heaters' outermost metallic covering consists of a unique alloy that expands less under heat than the barrel. This difference in thermal expansion makes the heater grip firmly as it gets energized, thus improving heat transfer which extends the heater's life time (Heating Elements Plus, 2022). **See Figure 36**

Figure 36. Mica band heater.
Source: https://www.heatingelementsplus.com/

3.11 Control Unit.

A proportional integral derivative (PID) controller is an electronic device that regulates temperature, flow, pressure, speed, and other process variables in industrial control applications. PID controllers are the most precise and reliable controllers because they employ a control loop feedback mechanism to regulate process variables. PID control is a well-established mechanism of directing a system toward a specific point or level.

PID is universally used to control the temperature in scientific processes and automation applications. PID control employs closed-loop control feedback to maintain a process's actual output as close to the desired or setpoint output as feasible. A control panel includes a platform from which various elements of the extrusion process may be operated. **See Figure 37.**

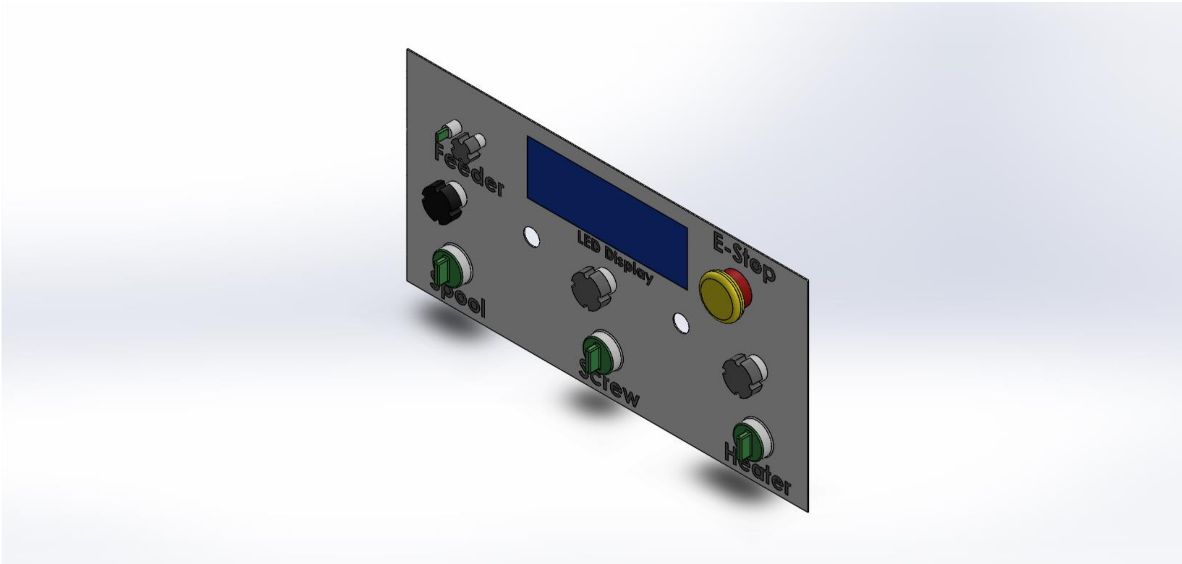


Figure 37. 3D CAD model representation of a Filament Extruder control panel (Own Work)

Hopper Volume Calculation.

The Volume, V_{hopper} of the trapezoidal hopper. **See Figure 34.**

$$V_{hopper} = \frac{1}{2}(b_1 + b_2)HL \tag{1}$$

Where, Height, H = 40 mm, b_1 = 14 mm, b_2 = 50 mm, and L = 50 mm.

$$V_{hopper} = \frac{1}{2}(14 + 50)40x50$$

$$V_{hopper} = 64000\, mm^3$$

3.12 Screw Geometry.

The screw is the most critical component of an extruder, and the screw design directly impacts the extruder's performance. By improving the screw design, an extrusion line's output rate may be significantly improved (Chan I. Chung, 2020). **Figure 38.** depicts the geometric features of a conventional single screw. The diameter and length of a screw describe its size usually given by the length-to-diameter ratio (L/D).

A typical screw is comprised of three separate sections: (1) a feeding section at the hopper end with deep channel depth called “feeding depth”, (2) a compression section between the feeding and metering sections with a decreasing channel depth, (3) a metering section at the end of the screw with shallow channel depth called “metering depth” (Chan I. Chung, 2020).

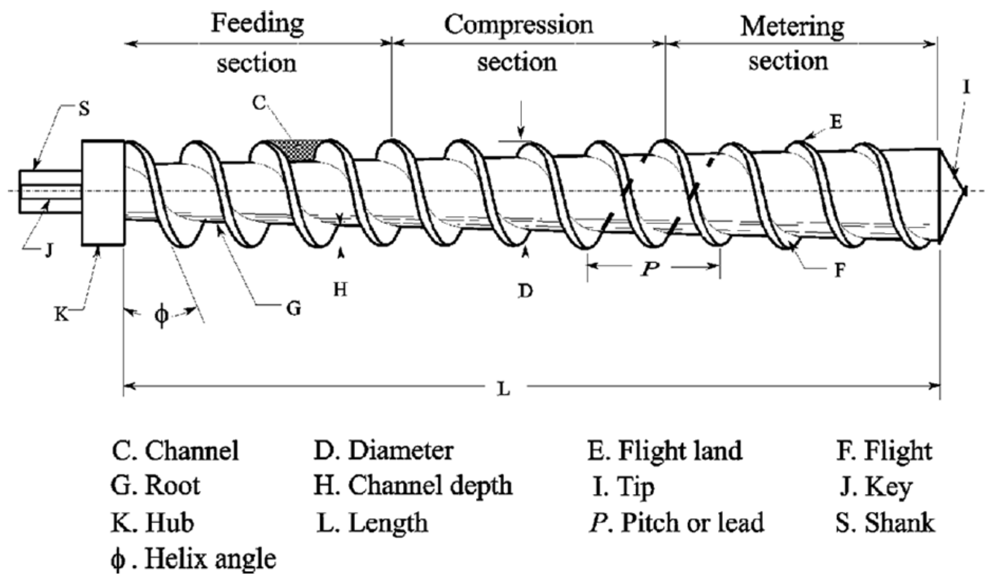


Figure 38. Geometric description of a single screw (Chan I. Chung, 2020).

Helix angle, φ

$$\tan\varphi = \frac{P}{\pi D_s} \tag{2}$$

Where; D_s = Screw diameter = 20 mm, P = Screw pitch = 20 mm

$$\varphi = \tan^{-1}\left(\frac{P}{\pi D_s}\right)$$

$$\varphi = \tan^{-1}\left(\frac{20}{\pi 20}\right) = 17.6^0$$

Calculation for metering depth, (H_m)

From technical drawings (**See Appendix E**), metering section depth (H_m) is 3.5mm

$$H_m = 3.5\,mm$$

Calculation for Length/Diameter (L/D) Ratio.

Considering a screw length, L_s = 270 mm,

$$L/D = \frac{L_s}{D_s} = 13.5$$

From technical drawings (**See Appendix E**), flight width, *e* is 7mm.

$$e = 7\,mm$$

Screw speed, *N(rpm)*

Small diameter screws, smaller than 90 mm in diameter operating at 100-250 rpm, whereas big diameter screws run at 50-150 rpm (Chan I. Chung, 2020).

$D_s \leq 90\,mm,\ 100 < N < 250$; $D_s > 90\,mm,\ 50 < N < 150$.

Since $D_s = 20\,mm,$ then $N = 200\,rpm,$ is chosen for this design.

Table 20. Screw Design Parameters (Own Work)

Screw Geometry Specifications	
Screw Diameter, D_s	20 mm
Barrel diameter, *D*	40 mm
Length, L_s	270 mm
Pitch, *P*	20 mm
Helix angle, φ	17.6°
Metering depth, H_m	3.5 mm
Flight width, e	7 mm
L/D	13.5
Screw speed, *N*	200 rpm

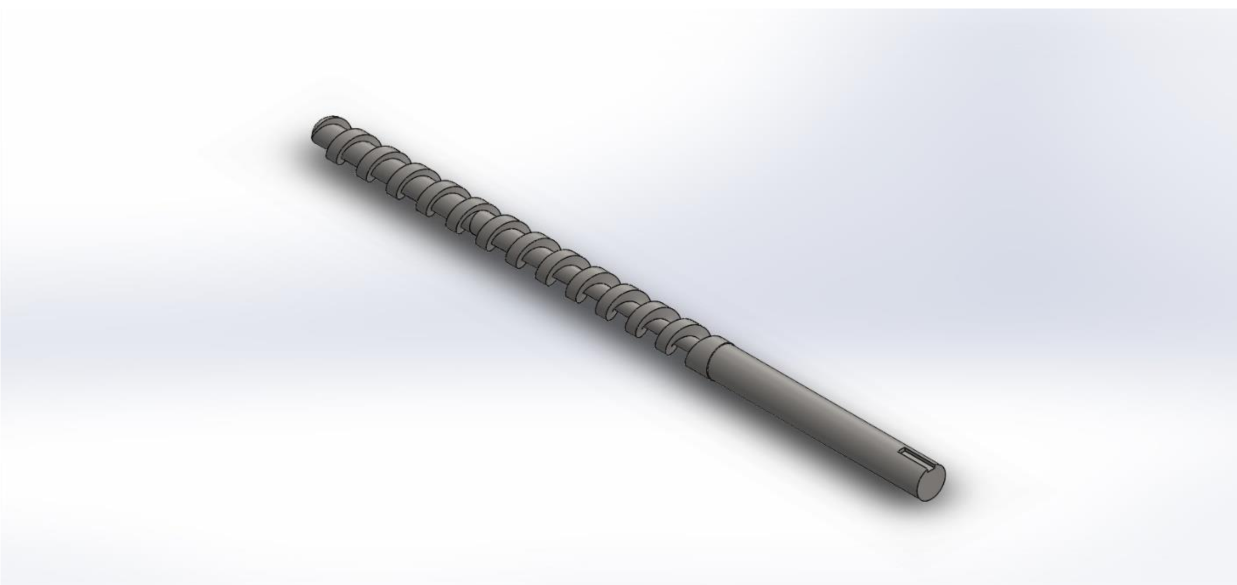


Figure 39. 3D CAD model of the Screw (Own Work)

For screw technical drawings, (**See Appendix E**)

3.13 Extruder Throughput Calculation

The net discharge rate from the extruder (Q) is equal to the algebraic sum of the drag flow, the pressure flow, and the leakage flow. The extruder equation is the flow equation for the extruder, and a material balance is made assuming that the liquid is incompressible (John R. Wagner Jr, 2016).

$$Q = Q_d - Q_p - Q_l \tag{3}$$

Where; Q_d = the drag flow, Q_p = the pressure flow, Q_l = the leakage flow

Leakage flow is the flow over the extruder flights and is generally insignificant, then Eq (3) reduces to;

$$Q = Q_d - Q_p \tag{4}$$

Assuming a Newtonian Fluid flow, Eq (4) can be expressed in terms of the screw geometry to estimate the volumetric flow rate (Crawford & Martin, 2019) Q.

$$Q_d = \frac{1}{2}\pi^2 D_s{}^2 N H_m \sin\varphi \cos\varphi \tag{5}$$

$$Q_p = \frac{\pi D_s (H_m)^3 \sin^2\varphi}{12\eta} . \left(\frac{P}{L_s}\right) \tag{6}$$

Therefore, from Eq (4),

$$Q = \frac{1}{2}\pi^2 D_s{}^2 N H_m \sin\varphi \cos\varphi - \frac{\pi D_s (H_m)^3 \sin^2\varphi}{12\eta} . \left(\frac{P}{L_s}\right) \tag{7}$$

Where, P = pressure at the end of the extruder, η = polymer melt viscosity, L_s = Length of the screw (Crawford & Martin, 2019).

$$\eta = m\dot{\gamma}^{(n-1)} \tag{8}$$

Where, m = consistency index, n = power law index, η = Viscosity of the polymer melt, $\dot{\gamma}$ = shear rate (John R. Wagner Jr, 2016).

For the design of extrusion dies or nozzles, the value of m lies between $(1x10^0 - 6x10^4 s^{-1})$, and the value of n lies between 0.2 - 0.7 for most polymers (Walter Michaeli, 2003).

$\dot{\gamma} = \dfrac{\pi N D_s \cos\varphi}{H_m}$ (Crawford & Martin, 2019).

From Eq (8), for $m = 2x10^4 s^{-1}$, n = 0.6, N = 200 *rpm;*

$$\eta = m\left(\frac{\pi N D_s \cos\varphi}{H_m}\right)^{(n-1)}$$

$$\eta = 2x10^4 \left(\frac{\pi \left({}^{200}\!/_{60} \right) 20\cos(17.6)}{3.5} \right)^{(0.6-1)} = 3968\, Pa.s$$

Maximum output is achieved in the condition of free discharge when there is no pressure build-up at the extruder's end (Crawford & Martin, 2019).

$$Q = Q_{\max} = \frac{1}{2}\pi^2 D_s{}^2 N H_m \sin\varphi \cos\varphi \tag{9}$$

$$Q_{\max} = \frac{1}{2}\pi^2 x 20^2 \left({}^{200}\!/_{60} \right) 3.5 \sin(17.6)\cos(17.6)$$

$$Q_{\max} = 6637\, mm^3/s$$

Maximum output is zero, ($Q_{\max} = 0$) when the pressure, P ($P = P_{\max}$) at the extruder's end is high enough to prevent the output (Crawford & Martin, 2019).

$$P = P_{\max} = \frac{6\pi N L_s D_s \eta}{H_m{}^2 \tan\varphi} \tag{10}$$

$$P_{\max} = \frac{6\pi \left({}^{200}\!/_{60} \right) x 270 x 20 x 3968}{3.5^2 \tan(17.6)}$$

$$P_{\max} = 346\, MPa$$

From Eq (7),

$$Q = \frac{1}{2}\pi^2 D_s{}^2 N H_m \sin\varphi \cos\varphi - \frac{\pi D_s (H_m)^3 \sin^2\varphi}{12\eta} \cdot \left(\frac{P}{L_s} \right) \tag{11}$$

$$Q = \frac{1}{2}\pi^2 x 20^2 \left({}^{200}\!/_{60} \right) 3.5 \sin(17.6)\cos(17.6) - \frac{\pi 20 (3.5)^3 \sin^2(17.6)}{12 x 3968} \cdot \left(\frac{346}{270} \right)$$

$$Q = 6637\ mm^3/s$$

Table 21. Polymer Properties for the Extruder Design (SD3D, 2022)

	FDM Feedstock Polymers		
	Density [kg/m^3]	Heat Capacity [J/kg K]	Extruder temperature [℃]
PLA	1240	1800	220
ABS	1040	1670	250
PET	1230	1200	250

Source: https://www.simplify3d.com/support/materials-guide/properties-table

3.14 Power Calculation.

The following energy balance equation determines how much power is required to extrude the feedstock material.

$$Power, P = \rho.Q.C(T_m - T_0) \tag{12}$$

Where; ρ = material density, Q = Flow rate, C = Heat Capacity, T_m = material melting temperature, and T_0 = room temperature, = 25℃

Considering PET material properties from Table 21.

$\rho = 1230\ kg/m^3, Q = 6637\, mm^3/s \cong 6.637x10^{-6}\ m^3/s, C = 1670\ J/kgK, T_m = 250^0 C$

From Eq (12)

$$P = \rho.Q.C(T_m - T_0)$$

$$P = 1230x6.637x10^{-6}x1200(250 - 25)$$

$$P = 2216W \equiv 2.216\,kW$$

3.15 Required Torque

The equation below estimates the torque required to run the motor.

$$T = \frac{P60}{2\pi N} \tag{13}$$

$$T = \frac{1260x60}{2\pi x200} = 60Nm$$

3.16 3D CAD Model Design of a Desktop Polymer Filament Extruder.

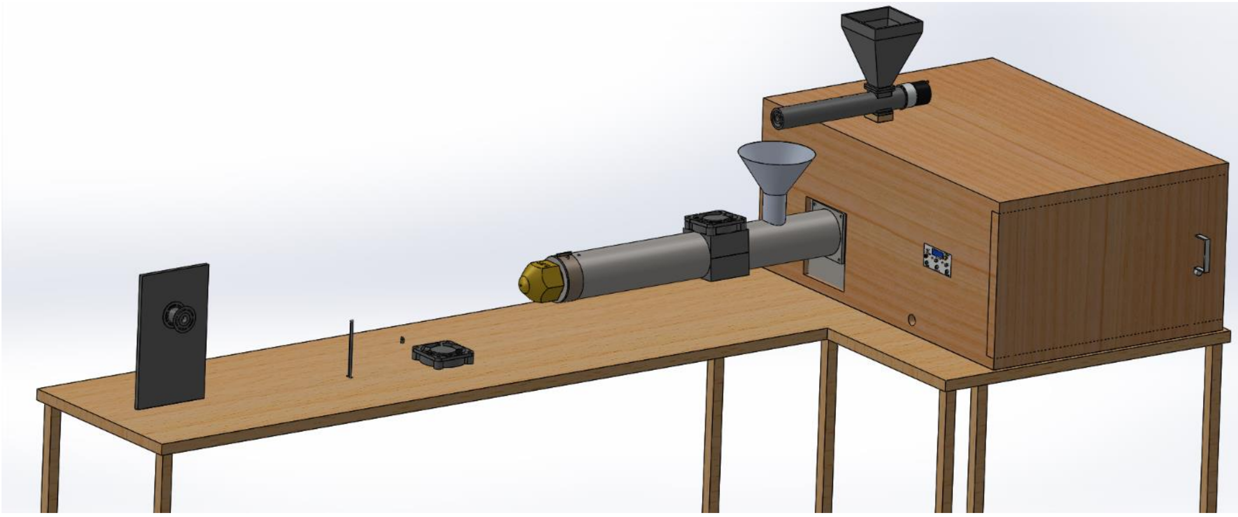


Figure 40. 3D CAD Model Design Assembly of the Desktop Filament Extruder (Own Work)

3.17 Operation Principle of the 3D CAD-Designed Filament Extruder

The extruder's screw rotates and generates enough pressure to drive the material through a die and create objects with the desired geometry. An extruder has five major components: a screw, an extruder drive, a barrel, a feed hopper, and a nozzle. An extruder drive is an electric motor that provides power to rotate the screw. The design of the screw has a significant impact on the stability and quality of the product. The screw is housed in an extruder barrel, which has heating capabilities. The raw material is delivered from the feed hopper via the supply screw through a funnel linked to the barrel via a feed throat. **See Figure 41**

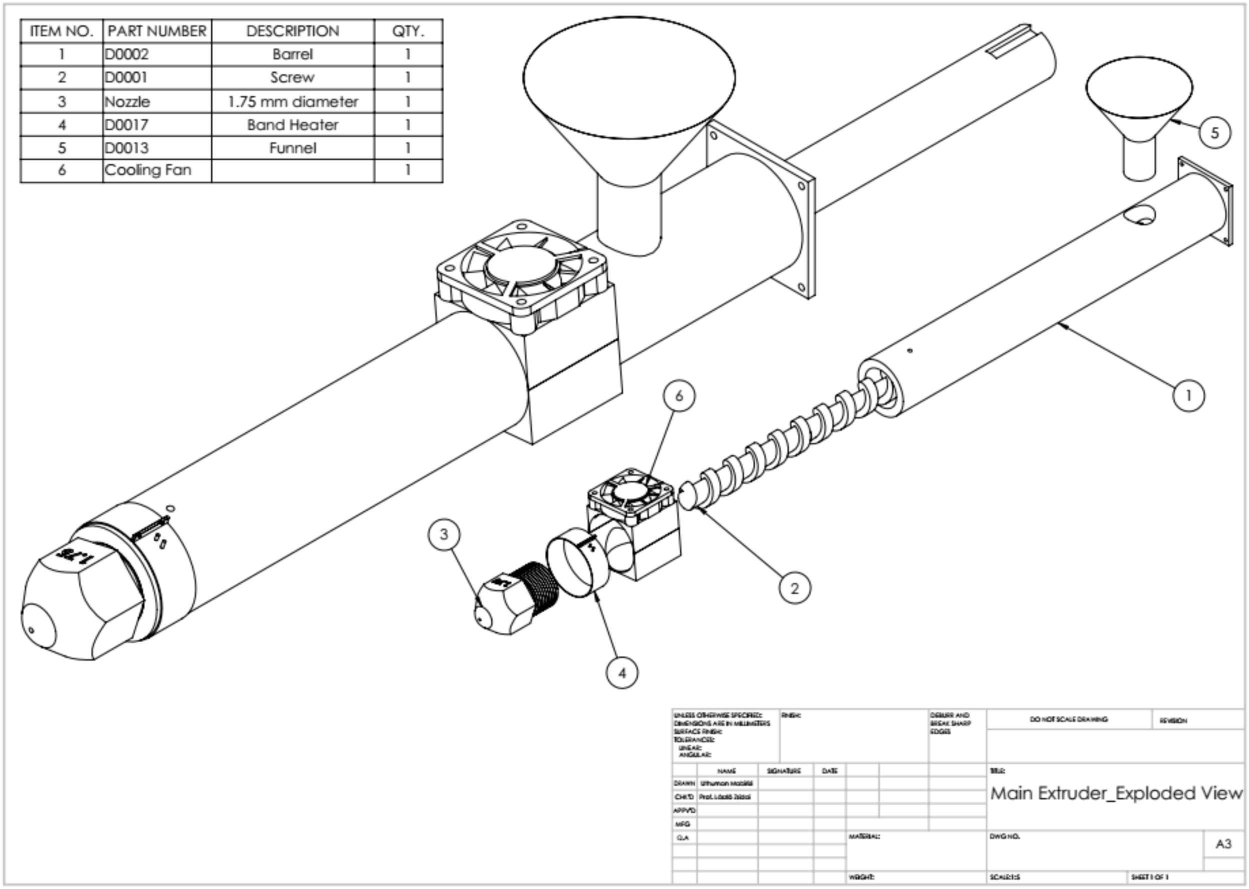


Figure 41. Exploded View of the Extrusion Section Assembly (Own Work)

The feed hopper is designed to hold plastic pellets and maintain a consistent flow into the barrel. The nozzle is located at the extruder's exit and determines the filament's geometry. A fan cools the extruded filament where necessary. The filament guide directs the extruded filament on the spool for winding. **See Figure 42**

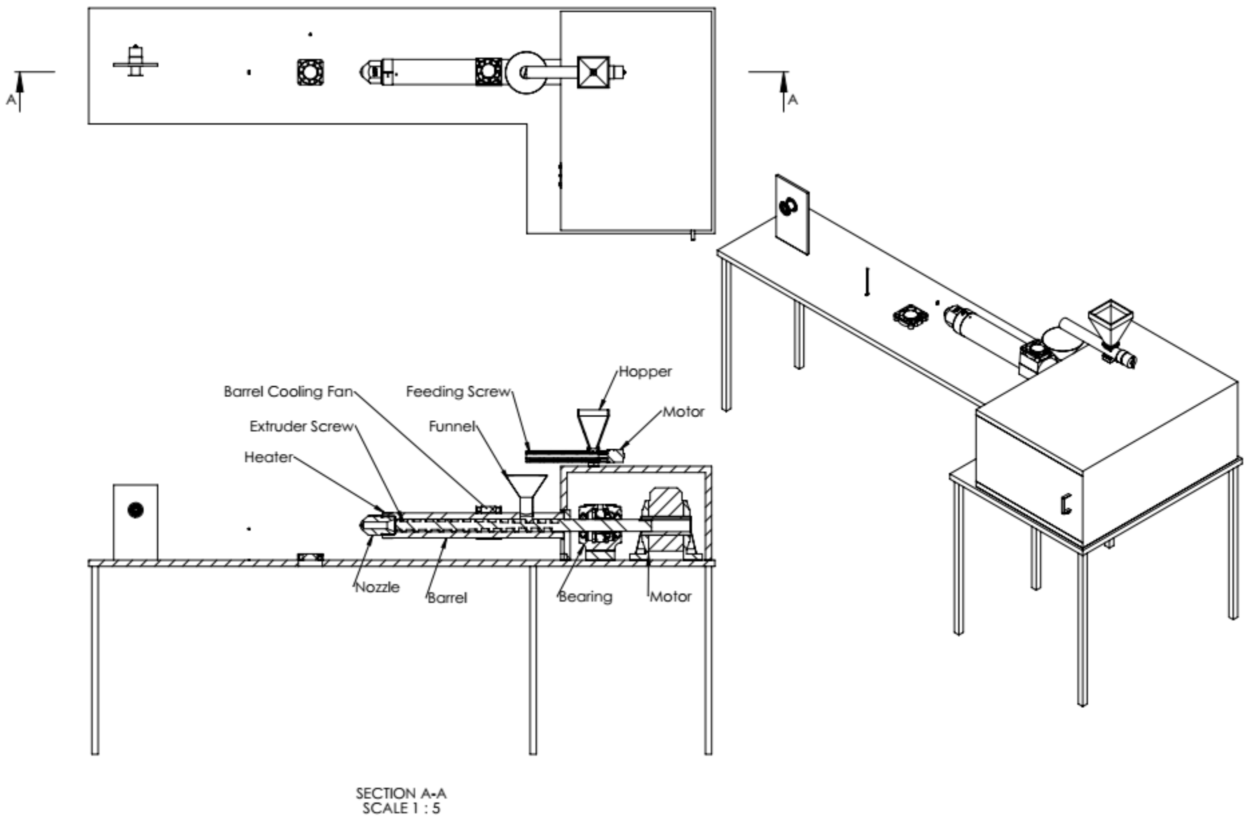


Figure 42. 3D CAD Model Design Assembly drawing view of the Desktop Filament Extruder (Own Work)

4 Cost Estimation of the 3D CAD Model Design

Table 22 shows the estimated cost prices of the design components.

Table 22. The Estimated Cost price of Components (Own Work)

Component	Description	Price (€)	Quantity
Motor (Extrusion)	Nema23	47	1
Motor (Feeding Screw, Winding)	DC 12V	15	2
Bearing	SNL 505 + 1205 K + HE 205 + TSN 505 C	15	1
Nozzle	1.75 mm diameter	5	1
Funnel	Pellets feed supply	12	1
Fan	Cooling Fan	15	2
Filament guide	Filament winding direction	2	1
Spool set	Filament winding	9	1
Heater	Mica band heater	59	1
Total		209	

Source: https://www.aliexpress.com/, https://www.heatingelementsplus.com/

Materials market prices are shown in Table 23.

Table 23. The estimated cost price of material

Material	Price (€) /Kg	Reference
Carbon Steel	0.752	(MEPS, 2022)
PA 6	3.35	(Plastech, 2023)

Table 24. The Estimated Screw Manufacturing Cost (Own Work)

Model Name:	D0001
Date and time of report:	3/25/2023 1:10:37 PM
Material:	Plain Carbon Steel
Estimated Cost per part:	70.20 USD
Costing template used:	machiningtemplate default(metric).sldctm

Estimate	Number of Parts	Unit Price	Total Price
	1	70.20 USD	70.20 USD

The most critical component of the extruder screw is its end section, which connects directly to the driving system. The screw can be bought online (Aliexpress, 2023), but for a comprehensive analysis of its production costs, (**See Appendix F**)

Table 25. The Estimated Barrel Manufacturing Cost (Own Work)

Model Name: D0002

Date and time of report:	3/25/2023 2:17:33 PM
Material:	Plain Carbon Steel

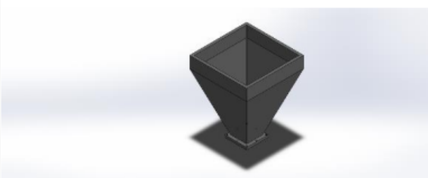
Estimated Cost per part: 152.17 USD

Costing template used:	machiningtemplate_default(metric).sldctm

Estimate	Number of Parts	Unit Price	Total Price
	1	152.17 USD	152.17 USD

For a detailed analysis of the production costs, (**See Appendix G**)

Table 26. The Estimated Hopper Manufacturing Cost (Own Work)



Model Name: D0021

Date and time of report:	3/25/2023 2:36:42 PM
Material:	PA 6

Estimated Cost per part: 15.20 USD

Costing template used:	machiningtemplate_default(metric).sldctm

Estimate	Number of Parts	Unit Price	Total Price
	1	15.20 USD	15.20 USD

For a detailed analysis of the production costs, (**See Appendix H)**

Table 27. The Estimated Hopper Base Manufacturing Cost (Own Work)

Model Name: D0005

Date and time of report:	3/25/2023 2:54:09 PM
Material:	PA 6

Estimated Cost per part: 14.23 USD

Costing template used:	machiningtemplate_default(metric).sldctm

Estimate	Number of Parts	Unit Price	Total Price
	1	14.23 USD	14.23 USD

For a detailed analysis of the production costs, (**See Appendix I**)

Table 28. The Estimated Feed Screw Manufacturing Cost (Own Work)

Model Name: D0004

Date and time of report:	3/25/2023 3:14:05 PM
Material:	PA 6

Estimated Cost per part: 13.57 USD

Costing template used:	machiningtemplate_default(metric).sldctm

Estimate	Number of Parts	Unit Price	Total Price
	1	13.57 USD	13.57 USD

For a detailed analysis of the production costs, (**See Appendix J**)

Table 29. The Estimated and Standardized Total Cost of Manufactured Components (Own Work)

Part No.	Part Name	Material	Manufacturing Cost (€)	Manufacturing Method	Stock body Dimensions (X.Y.Z) [mm]	Material Standards
D0001	Screw	Carbon Steel	65.11	Machining	410x20x20	ASTM A36
D0002	Barrel	Carbon Steel	141.14	Machining	45x45x290	ASTM A36
D0005	Hopper base	PA 6	13.2	3D Printing	21x23x130	ASTM D 4066
D0021	Hopper	PA 6	14.1	3D Printing	16x16x130	ASTM D 4066
D0004	Feeding Screw	PA 6	12.6	3D Printing	50x62x50	ASTM D 4066
Total			246.15			

SOLIDWORKS Costing Tool

Overall Estimated Cost: €455.15

4.1 Limitation and Study Forward

The study did not examine the optimization of system parameters during extrusion. Additional studies are necessary to develop a synchronization mechanism between the extruder and the winding process to create a uniformly sized filament suitable for 3D printing. Furthermore, it is necessary to use a filament-conditioned box in case of hygroscopic extruded filaments.

5 Summary

Using additive manufacturing methods like Fused Deposition Modeling (FDM) can create complex industrial applications by printing high-quality materials with suitable characteristics. FDM technology aligns with the "industry 4.0" philosophy and is a sustainable enabler for producing customized, high-quality products in intelligent factories with high productivity and cyber-physical integration.

However, FDM's potential for constructing components with desired functional properties could be improved by the availability of inexpensive filament materials.

To address this limitation, this study aimed to design a 3D CAD model of a desktop polymer extruder that can produce filamentous feedstock for testing purposes. The proposed design includes a feed control mechanism and can make a filament with a diameter of 1.75mm.

However, the study did not examine the optimization of system parameters during extrusion. Additional studies are necessary to develop a synchronization mechanism between the extruder and the winding process to create a uniformly sized filament suitable for 3D printing. Furthermore, it is necessary to use a filament-conditioned box in case of hygroscopic extruded filaments.

Once these challenges are overcome, individuals can use FDM technology comparable to a personal computer using the proposed design for manufacturing polymer filaments with desired features using different materials at appropriate extrusion temperatures.

5.1 References

1. 3devo. (2022, November 28). *Make 3D Print Materials - Desktop Filament Maker and Shredder | 3devo*. https://www.3devo.com/
2. Adel, M., & Khalil, A. M. (2018). Polishing of fused deposition modeling products by hot air jet: Evaluation of surface roughness. *Journal of Materials Processing Technology*, *251*, 73–82. https://doi.org/10.1016/j.jmatprotec.2017.07.019
3. Aguilar-Duque, J. I., Hernández-Arellano, J. L., Avelar-Sosa, L., Amaya-Parra, G., & Tamayo-Pérez, U. J. (2018). Additive manufacturing: Fused deposition modeling advances. In *Best Practices in Manufacturing Processes: Experiences from Latin America* (pp. 347–366). Springer International Publishing. https://doi.org/10.1007/978-3-319-99190-0_16
4. Ahmad, N., Professor, A., Gopinath, P., Professor, A., & Dua, R. (2019). *3D Printing Technology in Nanomedicine*.
5. Ahn, S. H., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, *8*(4), 248–257. https://doi.org/10.1108/13552540210441166
6. Algarni, M., & Ghazali, S. (2021). Comparative study of the sensitivity of pla, abs, peek, and petg's mechanical properties to fdm printing process parameters. *Crystals*, *11*(8). https://doi.org/10.3390/cryst11080995
7. Aliexpress. (2023, March 25). *Extruder Screw Barrel | Screw Diameter 50mm | 30mm Extruder Screw | Extruder Screw Set - Linear Guides - Aliexpress*. https://www.aliexpress.com/item/1005004417673071.html?spm=a2g0o.productlist.main.13.1be22c2cXwX0ZT&algo_pvid=fc802a91-9215-497e-995b-6dd81f3a07e3&algo_exp_id=fc802a91-9215-497e-995b-6dd81f3a07e3-6&pdp_ext_f=%7B%22sku_id%22%3A%2212000029145578217%22%7D&pdp_npi=3%40dis%21CZK%2110266.79%2110266.79%21%21%21%21%21%40211bf31716797482776628073d06ce%2112000029145578217%21sea%21CZ%210&curPageLogUid=GxCK1h8JzHUs
8. All3DP. (2022). *The Best Filament Extruders of 2021 | All3DP*. https://all3dp.com/2/best-filament-extruder-maker-diy-buy/

9. Angelopoulos, P. M., Samouhos, M., & Taxiarchou, M. (2019). Functional fillers in composite filaments for fused filament fabrication: A review. *Materials Today: Proceedings*, *37*, 4031–4043. https://doi.org/10.1016/j.matpr.2020.07.069
10. Aumnate, C., Pongwisuthiruchte, A., Pattananuwat, P., & Potiyaraj, P. (2018). Fabrication of ABS/Graphene oxide composite filament for fused filament fabrication (FFF) 3D Printing. *Advances in Materials Science and Engineering*, *2018*. https://doi.org/10.1155/2018/2830437
11. Bandyopadhyay, A., & Heer, B. (2018). Additive manufacturing of multi-material structures. In *Materials Science and Engineering R: Reports* (Vol. 129, pp. 1–16). Elsevier Ltd. https://doi.org/10.1016/j.mser.2018.04.001
12. Belaid, H., Nagarajan, S., Teyssier, C., Barou, C., Barés, J., Balme, S., Garay, H., Huon, V., Cornu, D., Cavaillès, V., & Bechelany, M. (2020). Development of new biocompatible 3D printed graphene oxide-based scaffolds. *Materials Science and Engineering C*, *110*. https://doi.org/10.1016/j.msec.2019.110595
13. Cao, Q., & Xie, H. (2017). Characterization for elastic constants of fused deposition modelling-fabricated materials based on the virtual fields method and digital image correlation. *Acta Mechanica Sinica/Lixue Xuebao*, *33*(6), 1075–1083. https://doi.org/10.1007/s10409-017-0719-y
14. Chan I. Chung. (2020). *Extrusion of Polymers*.
15. Chaturvedi, E., Rajput, N. S., Upadhyaya, S., & Pandey, P. K. (2017). Experimental Study and Mathematical Modeling for Extrusion using High Density Polyethylene. *Materials Today: Proceedings*, *4*(2), 1670–1676. https://doi.org/10.1016/j.matpr.2017.02.006
16. Crawford, R. J., & Martin, P. J. (2019). *Plastics Engineering Fourth Edition* (4th ed.). www.elsevier.com/permissions.
17. Crowley, M. M., Zhang, F., Repka, M. A., Thumma, S., Upadhye, S. B., Battu, S. K., McGinity, J. W., & Martin, C. (2007). Pharmaceutical applications of hot-melt extrusion: Part I. In *Drug Development and Industrial Pharmacy* (Vol. 33, Issue 9, pp. 909–926). https://doi.org/10.1080/03639040701498759
18. Das, S. (2008). *Selective Laser Sintering of Polymers and Polymer-Ceramic Composites*.

19. Dave, H. K., & Davim, J. P. (2021). *Materials Forming, Machining and Tribology*. http://www.springer.com/series/11181
20. DeStefano, V., Khan, S., & Tabada, A. (2020). Applications of PLA in modern medicine. *Engineered Regeneration*, *1*, 76–87. https://doi.org/10.1016/j.engreg.2020.08.002
21. Dey, A., Eagle, I. N. R., & Yodo, N. (2021a). A review on filament materials for fused filament fabrication. In *Journal of Manufacturing and Materials Processing* (Vol. 5, Issue 3). MDPI AG. https://doi.org/10.3390/jmmp5030069
22. Dey, A., Eagle, I. N. R., & Yodo, N. (2021b). A review on filament materials for fused filament fabrication. In *Journal of Manufacturing and Materials Processing* (Vol. 5, Issue 3). MDPI AG. https://doi.org/10.3390/jmmp5030069
23. Dey, A., & Yodo, N. (2019). A systematic survey of FDM process parameter optimization and their influence on part characteristics. In *Journal of Manufacturing and Materials Processing* (Vol. 3, Issue 3). MDPI Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/jmmp3030064
24. Dilberoglu, U. M., Gharehpapagh, B., Yaman, U., & Dolen, M. (2017). The Role of Additive Manufacturing in the Era of Industry 4.0. *Procedia Manufacturing*, *11*, 545–554. https://doi.org/10.1016/j.promfg.2017.07.148
25. Drummer, D., Cifuentes-Cuéllar, S., & Rietzel, D. (2012). Suitability of PLA/TCP for fused deposition modeling. *Rapid Prototyping Journal*, *18*(6), 500–507. https://doi.org/10.1108/13552541211272045
26. Elkaseer, A., Schneider, S., & Scholz, S. G. (2020). Experiment-based process modeling and optimization for high-quality and resource-efficient FFF 3D printing. *Applied Sciences (Switzerland)*, *10*(8). https://doi.org/10.3390/APP10082899
27. Felfil. (2022). *Felfil Filament Maker | Make your own 3D printing filament with Felfil Evo*. https://felfil.com/?v=5ea34fa833a1
28. Fico, D., Rizzo, D., Casciaro, R., & Corcione, C. E. (2022). A Review of Polymer Materials for Fused Filament Fabrication: Focus on Sustainability and Recycled Materials. In *Polymers* (Vol. 14, Issue 3). MDPI. https://doi.org/10.3390/polym14030465

29. Filabot. (2022). *Filament Maker - Recycle Filament for Any 3D Printer – Filabot*. https://www.filabot.com/
30. Filafab. (2022). *Filament Extruder*. https://www.filafab.co.uk/
31. Filastruder. (2022). *Filastruder: 3D printing accessories*. https://www.filastruder.com/
32. Fu, X., Zhang, X., & Huang, Z. (2021). Axial crushing of Nylon and Al/Nylon hybrid tubes by FDM 3D printing. *Composite Structures*, *256*. https://doi.org/10.1016/j.compstruct.2020.113055
33. Gao, G., Xu, F., Xu, J., Tang, G., & Liu, Z. (2022). A Survey of the Influence of Process Parameters on Mechanical Properties of Fused Deposition Modeling Parts. In *Micromachines* (Vol. 13, Issue 4). MDPI. https://doi.org/10.3390/mi13040553
34. Gao, X., Qi, S., Kuang, X., Su, Y., Li, J., & Wang, D. (2021). Fused filament fabrication of polymer materials: A review of interlayer bond. In *Additive Manufacturing* (Vol. 37). Elsevier B.V. https://doi.org/10.1016/j.addma.2020.101658
35. Gebler, M., Schoot Uiterkamp, A. J. M., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy*, *74*(C), 158–167. https://doi.org/10.1016/j.enpol.2014.08.033
36. Geus, H. G. (2016). Developments in manufacturing techniques for technical nonwovens. In *Advances in Technical Nonwovens* (pp. 133–153). Elsevier Inc. https://doi.org/10.1016/B978-0-08-100575-0.00005-X
37. Gibson, I., Rosen, D., Stucker, B., & Khorasani, M. (2020). *Additive Manufacturing Technologies*.
38. Gibson, I., Rosen, D. W., & Stucker, B. (2010). Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing. In *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. Springer US. https://doi.org/10.1007/978-1-4419-1120-9
39. Gkartzou, E., Koumoulos, E. P., & Charitidis, C. A. (2017). Production and 3D printing processing of bio-based thermoplastic filament. *Manufacturing Review*, *4*. https://doi.org/10.1051/mfreview/2016020
40. González-Henríquez, C. M., Sarabia-Vallejos, M. A., & Rodriguez-Hernandez, J. (2019). Polymers for additive manufacturing and 4D-printing: Materials,

methodologies, and biomedical applications. In *Progress in Polymer Science* (Vol. 94, pp. 57–116). Elsevier Ltd. https://doi.org/10.1016/j.progpolymsci.2019.03.001

41. Guessasma, S., Belhabib, S., & Nouri, H. (2019). Printability and tensile performance of 3D printed polyethylene terephthalate glycol using fused deposition modelling. *Polymers*, *11*(7). https://doi.org/10.3390/polym11071220
42. He, J., Chen, J., Hellwich, K. H., Hess, M., Horie, K., Jones, R. G., Kahovec, J., Kitayama, T., Kratochvíl, P., Meille, S. V., Mita, I., Dos Santos, C., Vert, M., & Vohlídal, J. (2014). Abbreviations of polymer names and guidelines for abbreviating polymer names (IUPAC Recommendations 2014). *Pure and Applied Chemistry*, *86*(6), 1003–1015. https://doi.org/10.1515/pac-2012-1203
43. Heating Elements Plus. (2022). *Mica Band Heaters*. https://www.heatingelementsplus.com/mica-band-heaters.html
44. Herianto, Atsani, S. I., & Mastrisiswadi, H. (2020). Recycled Polypropylene Filament for 3D Printer: Extrusion Process Parameter Optimization. *IOP Conference Series: Materials Science and Engineering*, *722*(1). https://doi.org/10.1088/1757-899X/722/1/012022
45. Hill, N., & Haghi, M. (2014). Deposition direction-dependent failure criteria for fused deposition modeling polycarbonate. *Rapid Prototyping Journal*, *20*(3), 221–227. https://doi.org/10.1108/RPJ-04-2013-0039
46. Ivanova, O., Williams, C., & Campbell, T. (2013). Additive manufacturing (AM) and nanotechnology: Promises and challenges. *Rapid Prototyping Journal*, *19*(5), 353–364. https://doi.org/10.1108/RPJ-12-2011-0127
47. Jasiuk, I., Abueidda, D. W., Kozuch, C., Pang, S., Su, F. Y., & McKittrick, J. (2018). An Overview on Additive Manufacturing of Polymers. *JOM*, *70*(3), 275–283. https://doi.org/10.1007/s11837-017-2730-y
48. Jin, L., Zeng, T., & Cheng, S. (2018). Ceramics International. *Ceramics International*, *44*(17), 20992–20999. https://doi.org/10.1016/j.ceramint.2018.08.134
49. John R. Wagner Jr. (2016). *Biopolymers : processing and products*.
50. Kabir, S. M. F., Mathur, K., & Seyam, A. F. M. (2020). A critical review on 3D printed continuous fiber-reinforced composites: History, mechanism, materials and

properties. In *Composite Structures* (Vol. 232). Elsevier Ltd. https://doi.org/10.1016/j.compstruct.2019.111476

51. Kagermann, H. (2015). Change through digitization—value creation in the age of industry 4.0. In *Management of Permanent Change* (pp. 23–45). Springer Science+Business Media. https://doi.org/10.1007/978-3-658-05014-6_2
52. Khatri, B., Lappe, K., Habedank, M., Mueller, T., Megnin, C., & Hanemann, T. (2018). Fused deposition modeling of ABS-barium titanate composites: A simple route towards tailored dielectric devices. *Polymers*, *10*(6). https://doi.org/10.3390/polym10060666
53. Kloski, L. W., & Kloski, N. (2021). *Make : getting started with 3D printing*.
54. Kumar, R., Singh, R., & Farina, I. (2018). On the 3D printing of recycled ABS, PLA and HIPS thermoplastics for structural applications. *PSU Research Review*, *2*(2), 115–137. https://doi.org/10.1108/PRR-07-2018-0018
55. Laura, M., Lorenzo, D., & Androsch, R. (2018). *Industrial Applications of Poly(lactic acid)*. http://www.springer.com/series/12
56. Lee, J. Y., An, J., & Chua, C. K. (2017). Fundamentals and applications of 3D printing for novel materials. In *Applied Materials Today* (Vol. 7, pp. 120–133). Elsevier Ltd. https://doi.org/10.1016/j.apmt.2017.02.004
57. Li, X., Siahpour, S., Lee, J., Wang, Y., & Shi, J. (2020). *Deep learning-based intelligent process monitoring of directed energy deposition in additive manufacturing with thermal images*. *48*, 643–649. https://doi.org/10.1016/j.promfg.2020.05.093
58. Liu, J., Sun, L., Xu, W., Wang, Q., Yu, S., & Sun, J. (2019). Current advances and future perspectives of 3D printing natural-derived biopolymers. In *Carbohydrate Polymers* (Vol. 207, pp. 297–316). Elsevier Ltd. https://doi.org/10.1016/j.carbpol.2018.11.077
59. Mathur, R. (2016). 3D Printing in Architecture. In *IJISET-International Journal of Innovative Science, Engineering & Technology* (Vol. 3). www.ijiset.com
60. Medellin-Castillo, H. I., & Zaragoza-Siqueiros, J. (2019). Design and Manufacturing Strategies for Fused Deposition Modelling in Additive Manufacturing: A Review. In *Chinese Journal of Mechanical Engineering (English Edition)* (Vol. 32, Issue 1).

Chinese Mechanical Engineering Society. https://doi.org/10.1186/s10033-019-0368-0

61. MEPS. (2022, October 31). *MEPS Europe Steel Prices | EU Historical Steel Prices*. https://mepsinternational.com/gb/en/products/europe-steel-prices?#product-unit-measurement-conversion-form
62. Mikula, K., Skrzypczak, D., Izydorczyk, G., Warchoł, J., Moustakas, K., Chojnacka, K., & Witek-Krowiak, A. (2020). *3D printing filament as a second life of waste plastics-a review*. https://doi.org/10.1007/s11356-020-10657-8/Published
63. Mohan, N., Senthil, P., Vinodh, S., & Jayanth, N. (2017). A review on composite materials and process parameters optimisation for the fused deposition modelling process. In *Virtual and Physical Prototyping* (Vol. 12, Issue 1, pp. 47–59). Taylor and Francis Ltd. https://doi.org/10.1080/17452759.2016.1274490
64. Murphy, C. A., & Collins, M. N. (2018). Microcrystalline cellulose reinforced polylactic acid biocomposite filaments for 3D printing. *Polymer Composites*, *39*(4), 1311–1320. https://doi.org/10.1002/pc.24069
65. Nassar, M. A., El Farahaty, M. A., Ibrahim Ibrahim, S., Hassan, Y. R., & Nassar, P. A. (2019). Design of 3D filament extruder for Fused Deposition Modeling (FDM) additive manufacturing. In *International Design Journal* (Vol. 9).
66. Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018a). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. In *Composites Part B: Engineering* (Vol. 143, pp. 172–196). Elsevier Ltd. https://doi.org/10.1016/j.compositesb.2018.02.012
67. Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018b). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. In *Composites Part B: Engineering* (Vol. 143, pp. 172–196). Elsevier Ltd. https://doi.org/10.1016/j.compositesb.2018.02.012
68. Noztek. (2022). *Home - Noztek Extrusion Systems*. https://noztek.com/
69. O'Connell, J. O. (2021, October 24). *Best 3D Printer Filament: The Main Types in 2022 | All3DP*. https://all3dp.com/1/3d-printer-filament-types-3d-printing-3d-filament/

70. Padovano, E., Galfione, M., Concialdi, P., Lucco, G., & Badini, C. (2020). Mechanical and thermal behavior of ultem® 9085 fabricated by fused-deposition modeling. *Applied Sciences (Switzerland)*, *10*(9). https://doi.org/10.3390/app10093170
71. Park, S., & Fu, K. (Kelvin). (2021). Polymer-based filament feedstock for additive manufacturing. In *Composites Science and Technology* (Vol. 213). Elsevier Ltd. https://doi.org/10.1016/j.compscitech.2021.108876
72. Patil, H., Tiwari, R. V., & Repka, M. A. (2016). Hot-Melt Extrusion: from Theory to Application in Pharmaceutical Formulation. *AAPS PharmSciTech*, *17*(1), 20–42. https://doi.org/10.1208/s12249-015-0360-7
73. Penumakala, P. K., Santo, J., & Thomas, A. (2020). A critical review on the fused deposition modeling of thermoplastic polymer composites. In *Composites Part B: Engineering* (Vol. 201). Elsevier Ltd. https://doi.org/10.1016/j.compositesb.2020.108336
74. Pervaiz, S., Qureshi, T. A., Kashwani, G., & Kannan, S. (2021). 3D printing of fiber-reinforced plastic composites using fused deposition modeling: A status review. In *Materials* (Vol. 14, Issue 16). MDPI AG. https://doi.org/10.3390/ma14164520
75. Peterson, A. M. (2019). Review of acrylonitrile butadiene styrene in fused filament fabrication: A plastics engineering-focused perspective. In *Additive Manufacturing* (Vol. 27, pp. 363–371). Elsevier B.V. https://doi.org/10.1016/j.addma.2019.03.030
76. Plastech. (2023, February 28). *PlasticPortal.eu*. https://www.plasticportal.eu/en/polymer-prices/lm/14/
77. Prakash, K. S., Nancharaih, T., & Rao, V. V. S. (2018). Additive Manufacturing Techniques in Manufacturing -An Overview. *Materials Today: Proceedings*, *5*(2), 3873–3882. https://doi.org/10.1016/j.matpr.2017.11.642
78. Rahim, T. N. A. T., Abdullah, A. M., & Md Akil, H. (2019). Recent Developments in Fused Deposition Modeling-Based 3D Printing of Polymers and Their Composites. In *Polymer Reviews* (Vol. 59, Issue 4, pp. 589–624). Taylor and Francis Inc. https://doi.org/10.1080/15583724.2019.1597883
79. Rajendran Royan, N. R., Leong, J. S., Chan, W. N., Tan, J. R., & Shamsuddin, Z. S. B. (2021). Current state and challenges of natural fibre-reinforced polymer

composites as feeder in fdm-based 3d printing. In *Polymers* (Vol. 13, Issue 14). MDPI AG. https://doi.org/10.3390/polym13142289

80. Rauwendaal, C. (2014). *Polymer extrusion* (5th ed.).
81. ReDeTec. (2022). *ReDeTec Filament Extruder*. https://redetec.com/
82. Rett, J. P., Traore, Y. L., & Ho, E. A. (2021). Sustainable Materials for Fused Deposition Modeling 3D Printing Applications. In *Advanced Engineering Materials* (Vol. 23, Issue 7). John Wiley and Sons Inc. https://doi.org/10.1002/adem.202001472
83. Rosato, D., & Rosato, D. (2003). *Plastics Engineered Product Design*.
84. Saleh Alghamdi, S., John, S., Roy Choudhury, N., & Dutta, N. K. (2021). *polymers Additive Manufacturing of Polymer Materials: Progress, Promise and Challenges*. https://doi.org/10.3390/polym13
85. Sastri, V. R. (2022). *Polymers for 3D Printing: Methods, Properties, and Characteristics*.
86. SD3D. (2022). *3D Printing Materials - 3D Print Material Optimization Tool | SD3D Printing*. https://www.sd3d.com/3d-printing/materials/
87. Spoerk, M., Holzer, C., & Gonzalez-Gutierrez, J. (2020). Material extrusion-based additive manufacturing of polypropylene: A review on how to improve dimensional inaccuracy and warpage. In *Journal of Applied Polymer Science* (Vol. 137, Issue 12). John Wiley and Sons Inc. https://doi.org/10.1002/app.48545
88. Stansbury, J. W., & Idacavage, M. J. (2016). 3D printing with polymers: Challenges among expanding options and opportunities. *Dental Materials*, *32*(1), 54–64. https://doi.org/10.1016/j.dental.2015.09.018
89. Tan, D. K., Maniruzzaman, M., & Nokhodchi, A. (2018). Advanced pharmaceutical applications of hot-melt extrusion coupled with fused deposition modelling (FDM) 3D printing for personalised drug delivery. In *Pharmaceutics* (Vol. 10, Issue 4). MDPI AG. https://doi.org/10.3390/pharmaceutics10040203
90. Temesi J. (2002). Fundamentals of Decision Theory. *Aula*.
91. Terekhina, S., Skornyakov, I., Tarasova, T., & Egorov, S. (2019). Effects of the Infill Density on the Mechanical Properties of Nylon Specimens Made by Filament Fused Fabrication. *Technologies*, *7*(3), 57. https://doi.org/10.3390/technologies7030057

92. Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., & Martina, F. (2016). Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals - Manufacturing Technology*, *65*(2), 737–760. https://doi.org/10.1016/j.cirp.2016.05.004
93. Tofail. S, & Koumoulos. E. (2018). Additive manufacturing: scientific and technological challenges, market uptake and opportunities. In *Materials Today* (Vol. 21, Issue 1, pp. 22–37). Elsevier B.V. https://doi.org/10.1016/j.mattod.2017.07.001
94. Turner, B. N., Strong, R., & Gold, S. A. (2014). A review of melt extrusion additive manufacturing processes: I. Process design and modeling. In *Rapid Prototyping Journal* (Vol. 20, Issue 3, pp. 192–204). Emerald Group Publishing Ltd. https://doi.org/10.1108/RPJ-01-2013-0012
95. Valino, A. D., Dizon, J. R. C., Espera, A. H., Chen, Q., Messman, J., & Advincula, R. C. (2019). Advances in 3D printing of thermoplastic polymer composites and nanocomposites. In *Progress in Polymer Science* (Vol. 98). Elsevier Ltd. https://doi.org/10.1016/j.progpolymsci.2019.101162
96. Vidakis, N., Petousis, M., Velidakis, E., Liebscher, M., Mechtcherine, V., & Tzounis, L. (2020). On the strain rate sensitivity of fused filament fabrication (Fff) processed pla, abs, petg, pa6, and pp thermoplastic polymers. *Polymers*, *12*(12), 1–15. https://doi.org/10.3390/polym12122924
97. Vyavahare, S., Teraiya, S., Panghal, D., & Kumar, S. (2020). Fused deposition modelling: a review. In *Rapid Prototyping Journal* (Vol. 26, Issue 1, pp. 176–201). Emerald Group Holdings Ltd. https://doi.org/10.1108/RPJ-04-2019-0106
98. Walter Michaeli. (2003). *Extrusion Dies for Plastics and Rubber_ Design and Engineering Computations*.
99. Wellzoom. (2022). *Wellzoom – Wellzoom desktop filament extruder*. http://wellzoomextruder.com/
100. Whitaker, M. (2014). The history of 3D printing in healthcare. *The Bulletin of the Royal College of Surgeons of England*, *96*(7), 228–229. https://doi.org/10.1308/147363514x13990346756481

101. Whyman, S., Arif, K. M., & Potgieter, J. (2018). Design and development of an extrusion system for 3D printing biopolymer pellets. *International Journal of Advanced Manufacturing Technology*, *96*(9–12), 3417–3428. https://doi.org/10.1007/s00170-018-1843-y

102. Wickramasinghe, S., Do, T., & Tran, P. (2020). FDM-Based 3D printing of polymer and associated composite: A review on mechanical properties, defects and treatments. In *Polymers* (Vol. 12, Issue 7, pp. 1–42). MDPI AG. https://doi.org/10.3390/polym12071529

103. Woern, A. L., & Pearce, J. M. (2018). 3-D printable polymer pelletizer chopper for fused granular fabrication-based additive manufacturing. *Inventions*, *3*(4). https://doi.org/10.3390/inventions3040078

104. Wu, H., Fahy, W. P., Kim, S., Kim, H., Zhao, N., Pilato, L., Kafi, A., Bateman, S., & Koo, J. H. (2020). Recent developments in polymers/polymer nanocomposites for additive manufacturing. In *Progress in Materials Science* (Vol. 111). Elsevier Ltd. https://doi.org/10.1016/j.pmatsci.2020.100638

105. Yang, Y., Knol, M. F., van Keulen, F., & Ayas, C. (2018). A semi-analytical thermal modelling approach for selective laser melting. *Additive Manufacturing*, *21*, 284–297. https://doi.org/10.1016/j.addma.2018.03.002

106. Zaeh, M. F., & Branner, G. (2010). Investigations on residual stresses and deformations in selective laser melting. *Production Engineering*, *4*(1), 35–45. https://doi.org/10.1007/s11740-009-0192-y

107. Zanjanijam, A. R., Major, I., Lyons, J. G., Lafont, U., & Devine, D. M. (2020). Fused filament fabrication of peek: A review of process-structure-property relationships. In *Polymers* (Vol. 12, Issue 8). MDPI AG. https://doi.org/10.3390/POLYM12081665

108. Zhang, X., Chen, L., Mulholland, T., & Osswald, T. A. (2019). Effects of raster angle on the mechanical properties of PLA and Al/PLA composite part produced by fused deposition modeling. *Polymers for Advanced Technologies*, *30*(8), 2122–2135. https://doi.org/10.1002/pat.4645

5.2 DECLARATION

On authenticity and public assess of master's thesis

Student's name:	Mabirizi Uthuman
Student's Neptune ID:	ZHL2FL
Title of the document:	Design a Laboratory 3D Filament Extruder
Year of publication:	2023
Department:	Mechanical Engineering

I declare that the submitted master's thesis is my own, original individual creation. Any parts taken from another author's work are clearly marked, and listed in the table of contents.

If the statements above are not true, I acknowledge that the Final examination board excludes me from participation in the final exam, and I am only allowed to take final exam if I submit another master's thesis.

Viewing and printing my submitted work in a PDF format is permitted. However, the modification of my submitted work shall not be permitted.

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Student's signature

5.3 STATEMENT ON CONSULTATION PRACTICES

As a supervisor of Mabirizi Uthuman, NEPTUN ID: ZHL2FL, I here declare that the final essay/thesis/master's thesis/portfolio[1] has been reviewed by me, the student was informed about the requirements of literary sources management and its legal and ethical rules.

I recommend/don't recommend[2] the final essay/thesis/master's thesis/portfolio to be defended in a final exam.

The document contains state secrets or professional secrets: yes no*[3]

Gödöllő, 2023/05/02

Zsidai László

Dr. Zsidai László, Associate Professor.
Internal supervisor

[1] Please select applicable and delete non-applicable.
[2] Please underline applicable.
[3] Please underline applicable.

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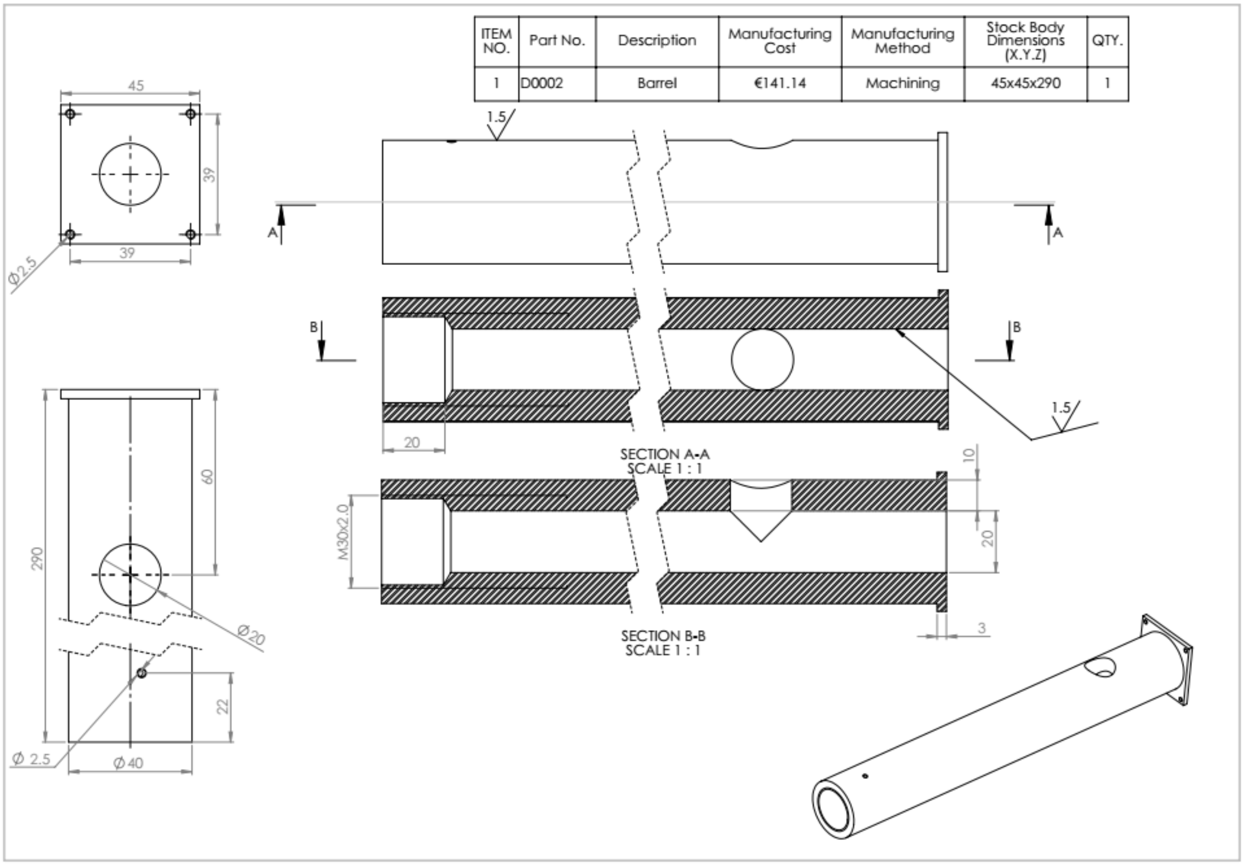
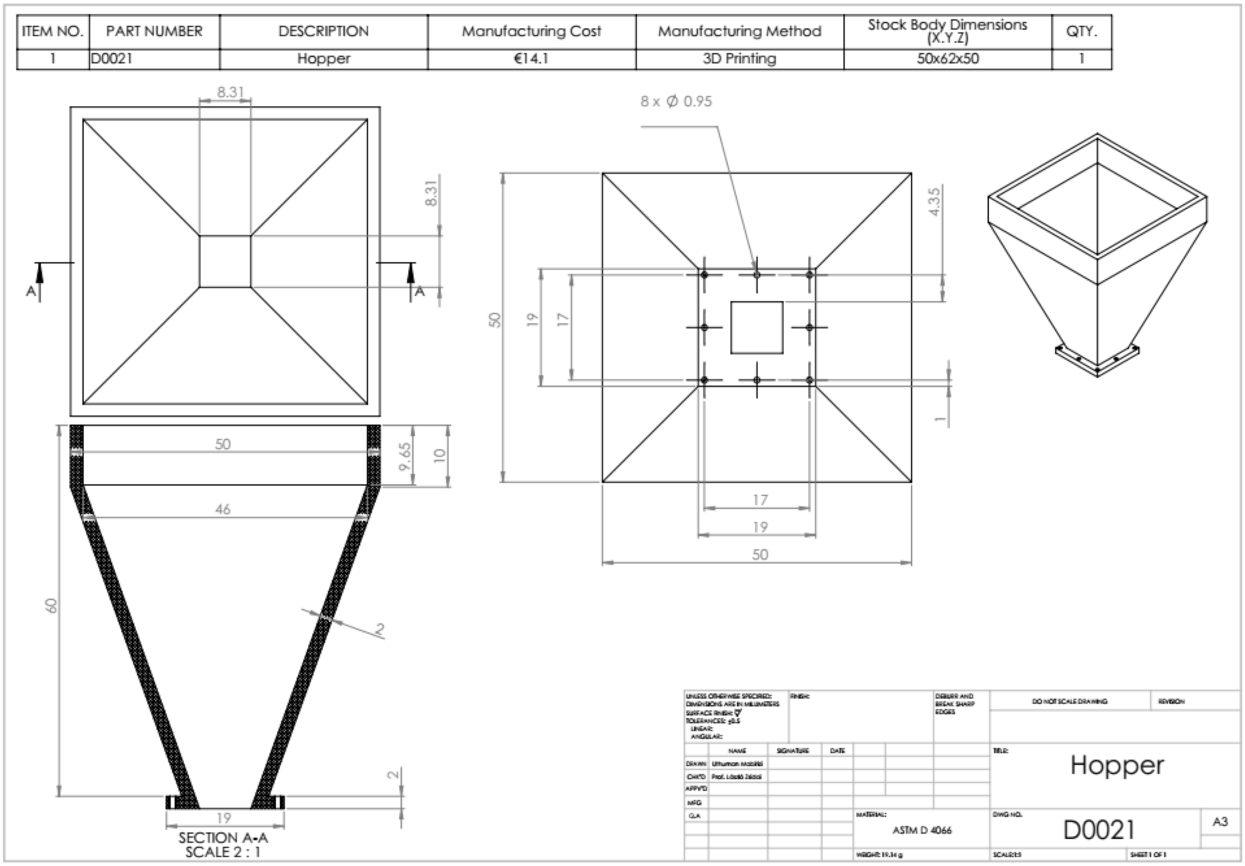
5.5 Appendices

Appendix A: Extruder Barrel technical drawings (Own Work)

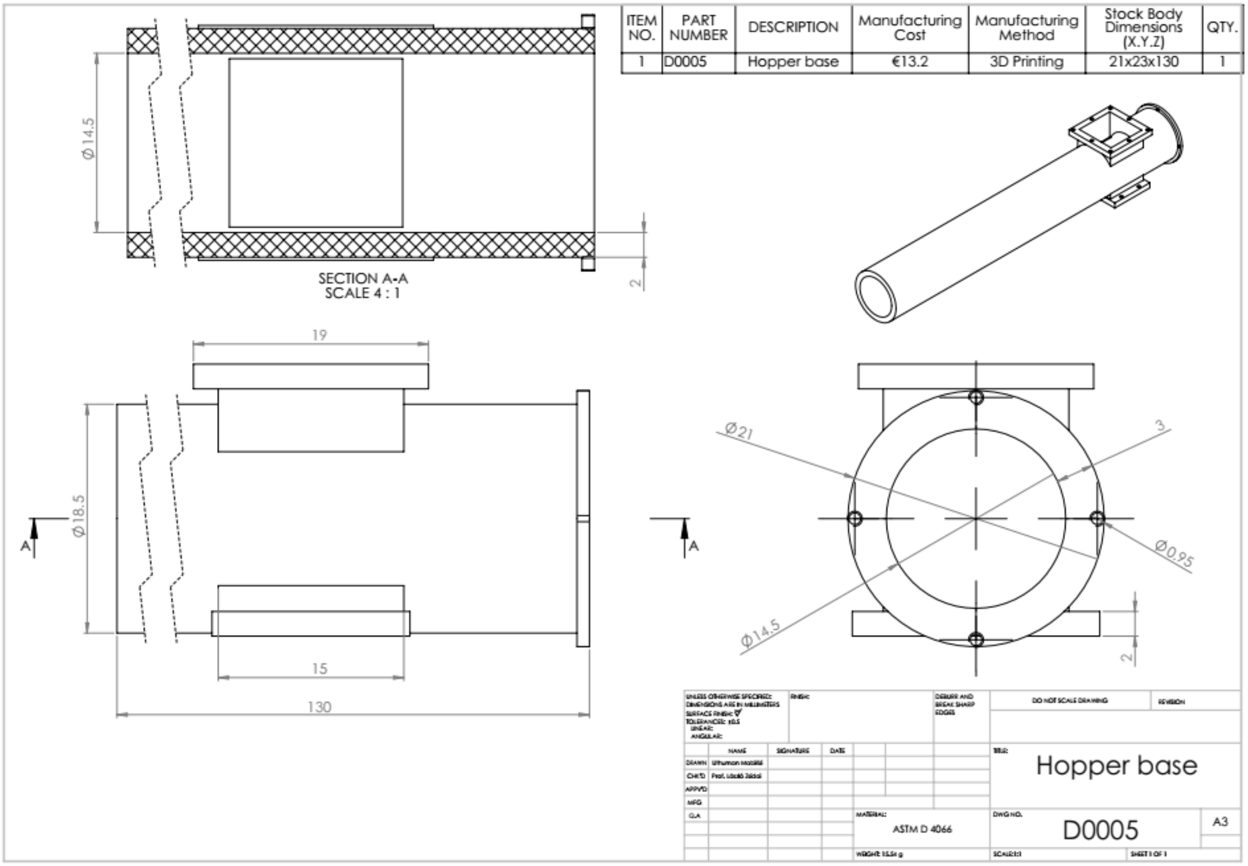


ITEM NO.	Part No.	Description	Manufacturing Cost	Manufacturing Method	Stock Body Dimensions (X.Y.Z)	QTY.
1	D0002	Barrel	€141.14	Machining	45x45x290	1

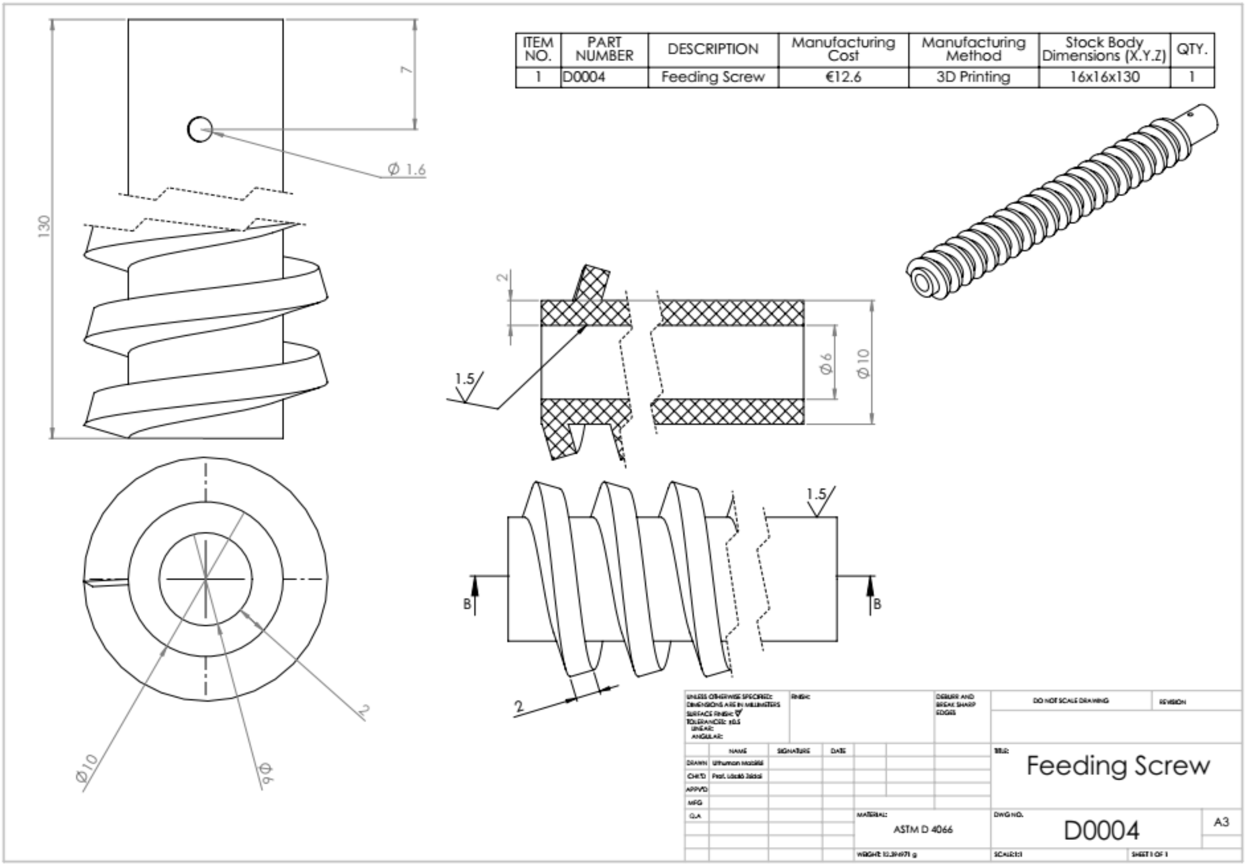
Appendix B: Extruder hopper technical drawings (Own Work)



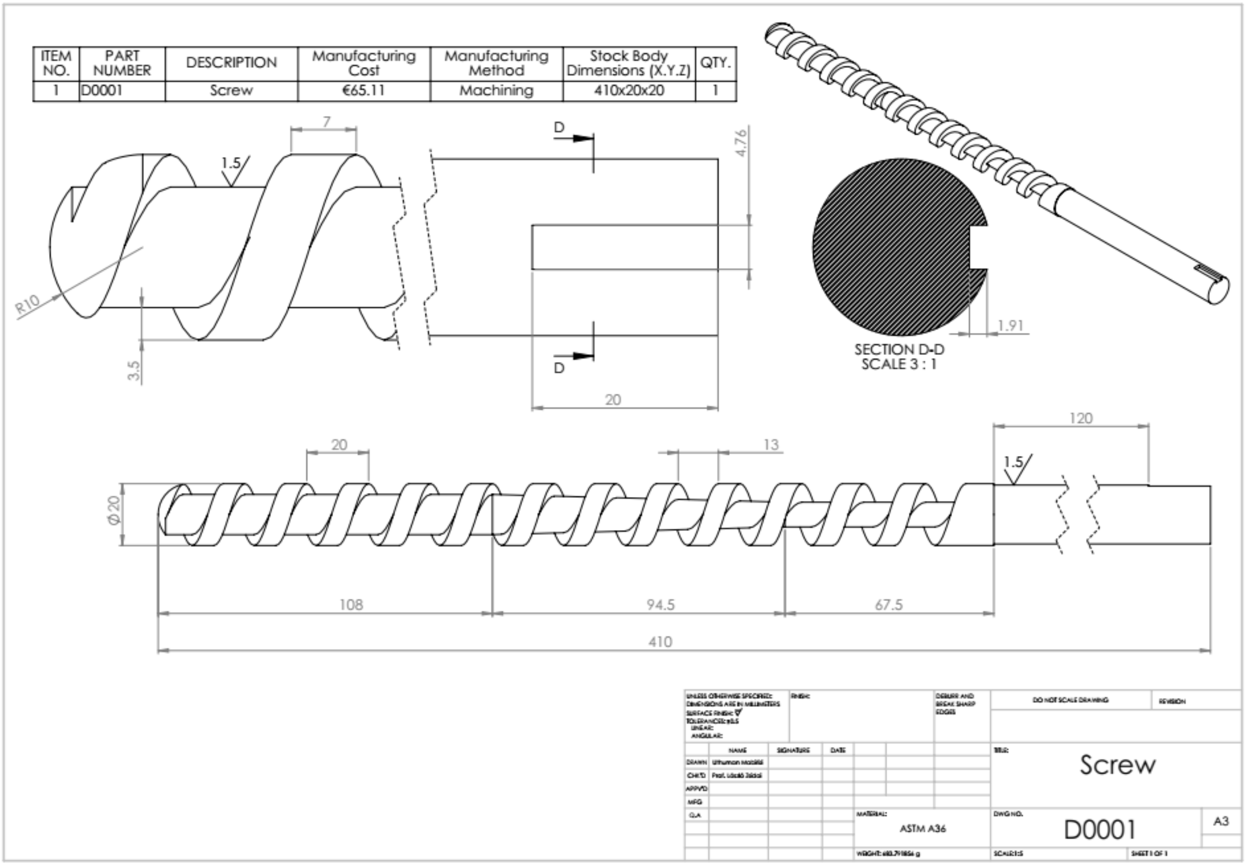
Appendix C: Extruder hopper base technical drawings (Own Work)



Appendix D: Extruder hopper Feeding screw technical drawings (Own Work)

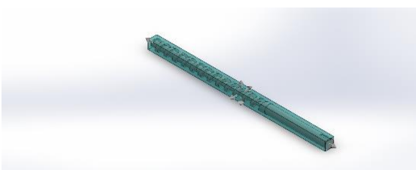


Appendix E: Extruder Screw Technical drawings (Own Work)



Appendix F: Extruder Screw detailed Manufacturing cost analysis.

SOLIDWORKS Costing Report



Model Name:	D0001
Date and time of report:	3/25/2023 1:24:38 PM
Manufacturing Method:	Machining
Material:	Plain Carbon Steel
Stock weight:	1.28 kg
Stock Type	Block
Block Size:	410.00x20.00x20.00 mm
Material cost/weight:	0.81 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	1
Lot size:	1

Estimated cost per part: 70.20 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	0% Current 70.20 USD Previous 70.20 USD

Cost Breakdown

Material:	1.04 USD	1%
Manufacturing:	69.16 USD	99%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 02:18:19

Setups:	02:10:00
Operations:	00:08:19

Cost Report

Model Name:	D0001	Material:	Plain Carbon Steel	Material cost:	1.04 USD	Total cost /part:	**70.20 USD**
				Manufacturing cost:	69.16 USD	Total time /part:	**02:18:19**
				Markup:	0.00 USD		

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	01:00:00	30.00
Setup Operation 9	01:00:00	30.00
Total	**02:00:00**	**60.00**

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 9	00:05:00	2.50
Total	**00:10:00**	**5.00**

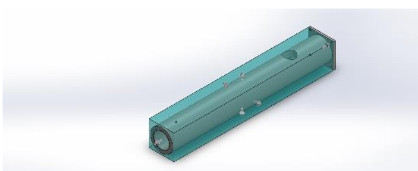
Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Slot 1	Roughing	200.87	00:00:01	0.01	Flat End Mill	N/A
Volume 1	Roughing	76120.26	00:08:18	4.15	Flat End Mill	N/A
Total		**76321.13**	**00:08:19**	**4.16**		

Setup Operations

1. Setup Operation 1
   a. Slot 1
2. Setup Operation 9
   a. Volume 1

Appendix G: Barrel detailed Manufacturing cost analysis.

SOLIDWORKS Costing Report



Model Name:	D0002
Date and time of report:	3/25/2023 2:26:28 PM

Manufacturing Method:	Machining
Material:	Plain Carbon Steel
Stock weight:	4.58 kg
Stock Type	Block
Block Size:	45.00x45.00x290.00 mm
Material cost/weight:	0.81 USD/kg
Shop Rate:	N/A

Quantity to Produce	
Total number of parts:	1
Lot size:	1

Estimated cost per part:	152.17 USD
Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	0% Current Previous

Cost Breakdown		
Material:	3.71 USD	2%
Manufacturing:	148.46 USD	98%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part:	04:56:55
Setups:	04:20:00
Operations:	00:36:55

Cost Report

Model Name:	D0002	Material:	Plain Carbon Steel	Material cost: Manufacturing cost: Markup:	3.71 USD 148.46 USD 0.00 USD	Total cost /part: Total time /part:	152.17 USD 04:56:55

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	01:00:00	30.00
Setup Operation 2	01:00:00	30.00
Setup Operation 3	01:00:00	30.00
Setup Operation 4	01:00:00	30.00
Total	**04:00:00**	**120.00**

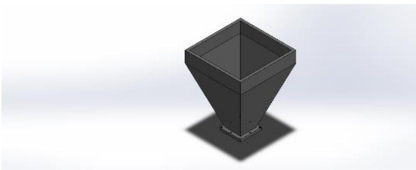
Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 2	00:05:00	2.50
Setup Operation 3	00:05:00	2.50
Setup Operation 4	00:05:00	2.50
Total	**00:20:00**	**10.00**

Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Volume 1	Roughing	2.21E+5	00:24:03	12.03	Flat End Mill	N/A
Total		**2.21E+5**	**00:24:03**	**12.03**		

Hole Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Hole 1	Drill	59.89	00:00:02	0.02	HSS Drill	N/A
	Tapping	35.34	00:00:02	0.02	HSS Tap	N/A
Hole 2	Drill	6283.19	00:00:43	0.36	HSS Drill	N/A
Hole 3	Drill	3.06E+5	00:10:19	5.16	HSS Drill	N/A
	Tapping	2.03E+5	00:00:25	0.22	HSS Tap	N/A
	C'Bore	12315.04	00:01:06	0.55	HSS Drill	N/A

Appendix H: Hopper detailed Manufacturing cost analysis.

SOLIDWORKS Costing Report



Printer Size: 200.00 x 200.00 x 200.00 mm

Model Name:	D0021
Date and time of report:	3/25/2023 2:41:42 PM

Manufacturing Method:	3D Printing
Material:	PA 6
Stock weight:	0.02 kg
Structural Material Cost:	10.00 USD
Wall Thickness:	5.00 mm
Material cost/weight:	3.61 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	1
Lot size:	1

Estimated cost per part:	15.20 USD
Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	0% Current 15.20 USD Previous 15.20 USD

Cost Breakdown

Material:	10.06 USD	66%
Manufacturing:	5.14 USD	34%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part:	01:42:52
Setups:	00:20:00
Operations:	01:22:52

Cost Report

Model Name:	D0021	Material:	PA 6	Material cost: Manufacturing cost: Markup:	10.06 USD 5.14 USD 0.00 USD	Total cost /part: Total time /part:	**15.20 USD** **01:42:52**

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:15:00	0.75
Total	**00:15:00**	**0.75**

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	0.25
Total	**00:05:00**	**0.25**

Additive Operation	Time (hh:mm:ss)	Manufacturing Cost(USD / Part)	Mold Cost(USD / Part)
3D Printing	01:22:52	4.14	N/A

Setup Operations

1. Setup Operation 1
    a. 3D Printing

Appendix I: Hopper Base detailed Manufacturing cost analysis.

SOLIDWORKS Costing Report

Printer Size: 200.00 x 200.00 x 200.00 mm

Model Name: D0005

Date and time of report:	3/25/2023 3:02:06 PM

Manufacturing Method: 3D Printing

Material:	PA 6
Stock weight:	0.01 kg
Structural Material Cost:	10.00 USD
Wall Thickness:	5.00 mm
Material cost/weight:	3.61 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	1
Lot size:	1

Estimated cost per part: 14.23 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	0% Current 14.23 USD Previous 14.23 USD

Cost Breakdown

Material:	10.05 USD	71%
Manufacturing:	4.19 USD	29%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 01:23:44

Setups:	00:20:00
Operations:	01:03:44

Cost Report

Model Name:	D0005	Material:	PA 6	Material cost: Manufacturing cost: Markup:	10.05 USD 4.19 USD 0.00 USD	Total cost /part: Total time /part:	**14.23 USD** **01:23:44**

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:15:00	0.75
Total	**00:15:00**	**0.75**

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	0.25
Total	**00:05:00**	**0.25**

Additive Operation	Time (hh:mm:ss)	Manufacturing Cost(USD / Part)	Mold Cost(USD / Part)
3D Printing	01:03:44	3.19	N/A

Setup Operations

1. Setup Operation 1
    a. 3D Printing

Appendix J: Feed Screw detailed Manufacturing cost analysis.

SOLIDWORKS Costing Report

Printer Size: 200.00 x 200.00 x 200.00 mm

Model Name:	D0004
Date and time of report:	3/25/2023 3:17:51 PM

Manufacturing Method:	3D Printing
Material:	PA 6
Stock weight:	0.01 kg
Structural Material Cost:	10.00 USD
Wall Thickness:	5.00 mm
Material cost/weight:	3.61 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	1
Lot size:	1

Estimated cost per part: 13.57 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	0% Current 13.57 USD Previous 13.57 USD

Cost Breakdown

Material:	10.04 USD	74%
Manufacturing:	3.53 USD	26%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 01:10:36

Setups:	00:20:00
Operations:	00:50:36

Cost Report

Model Name:	D0004	Material:	PA 6	Material cost:	10.04 USD	Total cost /part:	**13.57 USD**
				Manufacturing cost:	3.53 USD	Total time /part:	**01:10:36**
				Markup:	0.00 USD		

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 2	00:15:00	0.75
Total	**00:15:00**	**0.75**

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 2	00:05:00	0.25
Total	**00:05:00**	**0.25**

Additive Operation	Time (hh:mm:ss)	Manufacturing Cost(USD / Part)	Mold Cost(USD / Part)
3D Printing	00:50:36	2.53	N/A

Setup Operations

1. Setup Operation 2
    a. 3D Printing