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3D FILAMENT PRODUCTION UNIT USING PLASTIC WASTE AND PELLETS

A Thesis in
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ABSTRACT

The disruptive power of additive manufacturing (AM) technology is spanning across all fields of endeavor. The impact is felt in the supply chain, product development, prototyping, etc. It is classified as the fastest-growing technology. Its cumulative annual growth rate is projected to reach 13.5% between 2019 - 2026 in Africa. Many African countries are rapidly adopting the technology in different end-user areas, which will drive the market for the forecast period. Kenya located in East Africa is classified as a hub for innovation with several companies offering AM services with the support from the government and people to promote local production of parts.

There are seven processes of additive manufacturing, for the purpose of this thesis, we will be considering the material extrusion process. Fused deposition modeling (FDM) is a major material extrusion process that involves the extrusion of material via a nozzle and deposited layer by layer. The materials are in a melted state, so layers are being fused together upon deposition until the part is fully created. Plastic materials are commonly used in additive manufacturing which has enabled rapid prototyping and part creation in some industries. These have gained huge traction and there is a growing concern about the negative impact on the environment due to the plastic waste generated. To reduce the impact, it is possible to consider recycling and reduction of plastics waste generated. The most used plastics material in FDM is polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), the quality of the material is a critical requirement for part quality. The PLA and ABS are produced as filament, which is an input material for the extrusion process.

The need for PLA and ABS filament has increased greatly because of end-user activities and industries. Due to this demand, it is important to ensure the availability of the filament within the region. Supply chain and cost is a major driver of the availability of filament.

This thesis is focused on locally producing PLA and ABS filament from plastics waste generated and the production of pellets from local plastics industries in East Africa. There are important parameters to consider when producing the filament which are the diameter of the filament and its uniformity over its entire length. In most cases, the acceptable filament diameter is 1.75 mm with a tolerance of ±50 mm. Any variation above the tolerance makes the filament not usable for additive manufacturing. The recycling of thermoplastic materials will enhance the circular economy and locally producing pellets will promote manufacturing. The framework, and equipment for the fabrication of quality filaments in Kenya is determined from this study. It includes research on factors affecting the 3D printing hobbyist and enthusiast as well as the criteria required to set up a small-scale filament production unit locally. During the setting up of equipment, either by purchasing an existing small-scale filament unit or by adopting the DIY described in section 3.0, there are parameters that must be considered to ensure quality filament extrusion. Available raw materials (plastic waste or pellets), personnel with the necessary technical knowledge, extruder screw speed, material feed, cooling, and heating temperature. This framework can be replicated across various regions to enhance and promote the use of FDM printers for prototyping. Further investigation is required on identifying the ideal conditions for each region due to their peculiarity and how other recycled thermoplastic materials will enhance the choice for the materials for manufacturing and stimulates a circular economy.

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ABBREVIATIONS AND ACRONYMS

3D	**Three-Dimensional**
AB3D	**African Born 3D Printing**
ABS	**Acrylonitrile Butadiene Styrene**
AfCTFA	**African Continental Free Trade Agreement**
AM	**Additive Manufacturing**
CAGR	**Cumulative Annual Growth Rate**
DB3D	**Discovery Brands 3D Printing**
DIY	**Do It Yourself**
FAMA	**Future of Additive Manufacturing in Africa**
FDM	**Fused Deposition Modeling**
PLA	**Polylactic Acid**
RAPDASA	**Rapid Product Development Association of South Africa**

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1.0. CHAPTER 1 - INTRODUCTION

Additive manufacturing is the process of creating parts or products using a three-dimensional geometry from a CAD file or other sources. These parts are created by depositing the materials layer by layer using various processes. The manufacturing industries have embraced additive manufacturing and its contributory role to traditional manufacturing methods is gaining a lot of traction (Praveena, et al., 2021). There are seven additive manufacturing processes (ASTM F2792) and the focus for this research is fused deposition modeling (FDM). The most used material for FDM is PLA (Polylactic Acid) and acrylonitrile butadiene styrene (ABS), these materials are thermoplastics, hence, can be re-melt and extruded without noticeable loss of material. In this process, the molten thermoplastic is pushed through a nozzle attached to a programmed robotic arm which moves based on the information embedded in the Standard Tessellation Language (STL) file that describes the geometry (Manav, Ameya, Suraj, & Samadhan, 2022).

This technology is changing many manufacturing processes globally and revolutionizing our perspective of industrialization (Jin, Lei, Jingeng, Pai, & Lin, 2022). Africa as a continent has limited manufacturing capabilities and with the advent of Additive Manufacturing, the continent is gradually coming to the mainstream with South Africa and Kenya leading in its adoption and industry use for locally made goods. There are various organizations that are presently producing prototypes and replacement parts using additive manufacturing as well as providing educational services on AM in Kenya. These have resulted in some organizations coupled with few individuals importing filaments from other parts of the world due to limited or non-availability of 3D printing filament.

This research is focused on the material extrusion-based process, which involves the use of thermoplastics. We shall be considering two of such thermoplastics which are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). They are known for some unique properties like rigidity, insulating properties with high dimensional stability which makes them suitable for prototyping and some part creation. PLA is mostly considered because it has less environmental impact compared to other fossil-based polymers. It’s a compostable and a bio-based polyester discovered in 1932, it is biodegradable and has a low melting point (170 °C –

180 ^{o}C) compared to other plastics. It was first used in the biomedical sector. It is cheaper due to its production methods, thus enabling wider applications (Vincent, Salaaar, & Alonzo, 2020)

One of the major challenges with additive manufacturing in Africa is access to consumables like filaments and replacement parts, this is because the most popular and affordable type of AM process is material extrusion, as a result, the demand for filaments is rapidly increasing which has led to increasing in cost and supply chain logistics associated with importing the filaments. Our approach is to produce filaments locally to mitigate challenges associated with the supply chain and reduce the unit cost of filaments. To locally manufacture PLA filaments in East Africa, we need an extruder to produce them. One key thing to consider is the raw materials for the extruder, these materials can come from the recycling of waste plastics or the use of pellets as input materials for extrusion. Pellets are usually small rounded, spherical bodies made from different materials; we are considering plastics pellets for the extrusion process. The production of PLA-based pellets can be achieved through condensation and polymerization of carbohydrates extracted from plants such as corn cassava etc. This is not captured in this research. we shall be working with local plastics companies who might have the capacity to produce pellets and if not, we may consider importing pellets to support the filament production.

The use of recycled plastic waste is another source of raw materials for the extruder. It involves the following processes.

- Plastics are collected from suppliers and quality is ensured.
- Waste collected is dried, cleaned, and shredded into flakes.
- Extruder to convert flakes into filament by melting
- Quality checks ensure uniformity and dimensional accuracy

The quality of filament produced can be manipulated by the raw material quality and processing parameters such as extrusion speed and temperature.

1.1. RESEARCH OVERVIEW

How additive manufacturing can revolutionize Africa has largely been discussed more than it is being tested. Many technology experts, humanitarians, and academics have explored the possibility through localized manufacturing, conferences, and training. Its implementation is on a low scale. Startups and organizations do have some limitations that make adopting the technology more expensive compared to Asia, Europe, and the Americas (Aleksandra, 2018).

How do we feasibly, viably, and sustainably locally produce 3D printing filaments? This research explores what it takes to design a filament production unit to enhance low-cost locally made filament in East Africa with no compromise in quality. This filament production unit shall be modularized to enable ease of replication and appropriate scale for any location. The unit shall comprise of a shredder, de-humidifier, extruder, and a quality control section for extruded filaments. This project has the potential to promote efficient waste collection, sustainable manufacturing, and recycling of failed PLA and plastic waste. It is then the goal of this research to devise a plan to locally make cheaper filaments using the circular economy with no compromise in quality.

1.2. MOTIVATION FOR RESEARCH

A case study of Kenya illustrates the issues facing developing nations in terms of access to high-quality public protective facemasks during the COVID-19 pandemic. The fundamental cause of the problem is a lack of manufacturing capability and high levels of poverty. Despite the challenges, a prototype of reusable facemasks for the Kenyan people was produced. The facemask design may be easily made with a minimal amount of filament material (58 g) with a home, domestic, or desktop 3D printer that costs less than $200. The facemask was then put together using a non-woven polypropylene cloth that is widely available in Kenya. The facemask was made to fit a male infant, as well as both male and female adults (Mwema & Nyika, 2020)

In Sierra Leone, locally fabricated functional prostheses were reasonably priced. All beneficiaries were still wearing the prostheses after six weeks, and six of the eight had met their own rehabilitation goals. All the individuals no longer needed crutches after using their prosthesis. The use of 3D printing in making low-cost prostheses for low- and middle-income countries has opened a new channel for the application of the technology in Africa. (A.J, et al., 2021). Hobbyists, startups, and academia have little or no access to low-cost filament for further research and education. The need to enable the adoption and widespread of the technology lies in the availability of the consumables, which will aid the integration of the technology into manufacturing processes, startup operations, and other academic institutions teaching the technology.

During the future of additive manufacturing in Africa (FAMA) conference held in 2020, a survey was conducted which reveals that 75% of 3D printing filament consumers do experience downtimes and inaccessibility of filaments when needed. There is a great potential for 3D printing in Africa and the resources are available to spread the technology. One of the resources is the sale of low-cost FDM 3D printers across the continent and the major filament material required for the printers is plastics. Small-scale manufacturing is gradually becoming a part of the manufacturing landscape in Africa but due to the shortage of plastic filaments, the adoption rate of the technology is reduced. A 3D printing plastic filament production unit can be explored to mitigate this shortage. This modular unit will make use of recycled plastic waste and plastic pellets that will be produced by the existing local plastic industry in the region. The production of 3D filament locally will bridge the gap for high-cost filament and shortage in Africa.

2.0. CHAPTER 2 - LITERATURE REVIEW

The advancement and breakthroughs in some areas of additive manufacturing has led to the continuous growth of the technology globally. The production of prototypes, complex shape geometry is some of the significant benefits which has enhance the adoption in manufacturing processes (Redwood, 2020). In the FDM process, there is a growing concern of the negative impact on the environment due to the plastic waste from failed parts which is an addition to the plastic waste generated globally. There is sustainable approach on how additive manufacturing can contribute positively to the circular economy by advocating for the reuse and recycling of plastics and PLA waste into 3D filaments.

2.1. 3D PRINTING MARKET

According to a research report, the global 3D printing industry is estimated to have a revenue growth at cumulative annual growth rate (CAGR) 22.5% during the period 2021 - 2026. The 3D Printing filament market is estimated at $739 million in 2020 and projected to reach $2.55 billion by 2025, at a CAGR of 28.1% from 2020 – 2025 (Market and Market, 2020). Filaments made from materials such as thermoplastics and ceramics are used in FDM technology. Due to its low pricing when compared to some other forms of materials, they are beneficial in part production of complex structure objects and prototyping, which has led to a high demand for plastic filaments especially in producing medical devices and other components based on demand and location. The 3D printing market continues to grow despite the COVID-19 pandemic, a survey conducted by a startup Essentium reveals that during the pandemic, 57% of manufacturers increased 3D printing for production parts to keep their supply chains running. While 24% of respondents have 'gone all-in' on 3D printing investment, 25% of manufacturers are ramping up to meet supply chain needs, and 30% are evaluating industrial-scale 3D printing to fill supply chain gaps. (Liz, 2021). 3D printing has aided the fight against the pandemic. As a lot of hospitals struggle to get supplies, it was a solution that enables a faster response and was able to help reduce the supply chain shortages.

Some governments across the globe have policies in place to support 3D printing (CRS Report, 2019). Many African countries are taking up the initiative and started working on its adoption into the science and technology programs across the continent through partnership with private investors creating hubs and makerspaces. As a result of these initiatives, the number of 3D printers across Africa grew by 23% in 2017 and is expected to grow rapidly. The growth will increase competition with imported goods by promoting high-value manufacturing which is a major goal for African Continental Free Trade Agreement (AfCTFA). The AfCTFA is fostering some countries to develop the additive manufacturing roadmap and how it can be integrated to the goal of AfCTFA, which is projected to boost intra-Africa trade by 52% in 2022 (Aleksandra, 2018). The Rapid Product Development Association of South Africa (RAPDASA) and Future of Additive Manufacturing in Africa (FAMA) has embarked on trainings and conferences, which is creating awareness and sparking up more interest both from the public and private sector. These has posed a great value and is presently expanding the 3D Printing market in Africa.

2.2. 3D PRINTING FILAMENT IN AFRICA

There are many companies in the region, especially in South Africa, that focusses on sales of filament and hardware consumables for 3D printers. Most of them import the filaments or are representatives for other organizations that are in Europe or North America to sell their filaments and other accessories. One of the companies producing quality filament locally is Filament Factory. They are based in Roodepoort, South Africa with a low production capacity 20/50kg of filaments per day. 3D fusion recently announced the opening of a filament manufacturing plant in Mossel Bay, which will aid in supplying filament to customers in South Africa. The company will be working with Build Volume, a 3D printing reseller company in the region.

One of the significant center points for advancement in Africa is Kenya because of their colossal effects in innovation and the 3D printing space. There are few organizations offering 3D Printing services as entrepreneurs and very innovative about the products being 3D printed across various sectors of their economy. From personal experience, I have observed that, Kenyan’s love to create their own solutions, promoting home grown technology benefitted from 3D Printing. This enterprising spirit has improved the advancement of fab labs through the technology park laid out by the university of Nairobi. The fab lab started the implementation of 3D printing into Kenya and ever since has revolutionize the technology. AB3D also contributed to the industry by building their own 3D printers from locally sourced materials and aims to make it more accessible as soon as possible. Kuunda3D, though presently out of business contributed to the filament portfolio of African markets, they were a distributor for Copper3D's (a Chilean/US-based company) antibacterial filaments and distributors of other brands like Ultimaker 3D printers in the region. DiscoverBrands 3D printing (DB3D) is a social enterprise located in Nairobi, Kenya with the objective of reducing plastics waster and locally producing affordable 3D printing filaments using the circular economy approach. This initiative is in partnership with KEPSA, Coca-Cola beverages and Tech4Trade and others.

Despite the growth and the fab lab initiatives, one of the major challenges experienced by 3D print enthusiast, educators and industry is the growing cost of 3D printing filaments. The cost for a Kilogram of filament in Kenya is anywhere between $25 and $40 USD. However, in Kenya the price can go up to as much as $60 due to supply chain networks and availability. This factor is preventing individuals or communities that are interested in 3D printing from accessing the basic raw material at a reasonable price. How do we reduce the import rate, reduce the market price, and enhance the creativity of hobbyist, improve the education sector, and promote economic activity in the 3D filament production in Africa? A modular production unit that we can replicate across different localities can reduce the shortages and help make 3D printing filament easily accessible at a cheaper rate. This will also improve knowledge gap in the continent for filament production.

2.2.1. SMALL-SCALE 3D FILAMENT PRODUCTION

The production of 3D-printing filaments is a relatively simple process that can be tailored to a wide range of capabilities. There are several technology providers that have designed manufacturing processes for filament production; however, the differences between these technologies are frequently minor. The typical process is divided into four stages: mixing, drying, extrusion, and quenching. (Alzahrani, 2017). Extruders are typically distinguished by the number of screws inside the barrel (Fig 2.1) a schematic of an extrusion system (AZO Materials, n.d.). These screws can be single or twin etc. depending on the material (Fig 2.2) types of screw arrangements.

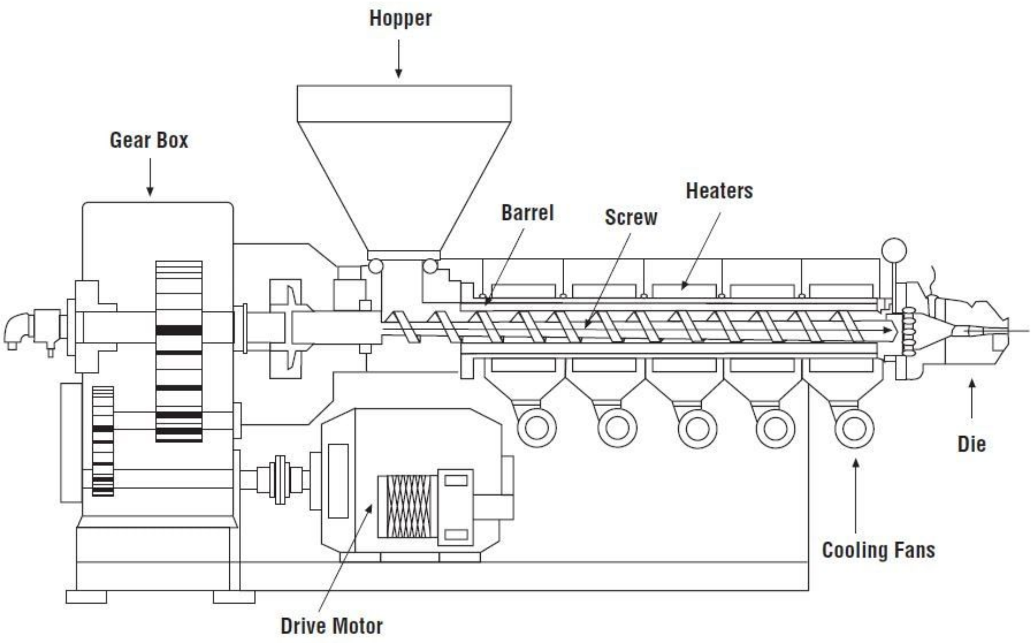

Figure 2.1: *A schematic of an extrusion system.*

Furthermore, the screw arrangement and design shape are frequently carefully selected based on the nature of the operation and the properties of the materials to be processed. The mechanism by which the melt is transported from the feed hopper to the die is the primary distinction between single and twin-screw arrangements. The barrel of some extruders is divided into zones, with the ability to control the temperature of each zone independently. This is critical when the operation is thermally sensitive or additives are introduced through and injection port (Janssen, 2004).

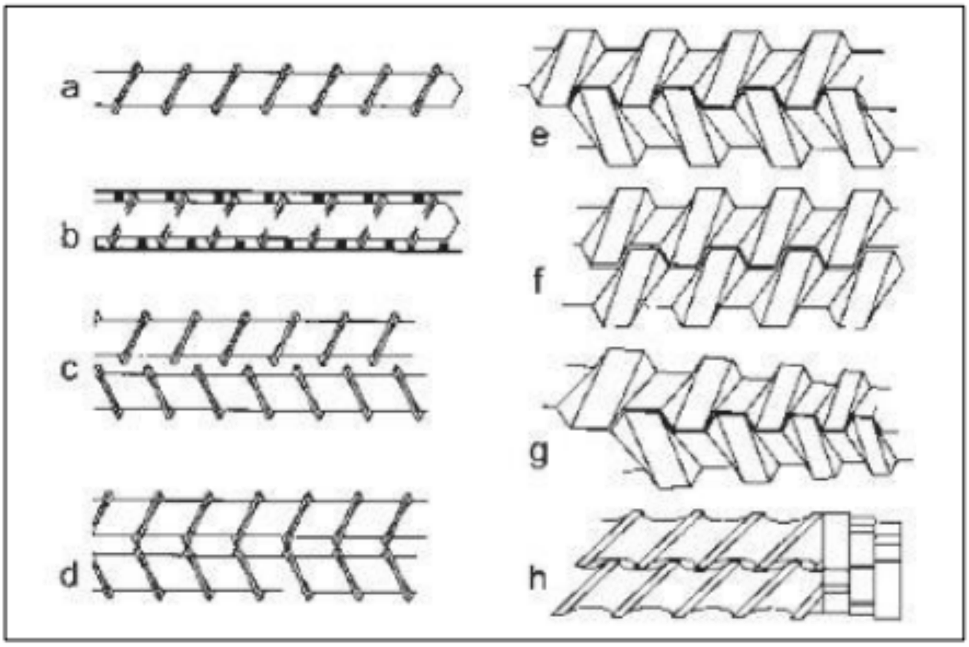

Figure 2.2: Types of screw arrangements: (a) Single-screw, (b) co-kneader, (c) mixing mode, (d) transport mode, (e) counterrotating, (f) corotating, (g) conical rotating, (h) self-wiping

Many small-scaled 3D Printing filament manufacturers like Filament factory, Elephab and 3D-fuel have capacity to deliver between 2-5 kg/hr. in almost any thermoplastic. There is a rapidly growing approach on how to increase capacity due to the surge in the 3D filament market. In Africa, some international manufacturers and suppliers have established a presence in South Africa by enlisting several South African companies in their reseller programs and through distributorship agreements. South Africa has more than fifteen companies directly involved in 3D printing services, which is a good number for Africa. In Nigeria which is the largest economy in the western has a very low adoption of the technology (Alex O. Inoma, 2020), many enthusiasts, private sector and government agencies do contact international organizations for 3D printing services. Ghana and Togo which are also in same region are nowhere compared to the number of organizations we have in South Africa. Kenya located in the East of Africa have a national policy framework and program to implement industry 4.0 which has fueled the early adoption of the technology in the region. The use case of 3D printing is becoming evident in Africa and there have been loads of activities and news geared towards its adoption in the buildings and manufacturing sector (World Economic Forum, 2021). Even as we establish a strong perception and likely adoption of 3D Printing across various regions on the continent, we must acknowledge that Africa has limited production capacity across 3D Printing value chain. The detail of the process is described in Sec.3.1 of this thesis.

2.2.2. RECYCLED 3D FILAMENT PRODUCTION

Refil, Fila-cycle, Filamentive, and Neflatek are among the companies that recycle plastic waste products into 3D printing filament. These companies hope to create filaments out of plastic waste so that customers can use their 3D printers in a more environmentally friendly manner. PET filament from PET bottles and commercial waste (Refil, n.d.), PLA filament from yogurt cups (Fila-cycle, 2015), and HIPS filaments from recycled window frames and thermoformed sheets are among the filaments they produce (Nefilatek, 2019). Each company has a distinct method for producing high-quality filament that is comparable to filament produced from virgin plastics. When Refil manufactures PET filament, they mix approximately 10% virgin PET during the melting process to achieve the required filament quality. PLA and ABS filaments are both 100 percent recyclable. They ensure that any contaminants in the shredded material are properly filtered before entering the melting process. Refil's materials are all REACH and RoHS compliant (Refil, n.d.). RoHS stands for restriction of hazardous substances and adheres to the directive using six different types of hazardous materials that are commonly found when manufacturing products from electronic and electrical components. (REACH) is an abbreviation for registration, Evaluation, Authorization, and Restriction of Chemicals. It is a European Union regulation that requires communication between the customer and the manufacturer to inform the customer of chemical substances that may be harmful to their health or the environment (Vista Industrial Products, Inc., 2018). With RoHS and REACH certification, Refil understand the composition of the material as well as guarantee the quality of the waste for recycling.

Fila-cycle guarantees that the industrial waste they use is clean and contaminant free. They tested each material to ensure its quality and were successful in making all their filaments from 100 percent recycled plastics (Fila-cycle, 2015). Filamentive guarantees a high percentage of recycled material in their filament while adhering to BS EN ISO 14021:2016, an international standard for self-declared environmental claims. This standard includes a process for evaluating and verifying the selected claims. To ensure the quality of the filament, they also ensure that it comes from a consistent waste source, which includes post-consumer and post-industrial waste.

Nefilatek is another company that is assisting in the reduction of the environmental impact of plastic pollution. When failed prints or waste from 3D printing are sent to Nefilatek to become new filament for printing, the waste cycles back into the plastic cycle. Filabot, a 3D printing filament extruder, is used by Nefilatek to create their filament (Nefilatek, 2019). Unfortunately, many companies and organizations that can convert waste into filament do not have open-source instructions on how to make these recycled filaments. Given the high quality of filament produced by companies, it is believed that the extra steps taken in manufacturing for recycling filament are essential in producing high-quality products.

TechforTrade developed a chopper for producing flake, and a filament extruder Fig.2.3 (Thunder head filament extruder), which is an open source with a total cost of $2,000. The filament extruder can produce 5-10 kg of filament a day. As greater number of small-scale filament producers are established, they may be able to aggregate their excess product and sell it to the international market. (Matthew P. Rogge, 2017) Given the high-quality filament produced by companies, it is believed that the extra steps taken in manufacturing recycling filament are important in producing high quality products.

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Figure 2.3: Thunderhead filament extruder prototype in Tanzania

2.3. 3D Printing Filament Production Unit

The main purpose of this thesis is to aid the adoption of additive manufacturing in East Africa by making available locally produced filaments. The research methodology section clearly defines the optimal parameters, processes and equipment required to achieve the purpose. AM is less wasteful compared to the traditional manufacturing methods, but due to its wide adoption, we need to develop strategy on how to sustain PLA waste generated. Academic research and studies focused on the sustainability of waste generated are gaining tractions because plastics is one of the major feedstocks for AM.

In manufacturing quality filament, companies follow a typical approach using plastic pellets. The pellets are dried in specialized dryers to remove humidity before being fed into the extruder's hopper via a closed system of feeders. A liquid dye is added at the same time as the main material, usually in the form of masterbatch. The polymer melts and combines with the dye in the plasticizing system. The material passes through the extruder until it reaches the appropriate pressure on the head, causing it to "swell" after exiting the extruder. The die (in the extruder tool, see Fig. 2.1) helps to control the thickness and shape of the extruded product, which is still deformable and stretches due to line tension. The material enters the feed throat (an opening near the back of the barrel) and makes contact with the screw. The rotating screw propels the plastic beads forward into the barrel, which is heated to the desired molten plastic melt temperature. It is then extruded through a die, which has two sizes in the case of 1.75mm and 3.0mm. Because the filament is still hot as it is extruded through the die, we recommend using a computer fan to cool it down, which will help keep the filament from kinking (Mercator, 2017).

2.4. PLASTICS INDUSTRY IN KENYA

We need to help improve our environment; it is estimated that 300 million tons of plastic waste is generated globally on a yearly basis which is about the weight of the world's population. Out of the over 8.3billion tons of plastics produced since early 1950s, nearly 60% ended up as waste. One of the ways to salvage the situation is the recycling of plastic waste generated in Africa for filament production. According to the Kenya Association of Manufacturers (KAM), the plastics industry in Kenya is vibrant and developed well enough producing goods made of polyvinyl chloride (PVC), polystyrene, and polypropylene. Though most of the materials are imported as granules, there is an ongoing initiative to reduce importation and start producing the raw materials locally. Polystar Machinery Co. Ltd. a leading manufacturer of plastics from Taiwan installed a set of cutter-integrated plastics film recycling machine in Kenya. It is based in Nairobi, and it supplies shrink film, bags, sheets, and PE sheets. The company produces and distributes plastic packaging products. A total of seven recycling lines are installed across Africa, in Kenya, South Africa, Egypt, Malawi, Algeria and Ethiopia. The machine can recycle polyethylene and flexible packaging material, printed and non-printed. It has a cutter pelletizing system integrated with the machine which eliminates pre-cutting the material, with less energy consumption, producing high quality plastic pellets at a productive rate.

The continent has encountered a few booms in the plastics business and Kenya has seen developing requests for trend setting innovations with the plastic business requesting handling and reusing machines that are exceptionally proficient, cost-saving, and adaptable. These necessities are being met by Polystar Machinery and it is possible to leverage on the current apparatus to create PLA plastics pellets for the measured 3D printing expulsion unit for fiber creation. There are different associations that are into plastics creation, we can use on their creation capacities and hardware to guarantee we have plastic pellets as contribution to our fiber creation unit. "On the specialized side, there is work to be finished with the extruder to ensure it dependably creates great fiber. We genuinely must make a fiber whose quality is just about as great as fiber produced using virgin plastic.

2.4.1. PLASTIC WASTE IN KENYA

Kenya is emerging as one of the first countries in East Africa to limit single use plastics and have invested in policies to combat plastic pollution. In conjunction with UNEP, they have developed a plastic waste management scheme, which aims to promote environmental consciousness by adopting the Green University Initiative. This has also evolved to student engagement and higher education offerings in environmental sciences and management. There has been an increase in investment in plastic recycling and new players are coming on board and making it easier to achieve the policy. The FlipFlopi project is one of the partners in Kenya that has campaigned aggressively for plastic-reuse revolution. They are a circular economy enterprise based in East Africa with a vision to have a world without single-use plastic. In 2007, they built the world’s first 100% plastic sailing boat on the island of Lamu, using traditional builders and techniques covered with multicolored flip flops, hence the name. Invariably, they built a boat using plastic waste and merged the waste collection process with their traditional craft to collect waste and educate the communities about converting plastic waste into useful resources. They also developed a free toolkit to aid new businesses on how to start a sustainable business with plastic waste.

The waste to profit initiative has created enormous interest in waste management which is enabling green jobs and promoting a greener environment. There are waste recycling companies that are generally involved in converting waste materials into useful and reusable materials. We shall be leveraging on their value chain to get quality plastic or PLA waste which will be an integral part of our operation. Table 2-1 is a list of organizations in Nairobi Kenya that are into waste recycling.

Table 2-1. Waste recycling organizations in Kenya

S/N	Company Name	Activities
1	Mr Green Africa	Converts locally collected plastic waste into high quality post-consumer recycles.
2	Ecopost Kenya	Recycles plastic waste to eco-friendly plastic lumber profiles
3	E-waste Kenya	Electronic waste management
4	Garbage Dot Com	Waste management, recycling, and recovery
5	Colnet Limited	Recycling and recovery
6	Taka Taka Solutions	Waste management and recycling company
7	Petco Kenya	Collection and recycling of post-consumer PET plastics

The plastic sourcing model for local filament production can be divided roughly into two models. Work with established recycling centers or directly with waste pickers to source plastic. Engaging waste pickers directly entails hiring reputable waste pickers to locate high-quality clean plastic waste. The benefits of working directly with waste pickers include having control over the entire plastic chain, being able to easily track impact and monetary exchanges, and not relying on a third party. This does, however, imply that you must invest significant time in developing a local network, establishing a tracking system for monetary exchange (for example, via mobile phone payments), rigorously controlling and checking the plastic quality input, creating clear instructions for cleaning and sorting, and developing your own facilities to shred waste and possibly a washing facility.

The proposed method for process of waste collection and segregation will be the prerogative of the existing waste management companies because they have a better collection and recycling process in place, and it would be most beneficial to leverage on the existing structures of waste management within the region.

2.5. CHALLENGES IN WASTE TO FILAMENT

Plastic recyclers are not always cost-effective for consumers to build or buy unless they use a substantial amount of filament. Based on the extrusion rate, an average recycler needs to run 40 to 90 consecutive hours to pay off its capital cost, shown in Table 2-1 popular plastics filament recycler and cost comparison (Yusheng Feng, 2020). A cost-effectiveness analysis compares popular and successful extruders such as the Filabot EX2 Extruder, Recyclebot, and others for small to medium-sized recyclers for low-level production. Because extruders account for most recycler costs, extruder prices are an accurate representation of the estimated amount required to make a recycler cost-effective. (Yusheng Feng, 2020). As shown in a feasibility study, recyclers have long-term benefits, but small businesses and hobbyists do not generate enough waste to compensate for the time and cost of building and operating a recycler. TechforTrade, 2016)

TABLE 2-2. *Cost comparison of the hours needed to pay off the capital cost of filament extruder*

Popular Plastics Filament Recyclers and Cost Comparison					
Machine	**Capital Cost, USD**	**Extrusion Speed, kg/hr**	**Amount of spools needed to pay off, kg**	**Time needed to pay off, hrs**	**Buy or Build**
Filabot EX2 Extruder	2,699	1	74.97	75	Buy
FilaFab Extruder	290	1	25.55	51	Buy
Filastruder	299	0.125 - 0.25	8.33	42	Buy
Ian McMill Diy Extruder	130 - 150	1	4.17	4.17	Build
Lyman Extruder	250-600	0.4	6.94	17.36	Build
Noztek Pro	1,205	0.5	33.47	66.94	Buy
ProtoCycler	1,699	0.55	47.19	86	Buy
Recyclebot	700	0.4	19.44	49	Buy

Developing a recycler to attain a high-quality filament is complex. Industrial recycling processes use precise equipment and have a controlled environment to make consistent filament for 3D printing. Small scale consumers such as hobbyist develop their own recycling process often substitute or skip steps, compromising the filament quality. Some mistakes in building a recycler include improper drying methods for the plastic before melting, uneven material extrusion rates, incorrect melting temperatures, inadequate material cooling methods, and insufficient equipment to measure filament diameter (Yusheng Feng, 2020). These parameters are dependent on the type of plastics used in producing the filaments. Although these are common missteps, there are homemade solutions that have shown to be successful since they fulfill the requirements, such as Filastruder and Filabot. These machines have been developed and used by other organizations as captured on the product review. As a maturing technology, overcoming these challenges is one of the biggest hurdles in establishing a sustainable 3D filament production unit.

3.0. CHAPTER 3 - METHODS AND MATERIAL

There are many new tech companies that have designed manufacturing processes for 3D filament production, but the differences between these technologies are often minor. As a result, this methodology will go over the main process engineering concepts used in the manufacture of 3D printing filaments and the equipment required to setup a filament production unit that can produce at a small scale to meet the needs in the community of interest. The process of recycling waste to filament was discussed referencing Fig.3.2 to illustrate the sequence of activities.

3.1. RESEARCH METHODOLOGY

This section explains the methodology utilized in this study. It is divided into several stages, each of which is discussed in this section. The research technique started with tactical design, which included identifying the problem, establishing requirements, and using existing solutions for similar challenges, as well as generating alternative ideas, evaluating the alternatives, and deciding on an acceptable solution. The chosen approach in this study, as shown fig 3.1, is a well-organized arrangement of the methods that are adopted to create the foundation of this research.

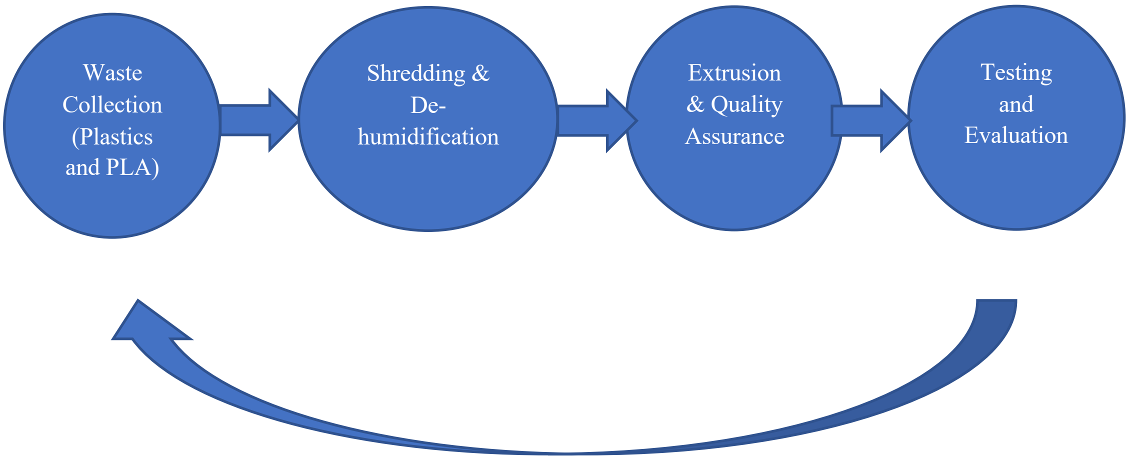

Figure 3.1 The methodology for 3D filament production

3.1.1. WASTE COLLECTION (PLASTICS AND PLA)

The primary goal of this work was to assess the need for sorting Plastics and PLA waste prior to mechanical recycling. It aids in the improvement of filament quality and purity, as well as the reduction of variation in the dimensions of extruded filaments. To create the useable waste, due to the various types of waste collected, we need to segregate and sort. We shall be leveraging on the existing organizations in waste management and create a list of requirements that would be most beneficial to ensure quality in our processes. The filament materials are chosen based on the requirements such as surface finish, color, hardness, strength, elastic properties, and so on. There are two types of plastic waste: biodegradable and non-biodegradable. The plastic waste is manually separated according to the type of material such as PLA, ABS, Carbon fiber and so on. Sorting of segregated waste can be continued based on color and size. Before beginning shredding, all materials must be cleaned and resized to fit the shredder input hopper. There are numerous automatic sorting techniques available in the market, but due to the small amount of waste material and limited number of different plastics used in this case, manual separation is recommended, and advanced techniques can be adopted as the scale increases.

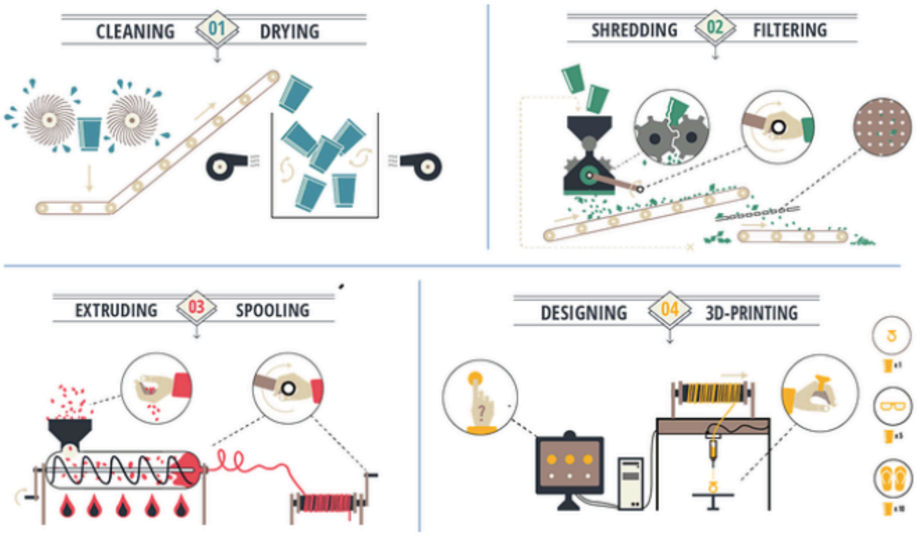

Figure 3.2; The general recycling process of plastic waste to 3D printing filaments.

3.1.2. SHREDDING AND DE-HUMIDIFICATION

The next step after waste collection and segregation is shredding. There are various shredding machines available in the market, ranging from JWC to 3Devo. The shredder must be an industrial grade granulator with the following capabilities

- Dual-shafter, slow speed, high-torque (Suitable for different materials, especially those that will not fragment easily in high grinding system)
- Automated monitoring and controls
- Hardened steel cutters for long life
- Shredder cutters should be designed for quick removal and re-installation to maximize production uptime.
- Customizable hopper and stands
- Recycle 5 -10 kg in an hour

There are more technical information about this machine on the manufacturers portal https://3devo.com/shred-it/.This machine consists of granulator blades, premium, reversible shredder blades, and hopper with stand. The hopper helps to prevent plastic scraps from escaping and ensure safe continuous input into the chamber. Fig. 3.3.

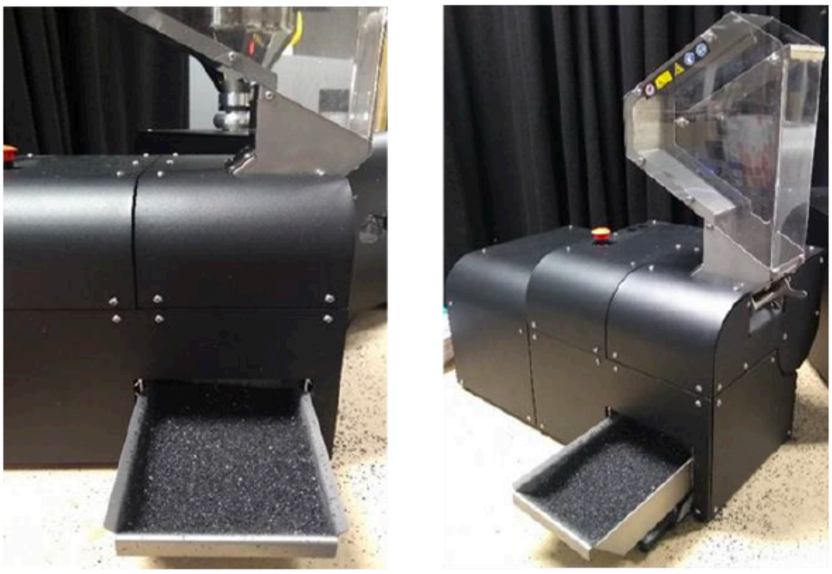

Figure 3.3. 3devo Shredder

The materials are collected from the granulate container after shredding. A mixture of different sizes of material is produced from the granulate container. The mixture granules are sorted based on size using three different types of filters; 1 mm, 2 mm, and 3 mm granule sized filters to sort the granules. Through investigation, it has been discovered that filtering the granules into their respective sizes will results in a better flow of material. This is due to uniform melting in the barrel during the melting and extrusion process.

After the material is sorted and filtered, each size category is dehumidified separately in preparation for the extrusion process. A typical example of humidifier is AIRID, a product from 3devo Fig. 3.2 which consist of a humidifier and a control panel to display information about the processes. This humidifier has a hopper with a capacity of 5 liters and a drying time of 1 kg every 3 hours. The dyer has an OLED display and allows you to easily customize requirements like blower speed, temperature, and mixer rpm with a single rotation and push control button. It has access to various material dryer pre-sets (Johnson, 2020).

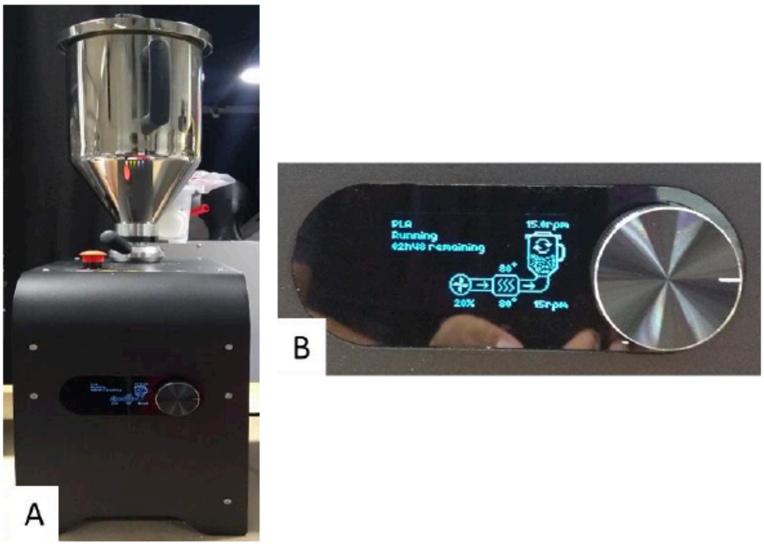

FIGURE 3.4. 3devo humidifier, B. Control Panel on dehumidifier

3.1.3. EXTRUSION AND QUALITY ASSURANCE

Shredded materials that have been dehumidified are ready for the extrusion process. The filament extruder is used for the extrusion process. First, dehumidified shredded material is loaded into the extruder's hopper. The extrusion process is then started by turning on the extruder and using the control panel in the extruder, which has convenient standard material pre-sets and customizable material temperature profiles.

Temperatures in the extruder's heater zones can be controlled independently. The filament is formed by a feed screw with varying speed for the material flow and a nozzle/die at the end of the feed screw.

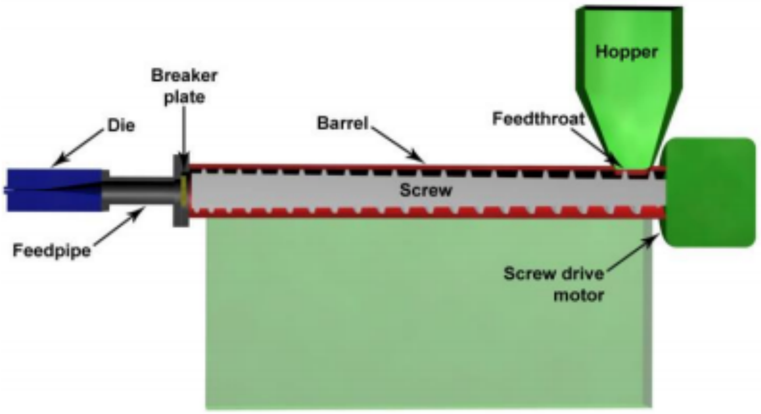

Figure 3.5. *A diagram of an extrusion machine*

The purity of the filaments and the consistency of filament diameter are used to assess filament quality. The purity of the filament can be controlled by cleaning and removing impurities and other foreign materials from the input shredded material. The optical sensor measures the thickness of the filament, which is controlled by the extruder's puller mechanism. The puller mechanism operates based on the material output flow and automatically adjusts the speed based on the thickness scanned by the optical sensor. As a result, if the material's output flow varies, it becomes extremely difficult for the optical sensor with the puller mechanism to respond and calibrate. (Yusheng Feng, 2020)

3.1.4. TESTING AND EVALUATION

The manufactured PLA filament is then tested on 3D printers. The quality of the filament used as feed materials determines the quality of the 3D printing product. Because of factors such as lighter per unit length, smaller diameter can be heated faster (less time for the heat to reach the center of the filament), and smaller diameter can be heated faster (less time for the heat to reach the center of the filament), most 3D printers use 1.75 mm diameter PLA filament for printing. It is possible to achieve faster printing, more precise plastic flow, and a lower risk of oozing. Furthermore, less pressure is generated in the nozzle, allowing the extruder to push the filament with less force. During 3D printing, the printer uses software to calculate the extrusion volume of the filament based on the filament diameter, nozzle diameter, and extrusion speed. As a result, as the filament diameter varies, so does the volume of the extruded PLA, and inconsistent extrusion leads to flaws in the manufacturing products. As a result, our developed PLA filament should have an absolute constant diameter along its entire length. A diameter tolerance of +/-0.05 mm is required for 1.75 mm diameter PLA filament. Fig.3.6 is an diagram of a filament sensor using ball bearing and a precision linear motion to ensure extruder filament has uniform diameter across its length. Jean Le Bouthillier (2016)

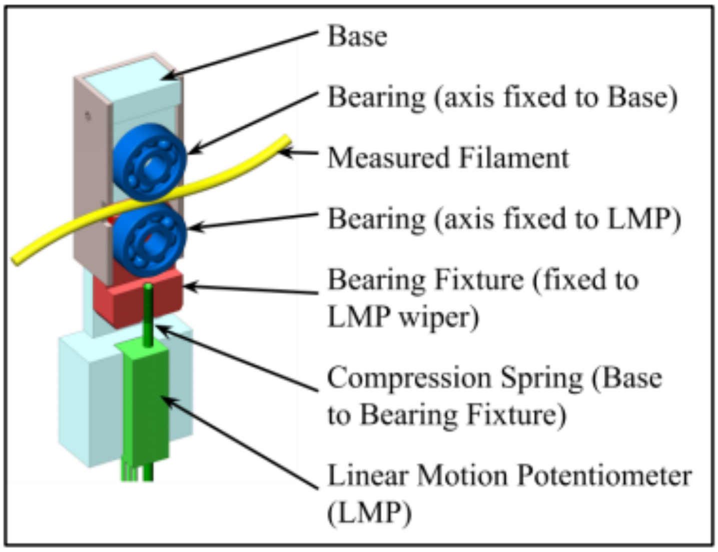

Figure 3.6: Filament diameter sensor using ball bearings and a precision linear motion

4.0. CHAPTER 4 - RESULTS AND DISCUSSIONS

An overview of the literature review and methods of manufacturing filament is critical at this stage to measure the viability of the proposed methodology in this research within the region vis-à-vis the fundamental challenges associated with the implementation. What are the key factors to consider and other variables that might affect execution and quality of products?

4.1. WASTE MANAGEMENT OPERATORS

In Kenya, a large percentage of the solid waste is managed by the private sector and NGOs due to public private partnerships. It is well known that understaffing and lack of skilled staff in waste management is a challenge within the region. An estimated 2,400 tons of solid waste is generated in Nairobi daily of which 20% is in plastic form, about 45% of which is recycled, reused or transformed into a form which can yield economic and ecological benefits, but this is far from the 80% target by the National Environmental Management Authority. (The World Bank (IBRD-IDA), 2021)

The process of collecting waste, processing and sorting are sets of daily activities for waste management operators. Their daily operation is a significant component for the success and viability of recycling plastic waste to 3D printing filament. It is pertinent to establish a contractual business to business agreement with the waste collectors/recycler to ensure continuous production cycle. The circular economy is a proactive approach that calls for designing products to reduce waste, using products and materials if possible and recycling end of life products back into the economy. The implementation of this research in Kenya will eventually help to achieve this goal in a more sustainable way.

4.2. EQUIPMENT AND COST

The choice of equipment and manufacturer for implementing the content of this research is dependent on the funding available and the daily production capacity required. Each of the hardware needed to setup a 3D filament extruder can be purchased and assembled depending on the technical capabilities of personnel and tools available (Ianmcmill, 2020). On the contrary, the equipment can be purchased from different manufacturers across the globe that has developed various technologies to ensure quality output at an optimal level. If you don't have much experience with mechanical construction and electrical configuration, you might want to stick to the pre-assembled options. The speed with which the machines can extrude filament is an important consideration. How many kilograms of filament can be produced in each amount of time? The maximum temperature an extruder can reach is also determined by the materials supported. The longer the list of material types that the extruder should theoretically be able to process, the higher the temperature.

Table 4-1 List of some low scale extruder manufacturers and price

Machine/Manufacturer	**Specification**	**Supported Materials**	**Cost, ($)**
Filabot EX2	1 kg/h, Max temp 450 ºC	PLA, ABS, PC, PEEK	2,750
Wellzoom Pellet Extruder	1 kg/10 h, Max temp 300 ºC	PLA, wood-infused PLA, ABS	600 - 700
3devo Precision 350	1 kg/h, Max temp 350 ºC	PLA, ABS, PC, Nylon	7,500
ReDeTec ProtoCycler+	1 kg/2 hrs., Max temp 250 ºC	PLA, ABS, Nylon	3,500
Noztek Pro Desktop Extruder	1 kg/2 hrs., Max temp 300 ºC	PLA, ABS, PP	1,600
Precious Plastics Extruder	2 kg/hrs., Max temp 300 ºC	HIPS, LDPE, PP	500

Any of the extruders listed above can be adopted for the pilot phase other manufacturers are also feasible, but the basic consideration in terms of material, speed and quality of the filament should be put into consideration during the selection process. The cost of setting up a small-scale production unit should include all components to study the viability, personnel salary, office rent and other reoccurring expenses (TechforTrade, 2016).

4.3. TECHNICAL CAPABILITIES AND SUSTAINABILITY

Though the concept described in this research is not new, but it would be ideal to consider the technical capabilities of personnel that will operate the equipment and to define a benchmark for quality filaments produced within the facility. As we know input is a major determinant of the output, as a result, capacity development for the personnel that will be operating the equipment should be the utmost on the list. Good technical trainings on the operations of the equipment, state of the art technology on filament production across the globe and maintenance requirements for the equipment. Aside from that, they should also be equipped with the overall process from waste to filament and this training should be a continuous exercise. This will in turn increase the capacity for filament production within the country. The sustainability component of this research should be explored; the market opportunities that exist for the filament are the Tech universities across the region, 3D hubs that provide regular trainings, local entrepreneurs, Fab Labs and Hobbyist printers. We have a ready market and quality of filament produced is paramount to the continuity and sustainability of the production unit. If we produce good quality filaments that is useful and meets consumer needs, it will in turn provide more opportunity to increase production capacity.

4.4. MECHANICAL TESTING AND QUALITY CONTROL

The geometric tolerance of the filament produces by this recycling process are critical to its effectiveness as 3D printer filament. Accordingly, a precise and accurate diameter of the extruder output is paramount in initial functional requirements. In an extrusion process whose input is a nonhomogeneous mix of shards of recycled plastic, which can be reasonably assumed to have subtly different material properties, a truly steady-state extruder output is not guaranteed. To ensure consistent output given a well-tuned extruder, an optical diameter sensor is proposed. Also, protruding contaminants of kinks in the filament due to the environmental effects or other factors could either give a misleading value to the sensor or jam the sensor altogether, resulting in plastic buildup at the extruder nozzle. The use of diameter sensing device would save the team a lot in ensuring a uniform diameter and roundness of the extruded filament.

The newly extruded filament should be collected and perform some series of mechanical test to measure the properties of the filament. The test should be in conformance with (ASTM) American Society of Testing and Materials. The test to conduct will be to reveal the tensile and compression properties of the filament, this will give a good insight on the behavior of the cellular materials, particularly expanded plastics under compressive loads. The test can be performed based on ASTM D1621 and tensile test as per ASTM D638. The 3D Printing market is relatively small, and the ecosystem need to overcome certain challenges for it to be viable (technical schooling, local 3D printer manufacturing, local use-cases) need to be solved before the product is market ready. There must be a perfect process to produce consumer ready filament, create local network of plastic collectors that can supply high quality waste on a continuous basis, setup a framework for distribution of produce and partner with local 3D printing partners to establish a 3D printing ecosystem.

4.5. OCCUPATIONAL HEALTH AND SAFETY

Thermoplastics do emit vapors, fumes, particulates, and gases that are potentially hazardous to the home and industrial environment. To fabricate components, a 3D printer can use a variety of materials, but the two most used thermoplastics are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), both of which have been found to emit toxic effluents such as ultrafine particles (UFPs), carcinogenic fumes, and volatile organic compounds (VOCs). The risks of 3D printing must be assessed to mitigate the impact of toxic emissions that may be produced during the process. These can include dangers from ultraviolet (UV) lights/laser beams, skin irritants, burns from molten materials, electric shocks, mechanical risks, high magnetic fields, and so on. It is therefore recommended to use the filament extruders in a well-ventilated area, train employees on how to use the machines correctly and safely, keep materials away from areas where food and drinks are stored, keep a safe distance from the extruders to avoid inhaling emitted particles and wear proper personnel protective equipment, such as eye and hand protection to reduce exposures and injuries. (Omiyale, 2021)

5.0. CHAPTER 5 - CONCLUSIONS AND FUTURE RESEARCH

The conclusion of this research is that the typical filament production process (Nithya Priya, 2021) can be modified with reasonable effort and resources to make local filament production viable. Local production can be cheaper than importing filaments and can, therefore, promote 3D printing in the community and across schools within the region. This is achievable by buying some pre-assembled filament extruders or by adopting the DIY processes to create a sustainable system that transforms plastic waste to useable 3D filaments that satisfy consumer needs.

We deduce that it is feasible to set up a filament production unit in Kenya putting into consideration the waste management system discussed, the existing plastic industry, and the equipment as discussed in Sec. 3.1. Though there are other factors that can mitigate the successful setup of the unit, which includes access to quality waste from operators, the willingness of the plastic companies to integrate pellet production into their product cycle, and the technical skills of the personnel required to do the work. From economic and environmental aspects, the recycling of plastics in 3D printing saves energy, reduces pollution, and preserves landfill space. It also helps to save energy and will have a positive impact on the environment through a reduction in the use of natural resources.

Finally, the methods and material discussed earlier present to us the equipment and technical considerations to set up a filament unit locally, however, it is pertinent to evaluate the prevailing business environment before adopting in a region that is not in east Africa. The business viability of this research also needs to be considered, with a focus on the supply chain for importing the extruders, pellets, and parts of the equipment vis-à-vis the financial implication of setting up one. It is estimated that the cost to set up a small-scale filament production unit ranges from 5,000–25,000 USD and the cost of a larger scale unit range from 40,000–80,000 USD.

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