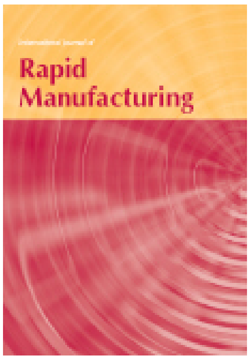

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A study on the process optimisation of filament extrusion for 3-D printing applications

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Abstract: In this study, we embark on a research on the optimisation of the filament extrusion process using statistical analysis. For this purpose, we develop our data collection scheme and corresponding precision and accuracy measures to assess the quality of the extruded filaments. The input factors are considered to be the type of the polymer (i.e., acrylonitrile butadiene styrene and polylactic acid), source of feedstock (i.e., recycled or virgin), and the extrusion temperature. The equipment utilised has been featured along with the developed performance measures. The interaction between polymer type and extrusion temperature has been found to significantly impact the precision of the filament. It has also been found that for polylactic acid, the feedstock obtained from virgin feedstock has lower variability with respect to filament diameter, whereas recycled feedstock has lower variability for acrylonitrile butadiene styrene filament.

Keywords: full factorial design; filament extrusion; additive manufacturing; accuracy; precision; process optimisation.

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1 Introduction

Additive manufacturing (AM) applications have received worldwide attention in the recent decades. There are many areas of applications of 3-D printing with the most common ones being manufacturing, medicine, architecture, custom art and design. The applications might vary from functional parts to purely aesthetics ones. AM processes include, but are not limited to, material extrusion [e.g., fused filament fabrication (FFF) and fused deposition modelling (FDM™)], vat photo-polymerisation [e.g., stereolithography (SLA)], powder bed fusion [e.g., selective laser sintering (SLS), direct metal laser sintering (DMLS), and electron beam melting (EBM)], material jetting (e.g., polyjet printing), and binder jetting [e.g., multi-jet fusion (MJF)] (Wikipedia, 2022).

The purpose of the study is to develop a statistical approach for process improvement of the filament extrusion process that might be used with the material extrusion process, specifically FFF 3D printers and FDM™ machines that dispense feedstock through a nozzle or orifice to build objects (herein collectively referred to as FDM or 3D printing for simplicity). FDM™ was initially developed by S. Scott Crump and Lisa Crump and it was patented by Stratasys in 1989. When the patent on FDM™ expired in 2009, a very similar AM process (i.e., FFF) originated, and Rep-rap is one of the first large-scale project that capitalise on this technology to produce affordable table top 3D printers (Team Xometry, 2022; Imagine that 3D, 2015). These new machines were referred to as FFF due to the FDM trademark. In FDM™, a continuous filament made from thermoplastic polymer has been employed (Hamzah et al., 2018). Filament is fed from a spool, through the moving printer head, where the polymer is heated beyond its glass transition temperature and deposited on the build platform layer-by-layer. The diameter of the filament is of an important concern in those applications because filaments having diameters larger than the nominal size might lead to nozzle clogging problems in the printer head and filaments having diameters under the nominal size might not be passed through the nozzle by the feed gear at the desired rate (i.e., undergo slippage) and lead to undercuts, and thus structural defects in 3D printed parts. In that regard, our objective is to develop a methodology for investigating the effects of the various input factors on the filament making process using the statistical approach where the effects of the input factors on the selected output performance measures are studied. The accuracy and precision performance measures for the filament diameter are developed in this study. In that regard the underlying filament making process are investigated in greater detail, and the factors that can play a role in improving the process are identified accordingly. The DOE-based approach that focuses on the full factorial design can be implemented to have a clearer picture between the input factors and output performance measures and point out the optimum parameters. The study also features t-tests for comparing the means of diameter of the filament obtained from virgin and recycled feedstock. This approach will be described in the upcoming sections.

The outline of this paper is as follows. After this introduction, in the second section, we will provide a literature review on the existing work that has been conducted on the filament manufacturing, mainly for the process optimisation for various applications. In the third section, we will discuss the selection of the input factors that can play a role on improving the filament making process and the selected output performance measures that can be used for quantifying process capability and product quality. In the fourth section, we will be providing additional information on the equipment and experimental setup for the filament making process. In the fifth section, we will be primarily focusing on the results of our approach and results of the quantitative analysis that establishes the relationship between the process factors and performance measures and selection of the optimum levels associated with the input factors. In the sixth section, we will be providing the conclusive remarks associated with the study and point out some future research directions.

2 Literature review

Numerous types of thermoplastics are used for 3D printing filament and each with unique chemical, physical, and mechanical properties. In the current study, we focus on acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) as they represent more common polymers used in 3D printing (Vidakis et al., 2020; Wu et al., 2020). The filament making process is considered as an upstream process for 3D printing. Sources of polymers for filament making include virgin material and previously used material (i.e., recycled). Details of options for using these sources in filament making are described in detail in Section 2.1 below.

2.1 Use of virgin and recycled polymers for filament making

Virgin polymer is commercially available in the form of pellets that can be extruded into filament. Some advantages of using virgin polymer for filament making include assurance of the polymer pedigree (i.e., source of ingredients), homogeneity (i.e., only the type of polymer stated by the manufacturer should be present), purity (i.e., free of residues from products that might have contacted the polymer such as detergents or oils in consumer packaging), and good dimensional tolerances. Potential disadvantages of filament making from virgin plastics include high energy costs and high consumer prices (Baechler et al., 2013; Song and Telenko, 2017).

Song and Telenko (2017) focused on the material and energy loss due to human and machine error in commercial FDM™ printers. These authors used a life-cycle approach and classified material wastes during four different stages: primary production, including polymerisation and granulate formulation; processing (i.e., filament making); FDM™ printing; and, end of life (i.e., disposal or recycling). Unused filaments, platform heating, part shapes, layer shift, removing process, printer stops, calibration, and skip layers were identified to be the major failure types that increased energy requirements. According to the authors, 9.3 MJ/kilogram of ABS filament was consumed including the waste and authors indicate that if waste could be prevented, approximately 35% of energy might have been saved, and thus energy needed for the extrusion of filament might be reduced to 6.08 MJ/kilogram. Hence, benefits of distributed recycling plastic for filament manufacturing includes reduced greenhouse gas emissions associated with waste collection and transportation and reduced energy and costs (Baechler et al., 2013; Song and Telenko, 2017; Woern et al., 2018). Potential disadvantages of filament making from recycled plastics include reduced assurance of the polymer pedigree, homogeneity, and purity as well as a reduction in the ability to produce filament with consistent diameter and density.

2.2 Brief review of filament making using ABS

As summarised in Table 1, there are limited studies in the literature that focus on filament production for various 3D printing applications. Cardona et al. (2016), using a pellet-based extruder, studied important factors affecting the diameter of the ABS-based filament. The authors indicated that extrusion speed and temperature played an important role in high diameter consistency and maintaining tight tolerances (±0.01 mm). In order to attain these characteristics, low extrusion speeds (25 cm/min) and low extrusion temperatures (180°C) were required. The findings contradict the results reported by Kotsar (2018) who studied the production of PLA filament; in those studies, higher extrusion speeds were generally found to improve the quality of the extruded filament. As in the case of the ABS-based filaments, having high extrusion temperatures and low extrusion speeds promotes reduction of the variance in diameter of the PLA-based filaments and this was also verified in a research conducted by the Johnson (2020). Unlike other studies, Johnson (2020) conducted research using recycled PLA pellets only.

2.3 Brief review of filament making using PLA

Mirón et al. (2017) studied filament production using a Filabot EX2™ extruder and presented a comparison with commercial filaments. They provided a flowchart of the filament making process as well as recommendations for extrusion temperatures. They indicated that an extrusion temperature of 175–180°C for the PLA-based filament leads to best results in terms of filament quality. The authors also pointed out that usually for the PLA-based filaments, typical extrusion temperatures varied between 175–195°C. Slow extrusion speeds (i.e., lower screw feed rates) and lower temperatures led to larger than specified filament diameter. On the other hand, greater screw feed rates and higher temperatures led to filament blisters and smaller than specified diameters. The authors also noted that in-house extruded filaments, in general, had higher maximum strength, smaller elongation, and comparable elastic modulus as compared to commercially available filaments. The authors also argued that differences might be attributable to the imperfections that might be caused by the irregularities or internal bubbles. This might in turn affect characteristic properties of the filament.

The recycling of the polymers that are used in the extrusion process is an important concern from the sustainability point of view. Kotsar (2018) provided a comparison between virgin PLA and recycled PLA. The factors that were used for this comparison were whether air cooling system was used or not, the temperature of the water bath, extrusion speed (rotational speed of the screw), and length of the filament extruded. The author indicated that in terms of the recycled PLA, two different approaches were taken. The first approach was using the feedstock obtained by utilising a granulator for extrusion process, and the second was extruding the shredded materials and converting the extrudate into pellets using a grinder and extruding the pellets. Although the author indicated that recycled material might lead to clogging problems, in general, for reduction of waste and energy, the filament could be successfully extruded directly from shredded parts. The author also indicated that increasing extrusion speed (i.e., 25 rpm as compared to 17 rpm), placing an air-cooling system before water bath, setting the temperature of the water bath around 45–50°C, and setting the temperatures zone within the extruder between 190–200°C improved the quality of filament. Table 1 highlights key characteristics of the research on filament extrusion.

Table 1 Overview of filament making conditions in the literature

Citation	*Polymer*	*Type*	$T_{extrude}$ *(°C)*	*Comment*
Peinado et al. (2015)	PLA	Virgin	175–185	Mechanical and rheological properties affected by melt strength enhancer and ano clay additive
Cardona et al. (2016)	ABS	Virgin	180	Diameter affected by extrusion speed (screw feed rate) and temperature
Mirón et al. (2017)	PLA	Virgin	175–180	Diameter affected by extrusion speed and temperature
Mohammed et al. (2017)	ABS ABS	Virgin Recycled	185–220	Diameter affected by extrusion temperature, pellet source (i.e., virgin and recycled), gravity. Recycled pellets have inferior mechanical properties as compared to virgin pellets.
Tanney et al. (2017)	PLA PLA	Virgin Recycled	175	Diameter optimised by tuning effects of gravity, extrusion temperature, and cooling rate
Kotsar (2018)	PLA PLA	Virgin Recycled	190–200	Quality affected by extrusion speed and placing an air-cooling system before the water bath
Mohammed et al. (2019)	ABS ABS	Virgin Recycled	185–215	Diameter affected by extrusion temperature and pellet source, mechanical properties degrade at the one-time recycled ABS, however at the second recycling run the mechanical characteristics of filaments improve.
Johnson (2020)	PLA	Recycled	175–210	Feed screw rate being set to 2 rev/min and temperatures of 180°C, 190°C, 200°C, and 210°C for four heating zones in the extruder would provide best results in terms of improving surface finish and minimising variation of thickness of filament

2.4 Additional perspectives on filament making from the literature

Kishore et al. (2016) provided the perspective on the high performance semi crystalline thermoplastics, i.e., polyphenylene sulphide (PPS) and poly (ether ketone ketone) (PEKK) and their composites with carbon fibre. The carbon fibre content was varied for the PPS and PEKK thermoplastics in the study. The authors set higher temperatures for the extrusion of the filaments for FDM™ process as compared to regularly used thermoplastics for this purpose (e.g., PLA or ABS). The authors report an extrusion temperature range for PPS of 280–290°C. For PEKK, the extrusion temperatures might reach to 390–400°C. The authors reported that mixing the carbon fibre with the PPS caused some filament feed issues. The authors also conducted rheological analysis and studied the effects of the temperature, shear rates, and the fillers on the viscosity of the polymer. They correlated the analysis to FDM™ process and further provided the comparison with ABS. The filament making process was carried out using the Filabot EX2™, which was the same equipment utilised for our research.

Gonzalez-Gutierrez et al. (2018) provided a literature review on the extruders that might be used for producing filaments. The authors indicated that for small batches, usually single screw extruders were used, whereas for the larger batches twin screw extruders were employed. They also indicated that if powders have been used initially, to prevent agglomeration, extruders with the breaker plates and screens might be utilised. They also mentioned that for making filaments for 3D printers, the tolerance on the diameter of the filament should be precise. Smaller diameter might lead to undercuts in the 3D prints, and larger diameter might lead to the overflow problems that might result in the poor definition associated with the fine features of a part. In addition to filament diameter, the authors stated that roundness also played an important role in terms of the quality of the 3D print. The roundness characteristics enabled filament to be adequately gripped by the feeding mechanisms and properly fed without slippage. The authors suggested that for ensuring the roundness, the hauling unit which would be used for carrying the filament away became important. The authors presented that for some material, a water-cooling stage could be used if the extrudate had low thermal conductivity. Laser micrometres were found to be ideal to measure the diameter or roundness of the filament. For this purpose, other optical devices might also be employed as well. The authors cited that extruder temperatures, rotational speeds, speed of the conveyor belt, speed of the haul-off unit, and speed of spooling were the most important factors that played a role on the diameter and roundness of the filament.

Garg and Singh (2016) studied the effect of the extrusion load, extrusion temperature, and proportion of the filler material on the material flow index of the Nylon6-Fe composite for FDM™ applications. Melt flow rate was basically the rate of extrusion of thermoplastics through an orifice at a predetermined temperature. The authors indicated that extrusion load was the major factor for determining the melt flow index and higher extrusion loads led to the higher melt flow index. The authors applied the Taguchi L9 orthogonal array and by designating the flowability as an output measure, they concluded that extrusion temperature of 230°C, extrusion load of 5 kg, and Fe filler proportion of 60% provided the best signal to noise ratio and led to a robust setting both for the minimisation and maximisation of the melt flow index.

Kristiawan et al. (2021) provided the perspective that even when the filament composition was the same, the mechanical properties of the filament such as the stiffness and tensile strength would largely depend on the extrusion process of the filament as well as the FDM™ process itself. They also indicated that using the polymer composites present additional advantages in terms of providing certain desirable structural properties and functional benefits. However, the optimisation of process parameters posed a significant challenge due to the interaction of materials used in the composites. In that regard, every reinforcement in a composite polymer would result in different characteristics, thus extensive studies is necessary to understand the dynamics of the overall process and to develop a well-defined characterisation of the composite. The authors concluded that the preparation of the polymer composite for manufacture was an important step and highlighted that mixing of the composite material before or after drying made a significant difference in filament properties. They indicated that die temperature, roller puller speed, spindle speed, and inlet temperature affected the filament diameter. These factors in turn affected the viscosity of the material, which led to the manufacturing of filaments that did not conform to the specified nominal diameter. They also indicated the extruder screw shape affected the regularity of the filament. This effect was more accentuated in the composite filaments, where the shape of the thread affected the isotropy of the composite by affecting the direction of the filler used in the filament.

3 Scope of the research

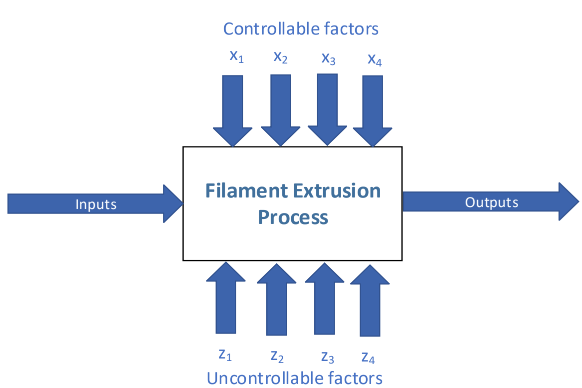
This research bridges an important gap by providing a comprehensive approach on investigating the effects of the important input factors on the selected output measures. By extensively studying the input factors and providing a mapping between inputs and outputs, it is possible to develop a structured approach on determining the effects of the selected input factors and their corresponding levels on the selected output measures. In order to expand the scope of the research, corresponding performance measures based on the precision and accuracy of the filament diameter have been developed. In total, we have three different input factors: polymer type (i.e., PLA or ABS), source of feedstock (i.e., recycled or virgin), and extrusion temperature (i.e., low, medium, and high). At the output side, we have two different performance measures. Specifically, the precision of the filament diameter is obtained by calculating the sample variance of the data points. The accuracy of the filament diameter is obtained by calculating the absolute value of the deviations from the nominal specified value. Filaments manufactured from materials in the form of virgin pellets and recycled parts from the shredded plastics were extruded and analysed in this manner.

In Section 3.1, we will provide additional details on the input factors associated with the filament extrusion process. In Section, 3.2, we will furnish more information on the output measures used for assessing the quality of the extruded filaments.

3.1 Input factors

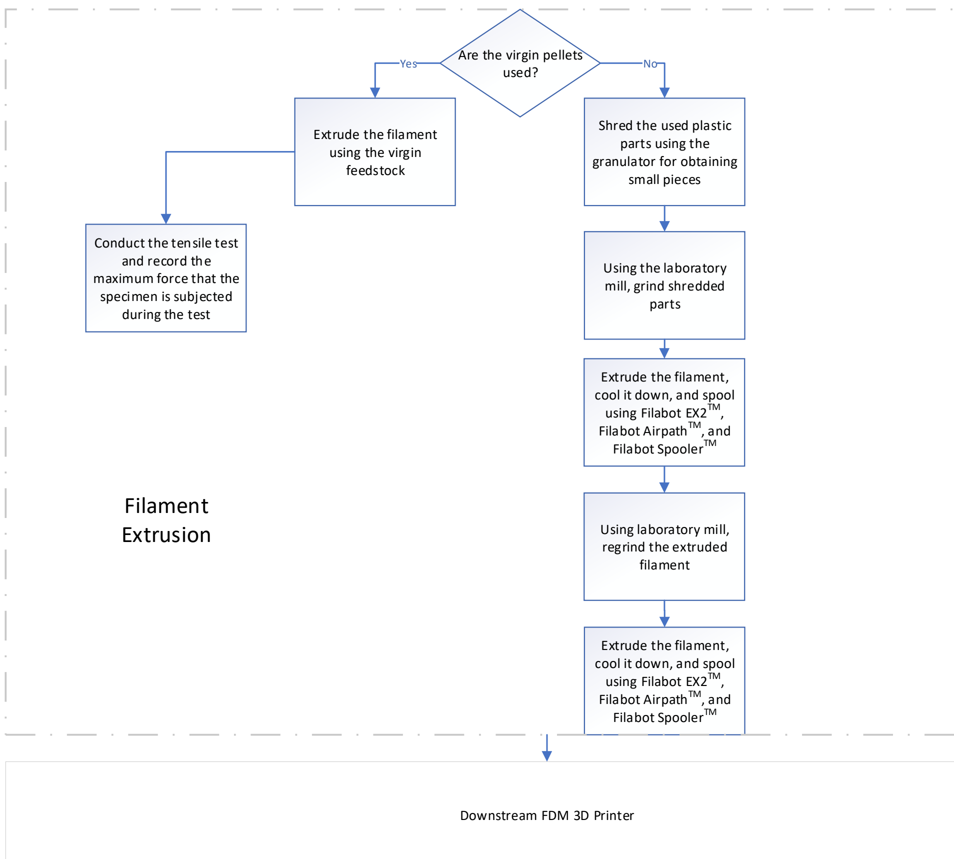
In the light of the previous research cited in Section 2, it is possible to develop a statistical approach to investigate the relationships between the inputs and the outputs of the process and provide the recommendations for improving the quality of the extruded filament. Figure 1 describes the schematic representation of the inputs and outputs treating the filament extrusion process as the black box.

Figure 1 The schematic representation of inputs and outputs regarding filament extrusion process (see online version for colours)



The selection of input factors for the process is crucial. As previously indicated in the literature, input factors play a role in the extruded filament quality, including the tensile strength, roundness, and the diameter of the filaments. Deviation from the nominal values might create some problems in the downstream FDM™ process. In order to prevent those types of problems, the input factors that might play a role in the outcome measure (i.e., diameter of the extruded filament) should be identified and corresponding factors should be carefully optimised to ensure the best results.

Figure 2 Flowchart for the filament extrusion procedure (see online version for colours)



3.1.1 Source of raw material

In terms of extrusion process' raw material sources, three different options exist. The first option is obtaining the feedstock from the pellets of the virgin material. The second option is recycling old or used 3D printed material and obtaining the feedstock from shredded parts. The third option is obtaining feedstock from the recycled parts using a double grinding scheme. Double grinding involves grinding shredded plastics, extruding filaments using those parts, and regrinding the extruded filaments in order to obtain a feedstock with a more homogeneous particle size for the final filament extrusion. Although additional energy and time is expended, our analysis indicates that double grinding provides better filament quality in terms of uniformity (smoothness) and a decrease in difficulties in the extrusion process as compared to the filaments that have been extruded directly from the shredded parts. Therefore, double ground feedstock has been used in the experiments as the recycled material along with the virgin pellets for the comparison purposes. The flowchart of the feedstock preparation for the filament extrusion is provided in Figure 2.

3.1.2 Filament extrusion process factors

Extrusion temperature is an important concern as an input factor (see Table 1). Extrusion temperature depends on the polymer type of the extruded filament. The required extrusion temperature for ABS is higher than that of PLA. Correspondingly, filaments made from ABS require higher nozzle temperatures as compared to the PLA during the 3D printing. It has been indicated that a lower extrusion temperature might produce filaments that have higher diameter than the specified nominal value. Conversely, higher extrusion temperatures might lead to the smaller diameters than the specified value and filament blister problems (Mirón et al., 2017). Although, there may be several contributing factors for this occurrence, we hypothesise that one of the primary factors might be thinning of the less viscous filament at higher extrusion temperatures due to the tensile forces exerted by the spooler. However, additional research is required to shed more light on this phenomenon. Moreover, lower viscosity of the filament is detrimental for the extrusion process in general.

Based on the literature review and our pilot runs, we chose the filament extrusion temperature as the main input factor associated with this study. Additional details will be provided in the following sections. All filaments were extruded using a Filabot EX2™ Extruder, which has a digital display for the set and actual temperature of the nozzle.

3.1.3 Type of polymers used in filament making

Another important consideration is the type of the polymers that would be used for the extrusion of the filaments. For this purpose, two different polymers were selected as listed below:

1 Acrylonitrile butadiene styrene (ABS)

2 Polylactic acid (PLA)

Acrylonitrile butadiene styrene (ABS)

It is a common thermoplastic polymer, which has a chemical formula of $(C_8H_8)_x \cdot (C_4H_6)y \cdot (C_3H_3N)z$. ABS is amorphous and has no actual single melting point, its range varying between 222–225°C (Prospector, 2020a). It is a preferred polymer for good impact resistance and toughness. It has been used as a raw material for a variety of products including but not limited to; pipes, automotive parts, helmets, and toys (i.e., Lego™). It has a glass transition temperature of approximately 105°C and has a density of 1.03 to 1.08 g/cm^3 (Rahman et al., 2016; Prospector, 2020a). As previously stated, there are two main sources associated with using ABS for extruding filaments for 3D printing. The first is virgin material purchased from industry, and the second is recycled plastic using a double grinding scheme as described in Figure 2.

Polylactic acid (PLA)

Polylactic acid, or polylactide (PLA) is a thermoplastic polymer with the formula of $[–C(CH_3)HC(=O)O–]_n$, and can be obtained by the condensation of lactic acid (Inkinen et al., 2011). It is used as a common feedstock for the consumer FFF 3D Printers (Gomez-Gras et al., 2018). Polylactic acid is denser than ABS, the density being around 1.24 to 1.25 g/cm^3, with a lower melting temperature around 154–171°C (Prospector, 2020b). As previously indicated, there are two sources available for PLA as well, the first source is the virgin material, and the second one is obtained by double grinding. It has a glass transition temperature varying between 50°C to 65°C (Omnexus Material Selection Platform, 2020).

3.2 Output measures

Performance measures focus on the precision and accuracy of the filament extrusion process based on the filament diameter. Additional information on this set of performance measures are provided in Section 3.2.1.

3.2.1 Precision and accuracy of the filament extrusion process based on the filament diameter

Two output measures based on the filament diameter are utilised for assessing the process capability. The first output measure, precision, is based on calculating the sample standard variance of the extruded filament diameter (i.e., filament extrusion process is capable of manufacturing filament that have consistent diameter throughout its extruded section). For this purpose, a digital calliper attached to the Filabot Spooler™ is used for measuring the diameter of the filament in an in-line setup. A picture of the digital calliper is provided in Figure 3.

Figure 3 Digital calliper for measuring the filament diameter (see online version for colours)

In order to assess the capabilities of the filament extrusion process, the variance formula based on sample has been implemented for representing precision measure. In that regard, digital calliper readings measuring the diameter of the extruded filament during the 5 minutes time window have been obtained at 5-second intervals. In total 60 data points are been obtained, and sample variance based on data points of the process has been calculated. The sample variance formula is as follows.

$$s^2 = \frac{\sum_{i=1}^{N} (x_i - \overline{x})^2}{N-1} \tag{1}$$

where s^2 is the sample variance, $\overline{x}$ is the mean diameter of the filament based on the sampled data points, x_i is filament diameter based on the data point i, N is the total number of data points (i.e., 60 in our study).

The second output measure is the accuracy of the diameter of extruded filaments. Extruded filaments for this study should have the nominal diameter of 2.85 mm, and deviation from the nominal diameter is a significant consideration. Any deviation might lead to quality related issues in the 3D printing process as discussed before. Smaller deviation from the nominal diameter can be considered as a better degree of the closeness to the true value.

For quantifying the accuracy of the filament extrusion process the average deviation from nominal filament diameter (i.e., 2.85 mm) has been calculated as shown in equation (2). As in case of precision, the same dataset has been used, and the absolute value of the difference from nominal diameter has been calculated. Based on those values, the average deviation of filament diameter has been obtained.

$$\underline{x}_{acc} = \frac{\sum_{i=1}^{N} \left| (x_i - x_{nom}) \right|}{N}. \tag{2}$$

$\underline{x}_{acc}$ is the accuracy measure of the filament accuracy process, x_i is the filament diameter based on the data point i, N is the total number of data points (i.e., 60 in our study), and xnom is the nominal diameter of the filament (i.e., 2.85 mm). Note that the absolute value of the deviation from the nominal diameter is adapted to account for negative and positive deviations and added up together to construct an accuracy measure.

3.3 Outline of the approach

There are three different input factors that were analysed using the approach outlined here. These are:

- extrusion temperature
- source of feedstock (i.e., virgin or recycled using double grinding)
- polymer type (i.e., ABS and PLA).

Student's t-tests based on diameter values of the filaments are used to quantify the effect of the input factors (i.e. source of the feedstock) on the diameter of the filament with respect to various extrusion temperatures both for PLA and ABS. Moreover, a full factorial design analysis has been implemented for studying the effect of the extrusion temperature and polymer type on the accuracy and precision associated with filament diameter. Additional information on the procedure will be outlined in Section 3.6.

3.4 Equipment

Virgin pellets are obtained from corresponding manufacturers, and recycled plastic feedstocks are obtained from previously used plastic products, that has been shredded, grinded, extruded, and reground again thus following a double grinding scheme. As previously mentioned, Figure 3 provides the flow chart associated with the filament making process.

Figure 4 Granulator (Rapid System Inc. Model Number: 611SR) (see online version for colours)

Figure 5 Laboratory Grinder/Mill (Willey Laboratory Mill Inc.) (see online version for colours)

The pictures of the granulator (Rapid System Inc. Model Number: 611SR) used for making coarse polymer particles, laboratory grinder/mill (Willey Laboratory Mill Inc.) used for making finer polymer particles, as well as the filament making equipment, Filabot EX2™, Filabot Spooler™, and Filabot AirPath™ are provided in Figures 4–8 respectively.

Figure 6 Filabot EX2™ Extruder (see online version for colours)

Figure 7 Filabot Spooler™ (see online version for colours)

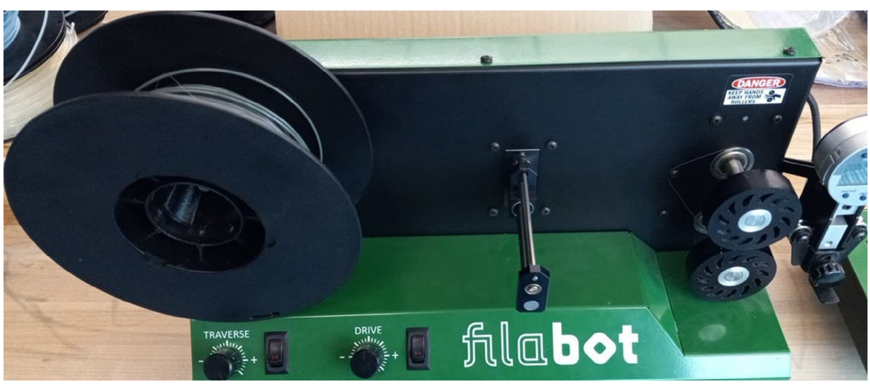


Figure 8 Filabot AirPath™ (see online version for colours)

3.5 Data source

An inline digital calliper has been added to the Filabot Spooler™ which measures the diameter of the filament in real-time during the filament extrusion process and captures data enabling us to calculate the accuracy and precision. Short video clips of the filament extrusion process are recorded and diameter of the extruded filament has been logged at a 5-second interval during the 300-seconds time window. In order to capture the data points, following scheme is utilised.

- *Phase 1 – No data collected until process stabilisation in term of filament thickness (0–2 minutes):* The data collection starts two minutes after the extrusion process starts. The reason for a 2-minute interval before the data being collected is that the process itself at the beginning produces filaments that exhibits high variation in terms of the diameter. A 2-minute time window would enable the extrusion process to stabilise so that filaments with consistent diameter can be obtained. It is a necessary step to avoid the variability associated with the uneven flow of softened polymer at the beginning of the extrusion.
- *Phase 2 – first data collection stage (2–4.5 minutes):* During a 2.5-minute time window, 30 data points regarding filament diameter are captured. Between each data point, 5 second time interval exists to reduce the correlation between subsequent readings.
- *Phase 3 – interim break (4.5-6.5 minutes):* After the first half of the data collection is completed, there exists 2-minute interval where no data is collected.
- *Phase 4 – second data collection stage (6.5–9 minutes):* After the 2-minute break, a set of 30 more data points are collected during a second 2.5-minute time window. The reason for a break between the data collection intervals is for conducting analysis on whether there is a shift in terms of filament diameter associated with the process. In order to determine whether such a shift exists, we employ the t-test between the two datasets each consisting of 30 data points. If the t-test indicates that there is no significant difference in terms of two datasets, these datasets are used as separate replications associated with the full factorial design for determining the effect of extrusion temperature and polymer type on the selected accuracy and precision figures.

For the t-tests on determining the effect of feedstock source (virgin or recycled) on the filament diameter across various extrusion temperature and polymer type, the four datasets each consisting of 30 datapoints are aggregated and single dataset consisting of 120 datapoints is formed for filaments extruded based on virgin feedstock. For recycled feedstock, two datasets each including 30 data points are aggregated to create a single 60-datapoint dataset, and t-test is performed between these two datasets.

3.6 An approach based on full factorial design for investigating the effect of input factors on selected output measures

In total, two types of statistical analyses are conducted. The first one is investigating the effect of the extrusion temperature and polymer type on the output measures developed based on the precision and accuracy associated with the filament diameter. The setup of the experiment is provided in Table 2.

Table 2 Input factors and levels featured in full factorial design

Polymer type	*Extrusion temperature*
Virgin PLA	165/170/175°C
Virgin ABS	185/190/195°C

Since ABS requires higher extrusion temperatures, we use an extrusion temperature that is 20°C higher for ABS as compared to PLA. Four replications for each factor/level have been adapted. The precision and accuracy measures have been calculated for each factor setting and analysis type using Minitab 18 software. Additionally, some runs are performed using the recycled ABS and PLA to conduct analyses for comparison of the filament made from virgin polymer with the recycled one using a double grinding scheme.

The second analysis involves conducting t-test on the filament diameter based on the feedstock type for the selected extrusion temperatures and polymer source (i.e., virgin and recycled). T-tests indicate whether there is a significant difference in terms of the mean filament diameter obtained from feedstock for each source (recycled versus virgin). Range figures, minimum and maximum values associated with the filament diameter, and variance have been provided as well. For conducting the analysis, Minitab 18 software has been used as well.

4 Results

Precision and accuracy measures for individual and over aggregated replications are calculated and provided in Table 3. Calculated values are rounded to six decimal digits.

Table 3 Accuracy and precision measures based on input factor and their corresponding levels for filaments obtained from virgin feedstock

Polymer (virgin)	*Extrusion temperature (°C)*	*Replication*	*Accuracy (mm)*	*Precision (mm2)*
ABS	185°C	1	0.026	0.000766
ABS	185°C	2	0.023333	0.000572
ABS	185°C	3	0.029667	0.001129
ABS	185°C	4	0.038333	0.001077
		Overall (replication 1–4)	*0.029333*	*0.00148*
ABS	190°C	1	0.021333	0.000557
ABS	190°C	2	0.023333	0.000825
ABS	190°C	3	0.019	0.000644
ABS	190°C	4	0.022	0.000696
		Overall (replication 1–4)	*0.021417*	*0.000671*

Table 3 Accuracy and precision measures based on input factor and their corresponding levels for filaments obtained from virgin feedstock (continued)

Polymer (virgin)	*Extrusion temperature (°C)*	*Replication*	*Accuracy (mm)*	*Precision (mm2)*
ABS	195°C	1	0.027333	0.000582
ABS	195°C	2	0.027333	0.000875
ABS	195°C	3	0.03	0.000289
ABS	195°C	4	0.029	0.000182
		Overall (replication 1–4)	*0.028417*	*0.000994*
PLA	165°C	1	0.021333	0.000397
PLA	165°C	2	0.016333	0.000355
PLA	165°C	3	0.028667	0.000550
PLA	165°C	4	0.035333	0.000446
		Overall (replication 1–4)	*0.025417*	*0.000734*
PLA	170°C	1	0.026	0.000239
PLA	170°C	2	0.026333	0.000532
PLA	170°C	3	0.013667	0.000283
PLA	170°C	4	0.027	0.000173
		Overall (replication 1–4)	*0.02325*	*0.000814*
PLA	175°C	1	0.029667	0.00021
PLA	175°C	2	0.017667	0.000212
PLA	175°C	3	0.015667	0.000272
PLA	175°C	4	0.011	0.000139
		Overall (replication 1–4)	*0.0185*	*0.000406*
All ABS			0.026389	0.001141
All PLA			0.022389	0.000786
Grand			0.024389	0.000967

Based on the p-values associated with performance measures on accuracy and precision of the filament diameter, following results associated with the significance of the factors analysed in this study are provided in Table 4.

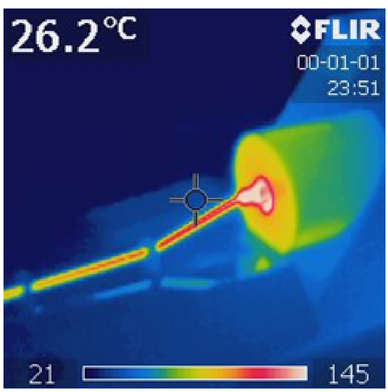
Table 4 p-values associated with the input factors based on selected performance measures

Input factor	*Accuracy*	*Precision*
Polymer type	0.124	0.00016*
Extrusion temperature	0.246	0.013*
Interaction (polymer type x extrusion temperature)	0.183	0.656

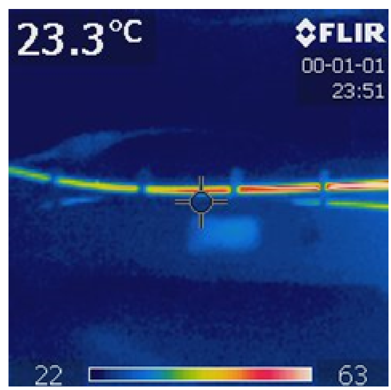
Note: *Significant at $\alpha = 0.05$ level

Analysis indicates that polymer type and extrusion temperature and their interaction effect do not play significant role with regard to accuracy with p-values of 0.124, 0.246, and 0.183 respectively. For the precision, the polymer type and the extrusion temperature play a significant role with p values of 0.00016 and 0.013 respectively. The interaction effect does not play a role in determining the precision value with associated p value of 0.656. For ABS, for minimising the desired output measure, it is recommended that the extrusion temperature should be set to 190°C. For PLA, the temperature should be set to 175°C. Higher temperatures tend to favour the precision of the PLA extrusion, whereas for ABS, extruding at medium temperatures is somewhat better. However, the results are not conclusive since factors are not statistically significant in terms of accuracy figures. One-way ANOVA is also conducted for each factor as well. ANOVA analysis provides results which correspond to the t-test analysis with p values of 0.143 and 0.291 for polymer type and extrusion temperature respectively.

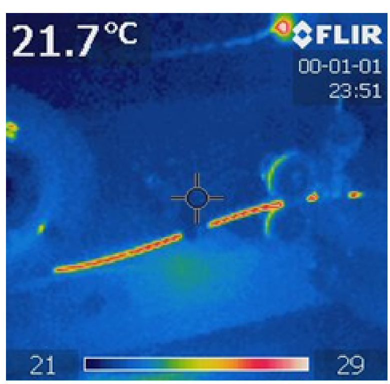
Figure 9 (a) Temperature profile of the extrusion of the ABS filament at 185°C at the extruder (b) Temperature profile of the extrusion of the ABS filament at 185°C at the air-cooling unit (c) Temperature profile of the extrusion of the ABS filament at 185°C at the spooler (see online version for colours)



(a)



(b)



(c)

With regard to precision measures, setting extrusion temperature to 190°C for ABS provides better performance as compared to other temperature settings. For PLA, 175°C provides the best performance in terms of both precision and accuracy measures. The results are in line with one-way ANOVA based p values of 0.01 and 0.08 respectively. The analysis indicates that the polymer type and extrusion temperature do play significant roles with p values of 0.00016 and 0.013 respectively. The interaction of extrusion temperature and the polymer type does not play a significant role either with the p value being 0.656. In general PLA provides better result in terms of accuracy and precision as compared to ABS.

The temperature profile of extrusion of the filament is captured by the infrared camera for the selected experimental settings. For the purpose of brevity, not all temperature profiles are provided here. As an example, the temperature profile of the extrusion of the ABS filament at 185°C at the extruder, air-cooling unit and spooler is provided in Figure 9(a), 9(b), and 9(c) respectively.

One of the objectives of the study is to investigate the effect of the polymer source in terms of the selected extrusion output measures (i.e., accuracy and precision). For this purpose, t-tests have been conducted on the diameter of the filaments extruded in the process using the digital calliper. The test has been used to investigate whether the polymer source (i.e., recycled versus virgin pellets) plays a role in the accuracy and precision of the diameter of the filament. For PLA, the t-test has been applied for three different extrusion temperatures (i.e., 165°C, 170°C, and 175°C). For the ABS, only recycled feedstock extruded at 185°C is included in the analysis for the t-test. The results of the t-test with the descriptive statistics on the diameters are provided in Table 5.

Table 5 T-test results for the filament diameters along with descriptive statistics between recycled and virgin polymers at selected extrusion temperatures/source and polymer type

Filament-extrusion temperature (°C)	*p-value*	*Polymer source (feedstock type)*	*Mean diameter (mm)*	*Minimum diameter (mm)*	*Maximum diameter (mm)*	*Range of diameter (mm)*	*Sample variance of diameter (mm^2)*
PLA-165	0.001258	Recycled	2.7983	2.61	2.91	0.3	0.005838
		Virgin	2.8326	2.76	2.91	0.15	0.000734
PLA-170	0.76771	Recycled	2.8552	2.73	2.98	0.25	0.004147
		Virgin	2.8526	2.78	2.91	0.13	0.000814
PLA-175	3.7E-10	Recycled	2.8217	2.72	2.89	0.17	0.001536
		Virgin	2.8605	2.81	2.9	0.09	0.000406
ABS-185	0.007759	Recycled	2.8408	2.75	2.91	0.16	0.001028
		Virgin	2.8555	2.78	2.95	0.17	0.00148

Results in Table 5 indicate that the diameter of the filament based on PLA polymer extruded at 170°C produces similar results for the recycled and virgin sources. For the other runs, there is significant difference in terms of the diameter of the filament with the p-values being smaller than 0.05, which indicates that there is significant difference between filaments extruded from virgin and recycled feedstock. For the runs that show statistical significance (i.e., PLA-165°C, PLA-175°C, and ABS-185°C), results show that the mean filament diameter is smaller and that the range of filament diameter is higher for the ones manufactured from recycled feedstock as compared to ones manufactured from virgin feedstock for the PLA filaments. For ABS-based filaments, the range is compatible (i.e., 0.16 mm for the recycled feedstock versus 0.17 mm for the virgin feedstock). Extruding the PLA based filament at 175°C provides a more robust result for minimisation of the range of diameter. Extruding virgin PLA at 175°C also provides the best mean results in terms of the accuracy and precision for the filaments. While extruding PLA made from recycled feedstock at 175°C provides the better result in terms of diameter range, a lower extrusion temperature of 170°C leads to better overall mean diameter. These observations are consistent with the recommended extrusion temperatures, albeit on the lower side of the spectrum found in literature, as provided in Table 1. The reason for this phenomenon might be due to increased viscosity at lower temperatures at the nozzle of the extruder, which leads to a more uniform process in terms of reduction of tensile forces exerted by the spooler as reflected in performance measures. Interestingly, increasing the extrusion temperature beyond 175°C in test runs provides inferior filaments which cannot be properly extruded therefore the upper limit of the PLA extrusion temperature is set to 175°C for our research.

Extruding ABS filament from recycled feedstock provides slightly better results in terms of precision and the range. For range, recycled ABS filament has slightly smaller range. The diameter precision is somewhat better as compared to virgin counterpart. This is in contrast to what is observed for PLA filament. Extruding PLA based-on recycled feedstock provides significantly worse sample variance result as compared to virgin feedstock. These results indicate a need for additional research.

5 Concluding remarks and future research directions

In this study, we investigated the effects of various input factors on the selected performance measures for filament extrusion process using statistical analysis of three factors. The filaments might be employed in FDM™ processes at downstream units. Filaments which have larger than nominal diameter might lead to the clogging problems, whereas smaller than nominal size filaments might lead to undercuts which can cause structural defects in the printed material. Two output measures are developed for assessing the quality characteristics of the filament based on the precision and accuracy of the diameter. The formulas for obtaining those measures are outlined in the previous sections.

For the input factors, in the first stage, the extrusion temperature along with the feedstock type is considered. For this purpose, two feedstock types (i.e., ABS and PLA) are analysed at three different extrusion temperatures. The effect of the extrusion temperature and feedstock polymer type on the precision and accuracy was analysed using full factorial design in joint fashion and one-way ANOVA in independent fashion. Neither the individual factors nor interaction effect were significant for the accuracy, as confirmed by one-way ANOVA based on individual factors. With respect to the precision measure, both polymer type and extrusion temperature play a significant role, however the interaction effect does not. Higher extrusion temperatures for PLA (i.e., 175°C) and medium extrusion temperatures for ABS (i.e., 190°C) improve precision and accuracy figures. In general, PLA provides better results as compared to ABS in terms of both accuracy and precision figures.

In the second stage, the effect of the extrusion temperature and source of the feedstock material (virgin or recycled using double pellet making scheme) on the accuracy and precision of the filament diameter are analysed using the t-tests. For the

PLA, three different extrusion temperatures are selected, for ABS, a single extrusion temperature is selected. For the PLA extruded at 165°C and 175°C, and ABS at 185°C, the t-test indicates that significant differences in mean filament diameters with respect to filament source (i.e., recycled versus virgin) exist. For the PLA extruded at 170°C, t-test indicates that no significant difference in mean filament diameters exist between recycled and virgin feedstock.

It is indicated that usually for the PLA, at selected extrusion temperatures, the filaments obtained from recycled polymers have higher variability as compared to virgin-based counterparts. This is also confirmed by the large range between the maximum and minimum filament diameter for these trials. Interestingly, the ranges and variance terms for ABS polymers are somewhat better for the filament obtained based on recycled pellets as compared to the filaments made from the virgin feedstock. The reason why significant differences exist between performances of recycled and virgin feedstock for different type of polymers deserves further attention and might be included as one of the items in future research.

A promising research direction might be expanding the study by introducing additional factors and levels for example, extrusion speed. Moreover, instead of the three levels adapted for the extrusion temperature, additional levels might be introduced as in the case of Mohammed et al. (2017, 2019). Careful consideration should be provided for determining the levels of the corresponding factor. For example, the spacing between the levels of extrusion temperature should be chosen to be greater than the variability of extrusion temperature at the nozzle. If the difference between two consecutive levels is set too small (e.g., 1°C), the factor effects specified at different levels might be blended together thus generating noise.

Moreover, additional tools based on Surface Response Methodology and Regression Analysis might be implemented to shed more light on the effect of factors on the selected performance measures and choosing the optimum levels for the factors. As previously discussed, those tools might help fine-tune the process and develop equations for predicting the performance at specified levels of factors for analysing the process in greater detail. It is also possible to verify the findings of this study by using different types of extruders operating at different extrusion speeds.

Another research direction might be increasing the scope of the research by including filaments made from other polymer types (e.g., low density polyethylene, high impact polystyrene, polyphenyl ether, high density polyethylene, etc.) and similar analysis followed in this research might be performed on investigating the effect of input factors on the output measures for process improvement purposes.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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