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Impact of Printing Process on Part Quality in Additive Manufacturing

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ABSTRACT

In an increasingly industrialized world, investigating different manufacturing techniques beyond traditional manufacturing can provide novel information that helps address complex issues surrounding sustainability, resource management, and innovative design practices. Additive manufacturing (AM), in which computer-generated models are printed three-dimensionally, increases design flexibility, and makes manufacturing more accessible to consumers, academics, and industry professionals alike. In this thesis, two popular AM techniques such as Fused Deposition Modeling (FDM) and Stereolithography (SLA) were selected to manufacture various spur gear designs. A full-factorial design generated various gear designs, which were analyzed for feature accuracy and quality tradeoff across both printers to understand how different printing techniques affect part quality across different length scales. After experimentation and analysis, SLA resulted in higher dimensional accuracy than FDM-manufactured parts; however, FDM parts returned a lower complexity score in terms of ease of manufacturing and accommodating for a range of designs. Ultimately, these results demonstrate the importance of printer selection during the design phase.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1

Literature Review

1.1 Introduction

Design is ubiquitous. Behind every building, part, or manmade object is a methodical design strategy that characterizes the function and considerations for the product based largely on the intended use of the audience. Design is unique in the sense that it is relevant in all industries, ranging from construction to medicine to the automotive industry, to name a few. This overarching practice of design has driven human innovation forward, as seen with prehistorical civilizations, through the industrial revolution, and up to modern society. However, as opposed to earlier times, there are higher stakes and expectations for designers today than perhaps ever before. Not only must a design be functional in the simplest sense of the word, but it must also be efficient, innovative, and more useful than the competition. Considering customer needs and industry applications is an essential pillar of design, and often determines a product's usefulness and drives the capitalist market forward. However, economic implications are not the only global factors that influence design. Designing ethically and sustainably is becoming increasingly important, both in the inherent worth and value to customers and businesses. Using renewable and environmentally conscious materials in manufacturing and mindfully considering the labor involved in the manufacturing process are key motivators behind improving the design. The shift from traditional to additive manufacturing is one movement that cohesively ties these considerations together and will continue to drive the future of design forward.

1.2 Additive Manufacturing

Additive manufacturing (AM) is playing an increasingly large role in various engineering fields and disciplines. AM is the process of creating new parts or objects by adding material, typically horizontally layer-by-layer, as opposed to subtracting material as seen in traditional manufacturing. The benefits of Computer-Aided Design (CAD) and AM are vast, ranging from the ability to generate quick, dimensionally accurate prototypes, to lowering cost and manufacturing time [1]. As opposed to traditional manufacturing, AM serves to create uniquely designed parts by depositing material onto a print bed in a methodical manner based on instructions derived from G-code, which is a Computer Numerical Control (CNC) programming language [2]. This G-code functions as a set of coordinates that precisely establish where each layer of filament should be deposited along the x, y, and z-axis. The G-code is derived based on information provided from an STL file, which converts the CAD file geometry into the cartesian coordinate triplet list, or (x,y,z), and the normal vector to the triangle [3]. These triangles are polygons that characterize the surface of the part, and as the CAD file is converted to an STL file, the part is meshed to create the part in terms of the surface geometry [4].

AM is not just composed of one technique of printing but is an umbrella term used to describe a variety of techniques of printing that vary in the equipment, material, and process used. Seven main types of AM categorize the various techniques – material extrusion, sheet lamination, binder jetting, material jetting, direct energy deposition, powder bed fusion, and vat photopolymerization [5]. These techniques are critical to the engineering design process in their ability to support the iterative process of prototyping and new product development. Each process contains tradeoffs in terms of cost, print accuracy, availability of materials, and complexity of geometry that determine which technique should be used in a given situation. This research focuses on the material extrusion and vat polymerization techniques because they characterize Fused Deposition Modeling and Stereolithography methods of printing, respectively.

1.2.1 Fused Deposition Modeling Printing

Fused Deposition Modeling (FDM) is an AM technique that uses a printing filament, most commonly polylactic acid (PLA) or ABS, to create a plastic replication of a part or object derived from a CAD file. As 3D printers such as the Ender 5 Pro are becoming increasingly affordable and easy to use for the average consumer, the ability to quickly print a quality part with limited wait time is an important goal. FDM is a popular and accessible technique of 3D printing that can effectively print objects of minimum to medium complexity [6]. Due to the relatively lower cost of the printer, FDM is a consumer-grade technique of printing that provides a more inclusive alternative to other forms of printing such as Selective Laser Sintering (SLS) technology [7]. The process occurs by melting the PLA and extruding it through the nozzle to print a cross-section of an object one layer at a time. Extrusion is the process by which a molten polymer is forced through a pre-shaped die to produce components of a fixed cross-sectional area [8]. PLA comes in the form of a wire on a spool which is fed into the extruder head on the printer. The printer bed lowers each new layer and the process repeats. In addition to printing the designed part, support structures can be added to attach certain features of the part such as overhanging pieces to the main body. These support structures enable the part to combat the effects of gravity and resist deformation or collapse [9]. Once printed, the part must be removed from the bed and the support structures stripped from the part.

In terms of the filament extruded through the 3D printer, PLA is one of the most popular plastics used for AM, providing a variety of benefits compared to other materials. PLA is relatively inexpensive and easy to procure. PLA is also advantageous for its low environmental impacts due to its renewable and biodegradable properties [10]. Strictly regarding the manufacturing field, PLA also possesses useful qualities when used in biomedical, tissue engineering, and antibacterial applications [7]. The chemical and mechanical qualities of PLA are important metrics to be assessed when discussing the advantages and disadvantages of the material. PLA is typically biocompatible and immunologically inert and can be tailored for a range of applications by manipulating mechanical, degradation, and chemical properties [11]. As Cuiffo discovered, potential changes in chemistry could occur due to the FDM process, with changes in vibrational frequencies of certain ligands and increased hydroxyl groups occurring after extrusion through the printing nozzle [12]. Additionally, shifts in the temperature range, cold crystallization, and melting characteristics were found to demonstrate changes to the PLA structure. As a result, the surface of a PLA-processed part using FDM is likely more chemically reactive [12]. In terms of mechanical properties, PLA maintains a favorable strength and stiffness, though considerably less than metals, while also retaining high dimensional accuracy [13]. However, the material can become brittle, and possess low toughness, low heat resistance, and a narrow processing window [7]. Another area of interest is the inconsistencies between the mechanical properties of PLA parts and their American Society for Testing and Materials (ASTM) counterparts, as Pastor-Artigues postulated [14]. Tension, compression, and bending were applied to PLA parts using FDM experimentally to procure data to simulate structural components using finite element analysis. The observed results were a double asymmetry in the tensile and compressive behaviors, indicating a need to be treated with a bimodular elasticity model [14]. Ultimately, new, more accurate characterization methods would better account for changes in the tensile and compressive forces present in PLA printed parts. In this regard, assessing the geometries of various parts can provide more insight into characterizing the complexity of PLA-printed parts.

PLA also requires certain hardware and printer settings to function effectively. An adequate build surface is necessary with options that include a glass plate or aluminum sheet. The extruder must operate between 90-220 °C, but no special hot end is required [15]. One of the most prominent issues with PLA is oozing or stringing. Due to the soft nature of the filament, when the filament continues to flow after a segment is finished, strings can appear on the part. High extrusion temperatures can lead to stringing or dripping of the filament, while low extrusion temperatures lead to clogging at the nozzle [16]. This can be addressed by dialing in the retraction settings to attempt to reduce the stringing as the nozzle moves across the xy-plane for each layer, and setting the extruder temperature at 200° [16]. Lastly, a cooling fan is essential for quality control because forced air cooling of PLA parts affects the mechanical strength and dimensional quality [15]. The extruded plastic layers must cool down below the glass transition temperature to avoid stringing or distortion of the object. Cooling airflow velocity can be adapted to fit the individual part and achieve better results across both metrics [15].

Optimizing mechanical, thermal, and morphological printing parameters and processing conditions results in the production of a high-quality 3D printed part. The most influential parameters include nozzle temperature, infill speed and density, and layer height and thickness [17]. For the Creality Ender 5 Pro, when considering a nozzle diameter of 0.4 mm, a respectable layer thickness is approximately 0.2 mm, according to the standard settings [18]. However, layer thickness must be leveraged against the time required to complete the print to find the optimum thickness. The layer thickness can be decreased to 0.1 mm, but the waiting time would be disproportionately increased compared to any benefit in terms of quality [19]. In the parameter experiment, Abeykoon conducted, the optimal process settings for the PLA parts are the following: 100% infill density, 215 degrees Celsius nozzle temperature, 90 mm/s infill speed, and linear fill pattern [17]. Moreover, it was discovered that decreasing layer thickness increases Young's modulus of the printed part [20]. Adjusting printing parameters simultaneously creates a tradeoff in print quality, mechanical properties, and printing time. The tradeoff of parameters is largely dependent on the needs of the customer. Isotropy, or materials with properties that remain the same regardless of which direction they are tested in, and build orientation are also key factors to consider when designing an additively manufactured part [21]. Rajpurohit found that raster angle, layer height, and raster width all affect the tensile strength of the parts. More specifically, a zero-degree raster angle produces the greatest tensile strength, while lower layer height and larger raster width improve tensile strength [22]. Considering isotropy is incredibly important in selecting the orientation of the print.

Robust statistical design methods such as the Taguchi method or the full-factorial design are useful for determining the relative influence of printing parameters on part quality. In Alani's study on the influence of printing parameters on mechanical properties, the Taguchi method is used to assess the influence of layer thickness, infill density, and printing orientation on the tensile, bending, and compression strength of PLA printed parts using FDM [23]. The results of this study showed that lowering the infill significantly reduces the time of the print, and a larger value for the signal-to-noise ratio (S/N) results in a larger value for tensile strength [23]. Lastly, increasing the infill density and thickness increased the mechanical strength. Essentially, infill density is the most influential printing parameter for mechanical properties while layer thickness influences printing time the most [23]. The orthogonal experimental design was also used by Lyu to investigate the effects of 3D printing parameters to improve mechanical properties and layer adhesion [24]. In this study, tensile tests allow the mechanical strength to be determined conforming to ASTM D638-14 standards. Optimal performance was obtained with 0.15 mm layer thickness, 50 mm/s printing speed, 200 °C nozzle temperature, and 50 °C bed temperature [24]. Moreover, optimal parameters reduced anisotropy, or the condition of being directionally dependent, and increased entanglement between PLA layers.

1.2.2 Stereolithography Printing

Another technique of AM is Stereolithography or SLA. Similar to FDM, this technique of 3D printing involves depositing polymer material to create a specified part via adding material as opposed to subtracting material as in traditional manufacturing. However, unlike FDM printing which uses PLA, SLA uses a liquid resin photocuring process in which a laser or other light source is strategically scanned over the resin surface by the predetermined programming to initiate polymerization [25]. In this process, the resin is converted from a liquid to a solid via chemical crosslinking or joining molecules by a covalent bond [26]. Visually, this results in a much smoother, homogenous part surface quality compared to FDM because the resin is cured by a laser as opposed to layers of plastic deposited layer-by-layer by a heated extruder [27]. Settings that establish the cure depth to be greater than the resin layer thickness enable this strong adhesion between layers observed in SLA [26]. Moreover, the standard-layer height mode is more effective than long exposure in terms of dimensional accuracy [28].

While SLA is advantageous in many regards, including high resolution, thermo-mechanical part performance and processing time are two areas that pose issues. To mitigate these issues, nanocomposites are developed to improve thermo-mechanical strength [29]. If a material is produced from two or more constituent materials, it is classified as a composite. If the scale of one, two, or three of the dimensions of any of the two phases is a billionth of a meter, the material is a nanocomposite [26]. Intentionally selecting materials which form nanocomposites serves to optimize the strength of the SLA print for various applications, including bio, structural, electronic, and magnetic material fields. In terms of print accuracy, SLA printing provides a higher resolution print compared to FDM, as seen in Finnes study of high-definition 3D printing [30]. With this variability and the use of a polymer cross-linking approach, printing via SLA provides an interesting comparison to FDM in terms of feature accuracy and complexity.

The resin used for the SLA printing in this research is the Grey Pro V1. This resin has increased elongation and significant toughness, with an ultimate tensile strength of 61 MPa [31]. The resin is optimized for high precision and resistance to deformation, with a low creep and high heat resistance [32]. This resin is ideal for applications including form and fit testing, jig and fixtures for manufacturing, and molds for injection molded product prototypes [31]. Regarding sustainability practices with resin, the upcycling of waste as feedstock for SLA resin is currently being researched, according to Maines [33]. This recycled waste used in new resin includes cooking oil and carbon dioxide. After a reaction with acrylic acid and boron trifluoride etherate to functionalize the triglycerides in the oil, a photopolymerization resin was generated [33]. Another sustainability strategy involves using reprocessable or degradable materials. The reuse of thermoplastics can serve to prevent excessive landfill waste after end-of-life.

In terms of optimal printer settings, SLA is similar to FDM in the sense that before assessing geometries for complexity and dimensional accuracy, consistent and optimized printer settings must be obtained. According to Badanova, a layer height of 0.1 mm was recommended for sufficient accuracy to printing time tradeoff [34]. Layer height also affects printing time, with a decreased layer height increasing printing time. Additionally, poor accuracy and surface finish could be related to increased printing speeds which decreased the laser exposure time. A 45° build angle resulted in a high precision and better-quality surface finish, and based on the Grey Pro resin, a form cure temperature of 80 °C is used for optimal mechanical properties [34]. Similar to stringing with FDM, ragging is a printing defect that can occur where partially cured resin forms and affects the cosmetic and even functionality of prints [35]. Compared to FDM, there is less research done on optimal printer settings for SLA, but it can be deduced that laser power and laser exposure time have the biggest influence on the photopolymerization process [34].

1.2.3 Current Strategies for Defining Complexity of a Part

Defining the complexity of a printed FDM or SLA part is a critical aspect of the AM process and significantly impacts design choice and motivation. Historically, defining complexity is largely based on the geometry of a 3D-printed part. Complexity affects the quality of the print; the greater the geometrical complexity, the more difficult it is to control the quality. Therefore, accounting for factors such as build orientation, wall width, and wall height are useful indicators for predicting the quality of a printed part [36]. Manipulating these factors to better suit the needs of the user can greatly improve the surface finish and durability of the part. For example, Chen advocates for avoiding the 60° orientation when printing structures with thin walls [2].

Machine learning and regression analysis are effective tools for predicting the complexity of FDM and SLA parts. Moreover, complexity indices serve to provide a numerical value to categorize the complexity of parts. Qamar asserts that for steel material profiles extruded through a die, complexity is characterized by more than geometrical factors. Complexity index variables and constants related to actual extrusion force and pressure have a significant effect on complexity in the profile section [37]. As the complexity of a part increases, the print quality decreases or is diminished to a potentially unacceptable threshold. For SLA, removing the support material mechanically plays a critical role in parts with complicated geometries. These more complex parts require structural supports to fabricate the freely suspended features [38]. However, while these supports are essential, they also provide issues with the functionality of the final part and must be removed mechanically for the best results. Ultimately, a more consistent metric for the complexity of both FDM and SLA printed parts would provide important insight for industry or commercial use.

1.2.4 Motivation

This research falls within the intersection between design and AM and can potentially provide important insight into both industries. While there are extensive, impressive research findings already published about AM and optimizing printing parameters under various conditions, a niche in the research space still exists that centers around defining part complexity with a consistent metric across different printing techniques that could function as an effective tool within the industry, academia, and consumer use as well. The results of this research would serve both in clarifying and establishing semantics by providing a consistent definition and provide practical uses to stakeholders that eventually save time, cost, and resources.

1.2.5 Research Objectives

The primary objective of this thesis is to analyze an industry-relevant part with various design parameters and compare the quality and complexity of the prints using different AM techniques and materials. A qualitative and quantitative metric for defining the complexity of 3D printed part geometry based on the established features will support this comparison. This metric would be developed experimentally and consist of a matrix with thresholds for complexity established based on quantifiable criteria or features that characterize the part. This primary objective can be achieved by pursuing the tasks listed below:

Task 1: Select an industry-related part to print. For this experiment, a spur gear was chosen as the manipulated part.

Task 2: Find a set of features and metrics that could be used to score or rate the complexity of the part and create a basis for comparison between different designs.

The second objective is to define the tradeoff between feature size and precision, in terms of the different printing parameters used. A full-factorial design will be used to establish the most important printing variables and their effect on precision and time to print. The tasks that consist of the experimental design for the second objective are listed below:

Task 1: Print the parts with different designs and sizes.

Task 2: Assess feature vs. precision tradeoffs. For example, a high score in complexity and a very small geometry part becomes an issue because of the penalty on feature size with increased complexity.

By performing the tasks that comprise each design objective, PLA processed using FDM is compared to resin using SLA to assess and define the impact of design complexity and uniformity of a spur gear in a novel and relevant manner.

Chapter 2

Methods & Procedures

2.1 Selection of Part

Regarding the experimentation component of this thesis and the objective to assess the complexity and reproducibility of various printing techniques compared to the CAD design model, selecting an appropriate part to print was essential. The selection criteria for this part involved the ability to be manipulated easily across various independent design parameters and retain a level of complexity that provided interesting insight but was still within the capacity of the consumer-grade plastic printer. Moreover, literature, mathematical, and computer-generated models must already exist to define this part, so that the complexity of the geometry related to print quality could be assessed without diverging from the scope of the research. After pursuing different options for parts, including a turbine blade and wheel, ultimately, a spur gear was the selected part to be printed and analyzed.

The spur gear proved to be the optimal choice to characterize this research, and the geometry contains multiple features of interest that were constructed in a CAD model and analyzed experimentally. The figure below is a schematic of a spur gear modeled in SolidWorks and created based on definitions found in “Engineering Information: Spur Gear Nomenclature” [39].

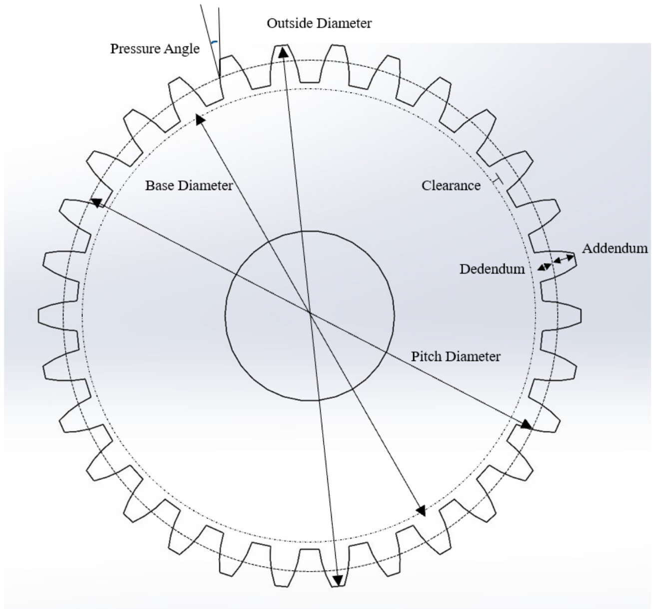

Figure 1: Labeled Schematic of a Spur Gear

In this thesis, the features of the geometry that were measured and analyzed include the number of teeth, the pressure angle, the outside diameter, the addendum, the dedendum, the clearance, the base diameter, and the pitch diameter. These features will be routinely referenced throughout the remainder of the thesis, and the above figure should function as a helpful reference point.

In addition, to spur gear features established in the literature, equations relating to the various features can be derived from the literature. The spur gear CAD model was constructed based on established industry and academia-accepted definitions to construct and calculate various features [40]. Not all the features above can be considered independent variables, and geometries such as the diametral pitch were calculated based on the accepted definitions from the literature. The table below provides the definitions used to construct the CAD model of each spur gear and calculate specific features of the printed part unable to be measured physically.

Table 1: Spur Gear Variables & Definitions

Variable	Symbol	Definition	Units
Number of Teeth	N	-	-
Diametral Pitch	P	-	1/in
Pressure Angle	ϕ	-	°
Pitch Diameter	D	N/P	in
Addendum	a	1/P	in
Dedendum	b	1.25/P	in
Clearance	c	b - a	in
Base Diameter	D_b	$D \times \cos(\phi)$	in
Outside Diameter	D_o	(N + 2)/P	in

These definitions were selected in part using the CAD model parameters by spur gear engineering design convention [39]. The dedendum geometry can be defined using slightly different variations of the definition listed in the table above; however, the relation 1.25/P was used to stay consistent with the previously determined SolidWorks spur gear model parameters [41]. Considering how research on the geometrical features of the spur gear as well as definitions relating the various features have been thoroughly established, the spur gear ultimately functions as an effective subject for comparing how different printing techniques perform in terms of the geometric complexity to feature precision and accuracy tradeoff.

2.2 Design and Parameters

The selected part chosen to conduct the design study for this thesis was the spur gear. As previously mentioned, the spur gear provides an interesting template for assessing complexity and quality due to the presence of many unique features, including but not limited to, the pressure angle, diametral pitch, base diameter, and outside diameter. Preceding the printing of the spur gears using FDM or SLA, the part was designed in SolidWorks using the Design Library Toolbox for ANSI INCH under the Power Transmission and Gear section [41]. Figure 2 provides an example of the spur gear model with the parameters for the first spur gear part.

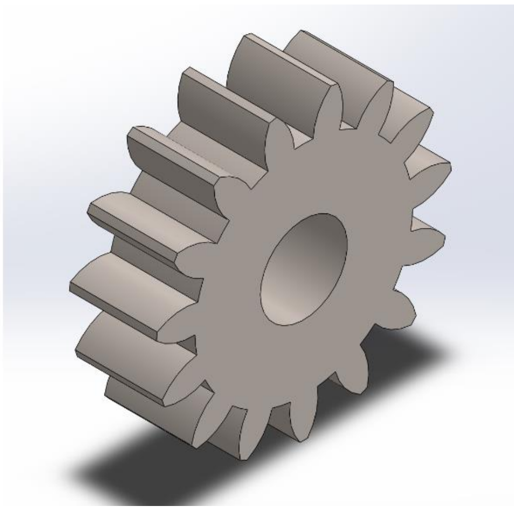

Figure 2: SolidWorks Model of Gear 1

The SolidWorks design interface allowed for each part to be modeled in its entirety within the software according to the established spur gear equations defined by the literature, and for selected parameters to be manipulated to generate each unique part. The independent, dependent, and fixed values for this design of experiment are listed in Table 2 below. The minimum and maximum values for the independent variables were intentionally selected to capture the extent of the design space and represent more complex iterations of the design, such as a part with a significant number of teeth and or a shallow pressure angle. However, the range of minimum and maximum values was intentionally chosen to not result in untenable printing quality issues that would inhibit the ability to obtain meaningful data. Untenable printing quality issues include prints that are so small that individual gear teeth could not be differentiated or pressure angles that were too close in size to obtain a measurable difference and did not reflect typical design choices found in industry. Additionally, for variables such as pressure angle, the only options available in the SolidWorks software consisted of 14.5 degrees or 20 degrees, which dictated the minimum and maximum values. After the minimum and maximum values for the independent variables were inputted into the SolidWorks design, the values for the dependent variables were automatically generated and designed based on the equations from the literature that defines the system. The fixed parameters define the variables that do not influence the relevant equations and stayed constant throughout the experiment for all printed parts.

Table 2: Experiment Parameters & Variables

Parameters		Minimum	Maximum	Units
Independent Variables				
Diametral Pitch	P	10	20	1/in
Number of Teeth	N	15	20	teeth
Pressure Angle	ϕ	14.5	20	degrees
Dependent Variables				
Outside Diameter	D_o	0.85	2.2	in
Pitch Diameter	D	0.75	2	in
Addendum	a	0.05	0.1	in
Dedendum	b	0.0625	0.125	in
Clearance	c	0.0125	0.025	in
Base Diameter	D_b	0.7	1.94	in
Fixed Parameters				
Nominal Shaft Diameter	D_s	0.25		in
Face Width	F	0.25		in
Hub style		none		
Keyway		none		

After the independent, dependent, and fixed variables and their respective minimum and maximum values were established, a full-factorial design with two levels, three independent variables, and eight runs was generated. Table 3 contains the eight different gear designs and their respective values for the independent and dependent variables.

Table 3: Full Factorial DoE

SOLIDWORKS MODEL

Gear	P (1/in)	N	ϕ (°)	D_o (in)	D (in)	a (in)	b (in)	c (in)	D_b (in)
1	20	15	20	0.85	0.75	0.05	0.0625	0.0125	0.70
2	20	15	14.5	0.85	0.75	0.05	0.0625	0.0125	0.73
3	10	15	20	1.7	1.5	0.1	0.125	0.025	1.41
4	20	20	14.5	1.1	1	0.05	0.0625	0.0125	0.97
5	10	20	20	2.2	2	0.1	0.125	0.025	1.88
6	10	15	14.5	1.7	1.5	0.1	0.125	0.025	1.45
7	20	20	20	1.1	1	0.05	0.0625	0.0125	0.94
8	10	20	14.5	2.2	2	0.1	0.125	0.025	1.94

Using the design parameters GUI in SolidWorks, the following eight parts were designed and the diametral pitch, number of teeth, and pressure angle were varied according to the DoE. The remaining features were automatically generated based on the values for the independent variables and the predetermined relationships between variables based on the literature.

2.3 Equipment and Printer Settings

The printer used to additively manufacture the selected spur gear parts in the FDM portion of this experiment is the Creality Ender 5 Pro printer, located in Reber 17 at the Pennsylvania State University. The printer can be seen in the figure below, specifically the extrusion nozzle, build plate, and chassis. As the PLA is heated up by the extruder, it is pressed through the nozzle and deposited onto the build plate according to the directions established by the G-code which provides coordinates along the x,y, and z-axis. This printer was used to create all the FDM-manufactured spur gear parts considered in this research.

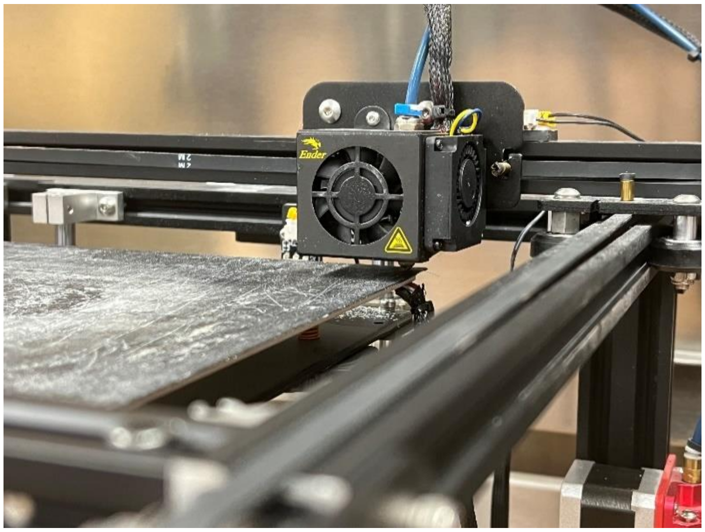

Figure 3: Creality Ender 5 Pro Nozzle

In terms of the printing parameters, according to the study described in the literature by Y. Lyu et al, optimal performance can be achieved at 200 °C printing temperature and 50 °C build plate temperature [24]. Using the Ultimaker Cura Software corresponds to the Standard Quality (0.2mm) settings for a 0.4 mm nozzle [18]. These settings were held constant throughout the experiment and did not vary from design to design. The Ender 5 Pro Standard Quality settings used for all FDM printing can be referenced below in Table 4.

Table 4: Ender 5 Pro Standard Printer Settings

Parameter	Value	Units
Layer Height	0.2	mm
Wall Thickness	0.8	mm
Wall Line Count	2	
Horizontal Expansion	0	mm
Top/Bottom Thickness	0.8	mm
Top Thickness	0.8	mm
Top Layers	4	
Bottom Thickness	0.8	mm
Bottom Layers	4	
Infill Density	20	%
Infill Pattern	Cubic	
Printing Temperature	200	°C
Build Plate Temperature	50	°C
Print Speed	80	mm/s

In addition to using the Ender 5 Pro and FDM to manufacture the spur gear parts, an SLA printer was used to provide a comparison and gather more relevant empirical data. The Formlabs Form 3+ SLA printer is shown below in Figure 4 and can be found in the Mechanical Engineering Toolbox in Reber Building at the Pennsylvania State University.

Figure 4: Formlabs Form 3+ SLA Printer

Similar to the Ender 5 Pro using FDM, standard settings that remained constant for all printed parts were also used with the SLA printer and can be referenced below in Table 5.

Table 5: Formlabs Form 3+ SLA Printer Settings

Parameter	Value	Units
Elongation at Break	13	%
Ultimate Tensile Strength	61	MPa
Modulus	2.2	GPa
HDT	62.4	°C, 1.8 MPa
Layer Height	0.1	mm
Resin	Grey Pro V1	

2.4 Data Collection and Analysis

The primary AM process of interest uses FDM with the Ender 5 Pro printer. After the graphical models for each spur gear part were designed based on the experiment parameters, each part was printed on the FDM printer. The printed parts can be seen below in Figure 5.

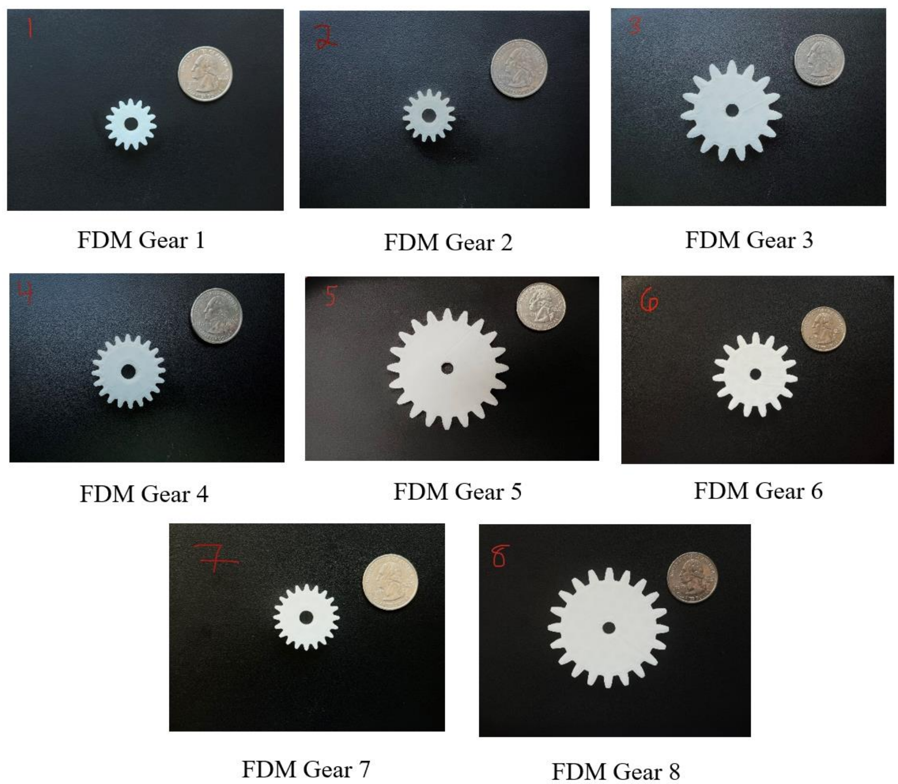

Figure 5: FDM Printed Spur Gears. A dime is placed to indicate the size.

In addition to being printed using FDM, each spur gear part was also printed using SLA on the Formlabs Form 3+ printer. Figure 6 shows the printed SLA parts. Both the FDM and the SLA printers use the same original SolidWorks design file and follow the design of experiment parameters. For example, Gear 2 using FDM directly corresponds to Gear 2 using SLA. All the spur gear parts were printed in the same location that remained at approximately the same ambient temperature and photographed within the same 24 hours they were printed. All gears were printed in the same orientation, rotated 90° to be flush along the x-y plane and 0° in the z-axis, flat against the printer bed.

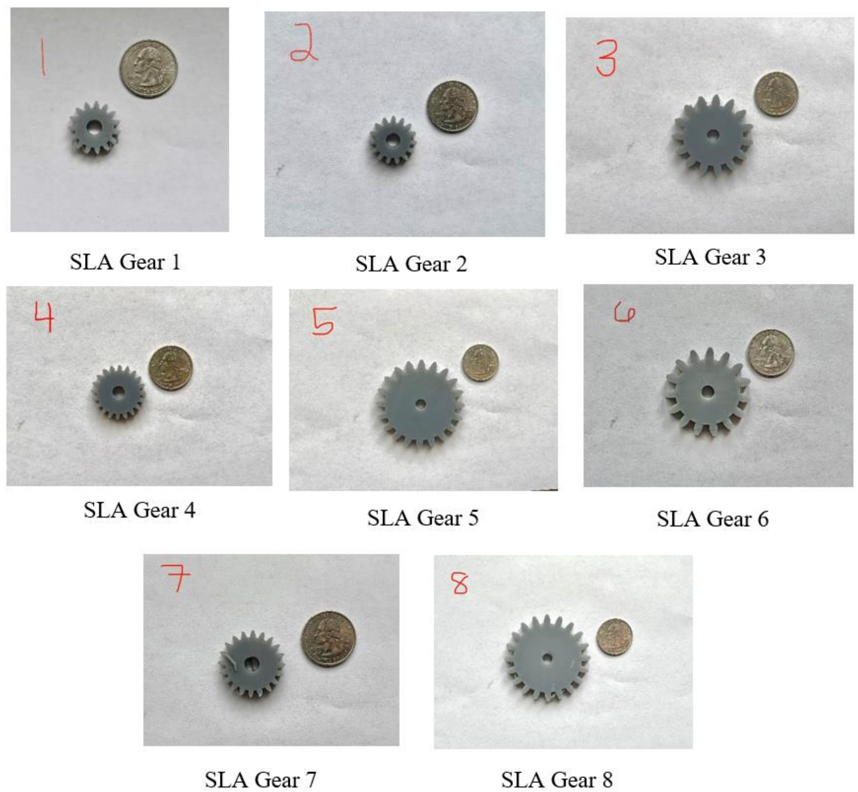

Figure 6: SLA Printed Spur Gears. A dime is placed to indicate the size.

Once the eight spur gear parts were printed using FDM and SLA, specific aspects of their geometries were analyzed experimentally to compare to the original model design values. The figure below shows a zoomed-in view of the Gear 7 design for FDM and SLA to demonstrate the difference in surface quality and print quality.

Figure 7: FDM Gear 7 Surface Quality

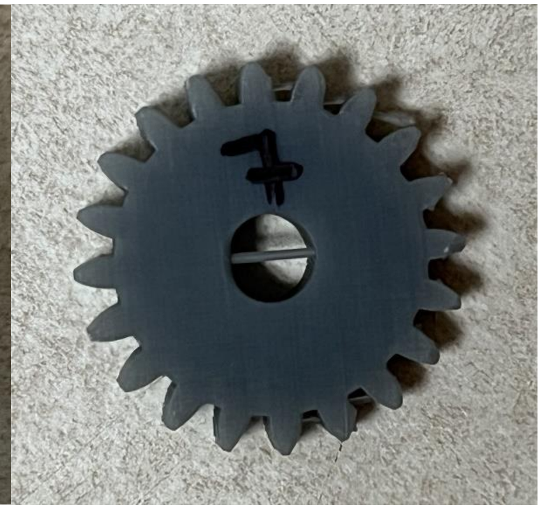

Figure 8: SLA Gear 7 Surface Quality

The features that were measured experimentally include the outside diameter, the number of teeth, the pressure angle, and the base diameter. These features were chosen in part due to their clear ability to be measured accurately and precisely from part to part. These measurements were obtained using the ImageJ software [42]. The figure below shows the ImageJ GUI and measurement tools.

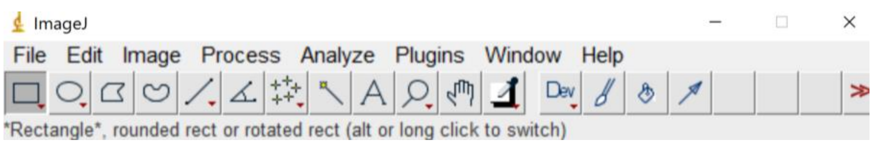

Figure 9: ImageJ GUI

Figure 10 below displays the outside diameter measurement taken from the tip of the tooth to the bottom of the tooth, as consistent with the spur gear diagrams in the literature. The quarter shown in each image is placed for reference and to determine the scale. Each of the images analyzed in ImageJ was taken on an iPhone 13 Pro at a horizontal 180-degree angle directly above the gear with a consistent black background. The straight line and angle tools within ImageJ were used to compute the empirical distance for each feature of interest. The number of teeth was physically counted for each part.

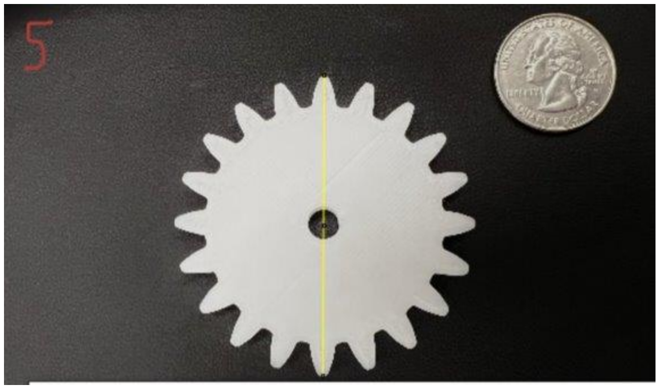

Figure 10: Outside Diameter Measurement. A dime is placed to indicate the size.

The pressure angle measurement is displayed in Figure 11 and measures the angle of the tooth from the vertical axis along the edge of the tooth, starting from the pitch line. That is, normal to the tooth surface, and the plane tangent to the pitch surface [39].

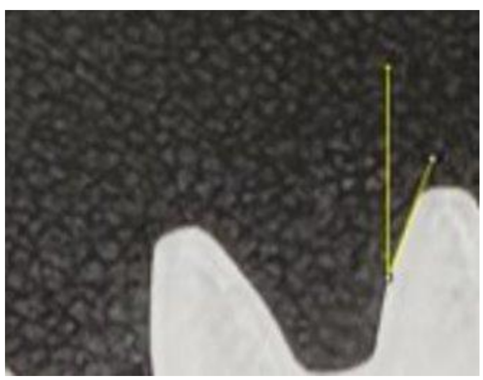

Figure 11: Pressure Angle Measurement

The base diameter measurement shown in Figure 12 represents the diameter of the base cylinder from which the involute portion of the tooth profile is generated [39]. The inner diameter excludes the teeth of the spur gear.

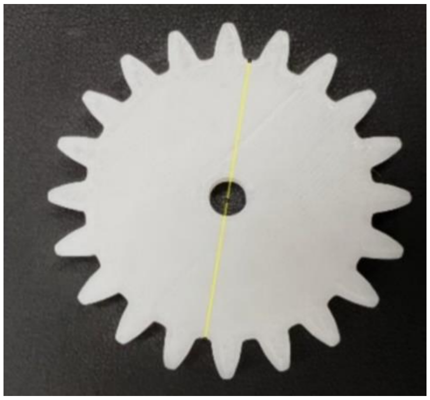

Figure 12: Base Diameter Measurement

This measurement procedure was repeated for both the FDM, and the SLA runs for each part. The resulting measurements for each part were then obtained and recorded to be compared against the model values and provide an FDM vs. SLA comparison, which is described in the results section.

Chapter 3

Results & Discussion

The premise of this experiment involves defining the complexity of a printed object, the spur gear, with different design parameters and printing techniques. The first printing technique uses PLA filament and FDM on the Creality Ender 5 Pro. The second technique of printing uses resin and SLA on the Form Labs Form 3 printer. After generating the design of the experiment consisting of eight runs with unique design parameters for three independent variables representing geometric features, the parts were printed with each technique and piece of equipment. Then, they were measured using ImageJ to obtain their empirical feature characteristics which were then compared with the original SolidWorks model to assess print quality related to design complexity.

3.1 Comparison of Feature Accuracy

The results of the FDM and SLA printed parts measured using ImageJ can be seen in the tables below.

Table 6: FDM Printed Part Measurements

FDM PRINTED PARTS									
Gear	**P (1/in)**	**N**	**ϕ (°)**	**D_o (in)**	**D (in)**	**a (in)**	**b (in)**	**c (in)**	**D_b (in)**
1	17.5	15	13.2	0.97	0.86	0.06	0.07	0.01	0.73
2	19.2	15	12.0	0.89	0.78	0.05	0.07	0.01	0.66
3	9.0	15	18.8	1.89	1.67	0.11	0.14	0.03	1.39
4	16.3	20	10.9	1.35	1.23	0.06	0.08	0.02	1.08
5	9.4	20	18.2	2.35	2.14	0.11	0.13	0.03	1.88
6	9.5	15	16.4	1.80	1.59	0.11	0.13	0.03	1.33
7	19.0	20	12.6	1.16	1.05	0.05	0.07	0.01	0.92
8	9.8	20	17.3	2.25	2.05	0.10	0.13	0.03	1.79

Table 7: SLA Printed Part Measurements

SLA PRINTED PARTS									
Gear	**P (1/in)**	**N**	**ϕ (°)**	**D_o (in)**	**D (in)**	**a (in)**	**b (in)**	**c (in)**	**D_b (in)**
1	19.2	15	22.8	0.88	0.78	0.05	0.07	0.01	0.66
2	19.1	15	17.0	0.89	0.78	0.05	0.07	0.01	0.66
3	9.5	15	23.9	1.79	1.58	0.11	0.13	0.03	1.31
4	18.7	20	14.8	1.18	1.07	0.05	0.07	0.01	0.94
5	9.5	20	18.8	2.32	2.11	0.11	0.13	0.03	1.84
6	9.5	15	15.6	1.79	1.58	0.11	0.13	0.03	1.32
7	18.8	20	23.1	1.17	1.06	0.05	0.07	0.01	0.93
8	9.7	20	16.4	2.27	2.06	0.10	0.13	0.03	1.80

After obtaining the feature measurements, the percentage error from the experimentally measured value to the model were calculated for all features across both printing methods, which can be seen in the tables below.

Table 8: FDM Feature Percentage Error Matrix

Gear	**P**	**N**	**ϕ**	**D_o**	**D**	**a**	**b**	**c**	**D_b**
1	12%	0%	34%	14%	14%	14%	14%	14%	3%
2	4%	0%	18%	4%	4%	4%	4%	4%	9%
3	10%	0%	6%	11%	11%	11%	11%	11%	1%
4	19%	0%	25%	23%	23%	23%	23%	23%	11%
5	6%	0%	9%	7%	7%	7%	7%	7%	0%
6	5%	0%	13%	6%	6%	6%	6%	6%	9%
7	5%	0%	37%	5%	5%	5%	5%	5%	2%
8	2%	0%	19%	2%	2%	2%	2%	2%	7%

Table 9: SLA Feature Percentage Error Matrix

Gear	P	N	ϕ	D_o	D	a	b	c	D_b
1	4%	0%	14%	4%	4%	4%	4%	4%	7%
2	4%	0%	18%	5%	5%	5%	5%	5%	10%
3	5%	0%	20%	5%	5%	5%	5%	5%	7%
4	6%	0%	2%	7%	7%	7%	7%	7%	3%
5	5%	0%	6%	5%	5%	5%	5%	5%	2%
6	5%	0%	7%	5%	5%	5%	5%	5%	9%
7	6%	0%	15%	6%	6%	6%	6%	6%	1%
8	3%	0%	13%	3%	3%	3%	3%	3%	7%

For both FDM and SLA printing, out of the nine features of interest shown in Table 4 of the Methods section, the feature that had the greatest average error between the print and the model was pressure angle. Pressure angle returned the greatest discrepancy for both FDM and SLA, with an average percentage error of 20% for FDM and 12% for SLA. The remaining features were relatively accurate compared to the design model and can be seen in the table below.

Table 10: FDM and SLA Average Percentage Error from Model

FDM Feature Average Percent Error from Model								
P	**N**	ϕ	D_o	**D**	**a**	**b**	**c**	D_b
8%	0%	20%	9%	9%	9%	9%	9%	5%
SLA Feature Average Percent Error from Model								
P	**N**	ϕ	D_o	**D**	**a**	**b**	**c**	D_b
5%	0%	12%	5%	5%	5%	5%	5%	6%

As seen in Table 10, for both techniques, the number of teeth printed exactly as the model prescribed. The outside diameter, pitch diameter, addendum, dedendum, and clearance measurements all returned the same error, with a 9% error for FDM and a 5% error for SLA. For FDM, the pressure angle returned an error 2.3 times greater than the average of the other feature errors (excluding number of teeth), and 2.4 times greater for SLA with the same criteria. From the data, it can be concluded that the most difficult geometrical feature to replicate from the model to either printing technique was the pressure angle. For all features across both techniques of printing besides pressure angle, the features printed with an error of less than 10% and relatively consistent error among features.

3.2 Comparison of Printing Technique

Concerning the two techniques of printing, FDM, and SLA, it can be observed that the SLA technique resulted in a lower percentage error from the model in all features except for base diameter. Interestingly, when comparing all features except for base diameter, the FDM technique produced a spur gear with an average percentage error that was roughly 1.7 times greater than the SLA technique. For base diameter, SLA returns a 1.2 times greater percentage error than FDM. Figure 13 below graphically displays these percentage error variations for each feature comparing FDM and SLA.

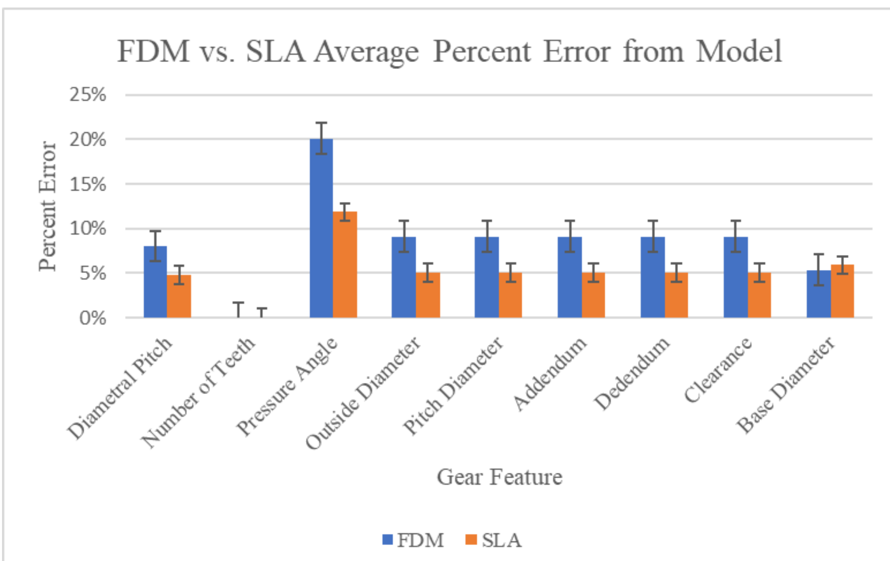

Figure 13: FDM vs. SLA Average Percentage Error from Model

The observed results show SLA resulting in greater dimensional accuracy compared to FDM, which is another benefit of SLA in addition to retaining a higher resolution than FDM, as discussed in the literature [30]. SLA printing conventionally results in a high print resolution and precision, due to the laser curing technology that transforms the liquid resin to a solid by chemical crosslinking. Therefore, in this experiment with a more complex geometric spur gear shape, the SLA printer more precisely replicated the original CAD model design, regardless of the design iteration or parameters.

3.3 Developing the Complexity Metric

After conducting experiments, analyzing the results, and determining which printing technique was most effective at printing the spur gear part consistently with the model, a metric for complexity to characterize the print designs was created. Complexity as it is defined by this thesis consists of a variety of factors, both qualitative and quantitative. This metric is informed by the quantitative experimental results found in the tables in section 3.1, which consider that for both printing techniques, certain features were more accurately replicated, whereas other features such as pressure angle proved to be less aligned with the model. Considering how out of the nine features of interest, pressure angle returned the greatest percentage error by far, this was the feature used in the quantitative complexity score. Additionally, qualitative results inform the metric derived from the imaging of each spur gear part directly after printing, with little to no interference to improve the surface quality or excess stringing material. The metric also displays which design parameters were most effective in reproducing the model dimensions between the three independent variables, diametral pitch, number of teeth, and pressure angle.

To create the complexity metric, the quantitative results were first analyzed to determine a consistent rating system. Accounting for the fact that pressure angle provided the most significant deviation from the model for both the FDM and SLA printing, this parameter was chosen as the key feature to calculate the percentage error from the model. The percentage error data can be found in Table 12. Once this percentage error was calculated, a rating system was established that assigned a number 1-5 to correspond to a range of percentage errors related to the discrepancies with pressure angle for each gear design. The complexity metric also factors in results observed visually, such as the surface finish quality, print quality, and presence of any feature defects, both aesthetic and functional. Print quality considers the presence of stringing or ragging observed in the prints. This scoring system can be seen in the table below.

Table 11: Complexity Scoring System

Quantitative		*Qualitative*			
Rating	*% Error*	*Rating*	*Surface Finish*	*Print Quality*	*Feature Defects*
1	<=5%	1	Exceptional	Low	Low
2	6-10%	2	Average	Average	Average; affects aesthetics
3	11-15%	3	Poor	High	High; affects utility
4	16-20%				
5	>=20%				

Once the percentage error results were calculated and the scoring system was established, each design iteration of the spur gear could be analyzed for how the individual parameters affected the accuracy and complexity of the design holistically. The percentage error results can be seen in the table below.

Table 12: FDM Percentage Error

Gear	P	N	ϕ	% Error ϕ
1	20	15	20	34%
2	20	15	14.5	18%
3	10	15	20	6%
4	20	20	14.5	25%
5	10	20	20	9%
6	10	15	14.5	13%
7	20	20	20	37%
8	10	20	14.5	19%

Table 13: SLA Percentage Error

Gear	P	N	ϕ	% Error ϕ
1	20	15	20	14%
2	20	15	14.5	18%
3	10	15	20	20%
4	20	20	14.5	2%
5	10	20	20	6%
6	10	15	14.5	7%
7	20	20	20	15%
8	10	20	14.5	13%

These parameters include the diametral pitch, number of teeth, and pressure angle. The table below displays the shorthand for each gear design which corresponds to the design of the experiment, and the results in the complexity metric table.

Table 14: Gear Design Identification

Gear	P (1/in)	N (teeth)	ϕ (°)
1	20	15	20
2	20	15	14.5
3	10	15	20
4	20	20	14.5
5	10	20	20
6	10	15	14.5
7	20	20	20
8	10	20	14.5

Up until this point, comparisons have been drawn between the accuracy of each printing technique, and which features were accurately reproduced. A further dimension to this analysis includes which gear designs were accurately reproduced, based on their initial design parameters and how complex each geometry was. The complexity metric table below uses the scoring system above as well as the quantitative and qualitative results to provide a tool to compare the complexity of spur gear prints by the printing technique and the design parameters in terms of the difficulty of model reproducibility and aesthetic or functional appeal. This complexity metric tool can be seen in the table below.

Table 15: Complexity Metric

	Percent Error for Key Feature								
	Gear 1	*Gear 2*	*Gear 3*	*Gear 4*	*Gear 5*	*Gear 6*	*Gear 7*	*Gear 8*	*Average*
FDM	5	4	2	5	2	3	5	4	3.8
SLA	3	4	5	1	2	2	3	3	2.9
	Surface Finish								
FDM	3	3	2	3	2	2	2	2	2.4
SLA	1	1	1	1	1	2	1	2	1.3
	Print Quality								
FDM	1	1	1	1	1	1	1	1	1.0
SLA	3	2	3	2	3	3	3	3	2.8
	Feature Defects								
FDM	2	2	1	1	1	1	2	1	1.4
SLA	3	3	2	3	2	2	3	2	2.5
	Complexity Score								
FDM	2.8	2.5	1.5	2.5	1.5	1.8	2.5	2.0	**2.1**
SLA	2.5	2.5	2.8	1.8	2.0	2.3	2.5	2.5	**2.3**
Total	**2.6**	**2.5**	**2.1**	**2.1**	**1.8**	**2.0**	**2.5**	**2.3**	

In the results section, it was previously determined that SLA printing resulted in the most accurate spur gear parts in terms of dimensional feature accuracy. While this is still true, after analyzing the full results, both qualitative and quantitative, for their complexity score, it can be stated that FDM printing results in a slightly lower complexity score than SLA, 2.1 compared to 2.3, predominantly due to the issues with print quality such as ragging found in the SLA print quality. Ragging can be seen in Figure 8, where excess resin connects the individual teeth that affect the cosmetics of the gear, and the functionality. Moreover, the SLA gear parts generated more feature defect issues than their FDM counterparts, 50% of which posed a threat to the functionality of the gear in addition to aesthetic appeal. This is seen in the SLA printed spur gear parts that contain such excessive ragging between each tooth that they not long interlock to enable the gear to function.

In terms of design parameters, Gear 1 holds the highest complexity score at a 2.6 total. Gear 2 and Gear 7 also return a high complexity score of 2.5. This aligns with the design parameters and knowledge that Gear 1 and 2 possess the smallest outside diameter with a value of 0.85 in and Gear 7 possesses the second smallest outside diameter value at 1.1 in, thus posing a greater degree of difficulty with the feature accuracy of a smaller part. The influence of each variable broken down into which design parameter was used for both FDM and SLA is shown in the table below. Based on the results, for both printing techniques, the 14.5-degree pressure angle resulted in a lower percentage error compared to the model.

Table 16: Feature Error Comparison

FDM Feature Error		
ϕ	14.5	19%
	20	22%
SLA Feature Error		
ϕ	14.5	10%
	20	14%

Therefore, as seen with Gear 1 and Gear 7, the larger pressure angle and the smaller print size resulted in a clear decrease in feature accuracy, and therefore generated a greater print complexity. Gear 5 obtained the lowest complexity score of 1.8, significantly due to its relatively large outside diameter of 2.2 in. The gears mentioned above represent the extremes of the design space, while Gears 3, 4, 6, and 8 fall in the middle with complexity scores in the 2-2.3 range.

Ultimately, this metric functions as a useful tool for comparing anticipated qualitative and quantitative properties of different techniques of printing across various design parameters with the intent to define the complexity of industrial parts, in this case, a spur gear. This scoring metric allows for comparison across multiple dimensions, including comparing printing techniques and design parameters.

Chapter 4

Conclusions

4.1 Summary

In this research, FDM and SLA printing techniques were used to additively manufacture spur gear parts with various design parameters. Eight runs with different geometries were printed by both printers and analyzed for their accuracy compared to the SolidWorks model and print quality between each technique. After analyzing the printed parts with imaging software and performing statistical analysis, results were obtained determining which features were most and least accurate, which printing technique was the most accurate, and which design parameters resulted in a low or high complexity score based on an experimentally determined metric. The most important findings of this research can be found in the list below.

Key Findings:

- The pressure angle feature contained the greatest deviation from the model across both printing techniques
- SLA printing resulted in a great dimensional feature accuracy compared to FDM
- FDM printing returned a lower complexity score compared to SLA, largely due to qualitative defects found with SLA
- Gear 1 and 7, designs with the greater pressure angle and smaller outside diameter dimensions, possess the highest complexity score

- The 14.5-degree pressure angle returned more accurate results compared to other design parameters for both printing techniques

Impact of Findings

The findings listed above contain relevance for both consumer and industry printing use. Considering how pressure angle was the most difficult feature to replicate for both FDM and SLA printing, it is important to be aware when designing spur gear parts that the dimensional accuracy of this feature may not meet the required need to the exact value. Moreover, understanding that the SLA printing technique results in parts with better dimensional accuracy than FDM is useful for consumers when evaluating which AM technique to use for their respective needs. Additionally, for individuals in industry using AM as a means of rapid prototyping, the knowledge of which geometries and features will possess a higher or lower accuracy compared to the model is relevant for making a more informed design decision. The complexity metric comparing the two techniques also serves to characterize the qualitative results of each method of printing, in addition with the quantitative results to provide a more holistic view when considering the design parameters and printer to use.

4.2 Suggested Future Research

The scope of this thesis focuses on a specific subset of the possible design field and provides analysis for a select few design options that were originally deemed most interesting for their application in industry and consumer accessibility. However, this research can be expanded across multiple dimensions to further provide a more comprehensive and extensive understanding of how to define the complexity of parts using AM. This thesis involved experimentation across the following dimensions: using different printing techniques, using different printing materials and processes, manipulating printer settings, varying the design parameters, and printing a chosen part with high practical relevance. Anyone, or a combination, of these dimensions could be manipulated to expand the results available and increase the depth of the experimentation. The list below provides examples of suggested future research areas and how to expand the scope of this work across each category.

Printing Technique

Incorporate different AM equipment and printing techniques to expand the results across liquid-based and solid-based printing [3].

- Print using PolyJet polymerization, which uses multiple materials in a print
- Print using Laminated Object Manufacturing (LOM)

Printing Material & Process

Expand the research to include different materials such as metal [3].

- Print using Selective Laser Sintering (SLS) with a melting powder
- Print using Electron Beam Melting (EBM)
- Print using the Prometal binding process, which ejects liquid binders onto metal powders
- Print using Laser Engineered Net Shaping (LENS) with a melting metal powder

Manipulating Printer Settings

Each piece of printer equipment used for each AM process uses printer settings that may be manipulated to generate different printing results. In this thesis, optimized, standard settings were used for all printers.

- Change the extruder nozzle and/or build plate temperature
- Increase or decrease the print speed, infill density, and/or infill pattern
- Change the layer heights, wall thickness, and/or number of layers

Adjusted Design Parameters

Manipulate and expand the design parameters to generate a wider range of results.

- Select more extreme values for each dimension or feature
- Increase the number of levels tested in the factorial design to create more runs
- Manipulate which different independent, and dependent variables are analyzed

Selected Printed Part

Select a different part to print and analyze. Choose a part with more novel or unique geometries, or relevance to a particular field of interest. Choose different geometries or features to measure.

- Bevel gear, helical gear, screw gear
- Turbine blade
- Motor assembly
- HVAC unit part

The options for increasing the scope and depth of the research listed above generate many permutations for experimentation; however, the list is by no means fully comprehensive, and significantly more opportunities exist beyond the suggestions listed for each category.

Another area of suggested future research independent of the dimensions previously listed includes performing a sustainability study on the various printing processes and materials. Determining which materials produce recyclable or reusable prints reduces the amount of waste associated with experimental iteration, uses resources more responsibly, and increases the possibility of a circular economy.

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ACADEMIC VITA

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EDUCATION

The Pennsylvania State University, University Park, PA **May 2023**
Schreyer Honors College
Bachelor of Science in Mechanical Engineering
Minor in Engineering Leadership Development

Honors:
The President's Freshman Award (2020), Dean's List, Schreyer Academic Excellence Scholarship, Leonhard Endowment (2021), SEN Grant (2021), Best Prototype & Presentation Award (2022), Second Place in the ACRP National Airport Management and Planning Challenge (2022)

WORK EXPERIENCE

Trane Technologies EPIC Engineering Intern **May 2022 - Present**
La Crosse, WI
- Project manager for HVAC productivity engineering project valued at roughly $50,000
- Led team of 10+ resources through concept generation into validation testing stage
- Coordinated lab testing to optimize heat exchangers & improve supply chain resiliency

Additive Manufacturing Lab Undergraduate Research Assistant **Aug. 2021 - Present**
The Pennsylvania State University, University Park, PA 16802
- Analyzed the impact of 3-D printing parameters using fusion deposition modeling
- Invested 8-10 hours per week in the laboratory conducting hands-on research
- Consolidated information and findings to write comprehensive honors thesis

Project Management Intern **May - Aug. 2021**
The Whiting-Turner Contracting Company, Pittsburgh, PA, 15212
- Performed quality control checks to advance a $40 million construction project in the medical field
- Conducted audits in the field for over 100 units of HVAC equipment and resolved multiple discrepancies
- Disseminated design information between 30 subcontractors and an architectural firm to rectify critical issues

Learning Factory Intern **June - Aug. 2021**
The Pennsylvania State University, University Park, PA 16802
- Redesigned the mode of delivery and content for the senior level Capstone course
- Created 7 weeks of curriculum teaching the engineering design process

OPEN Design Lab Undergraduate Research Assistant **June 2020 - Aug. 2021**
The Pennsylvania State University, University Park, PA 16802
- Optimized proxemics of airplane seating to account for new COVID-19 guidelines
- Analyzed data in MATLAB to improve ergonomics of airplane seat design

LEADERSHIP & INVOLVEMENT

SEDTAPP School Head Search Committee, Undergraduate Chair **July 2021 - Present**
- Advocated for student needs and proposed initiatives to consulting group
- Observed interview selection of potential candidates

Women in Engineering Program, Facilitated Study Group Leader **January 2021 - Present**
- Led weekly meetings teaching Calculus III curriculum to 10 underclassmen
- Created original content for over 12 course objectives

Phi Sigma Rho, Service Chair **May - Dec. 2020**
- Organized 5 service events for over 90 active members
- Coordinated 2 blood drives in affiliation with the American Red Cross

Schreyer Honors College, New Student Orientation Mentor **Feb. - Aug. 2020**
- Mentored and served as a resource to 8 first-year Schreyer Honors scholars

SKILLS

MATLAB, SolidWorks CAD, SketchUp, Windchill, Microsoft Office
Fluent in French