ABSTRACT

Title of Document:	PROPOSED BUILD GUIDELINES FOR USE IN FUSED DEPOSITION MODELING TO REDUCE BUILD TIME AND MATERIAL VOLUME
	Gregory Allen Teitelbaum Master of Science in Mechanical Engineering 2009
Directed By:	Associate Professor Dr. Linda C. Schmidt Department of Mechanical Engineering

The emergence of Fused Deposition Modeling as a small volume manufacturing process and a lack of explicit rules for improving the efficiency of this process bring necessity to the development of build guidelines. This work develops a proposed set of build guidelines for use in Fused Deposition Modeling (FDM). The guidelines are verified by the literature and experience, and validated by statistical analysis of quantitative FDM build data and qualitative review of example cases from student projects. The experimental data are obtained using the fabrication protocol for a Dimension SST Fused Deposition Modeling machine. Using simulation software known as Catalyst™, build time and material volume characteristics of many components of varying size and complexity were calculated. Eventually, this area of research should result in a robust set of rules that can fundamentally reduce the costs

associated with FDM and can assist its ascent as a feasible full-scale manufacturing process.

PROPOSED BUILD GUIDELINES FOR USE IN FUSED DEPOSITION MODELEING TO REDUCE BUILD TIME AND MATERIAL VOLUME

By

Gregory Allen Teitelbaum

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science in
Mechanical Engineering
2009

Advisory Committee:
Associate Professor Dr. Linda C. Schmidt, Chair
Emeritus Professor Dr. George E. Dieter
Professor Dr. Satyandra K. Gupta

Dedication

This thesis is dedicated to Brittany, whose unwavering support and motivation over the last two years have been the driving force behind my commitment to this research and all other work at the University of Maryland. Without her presence in my life, the devotion and energy necessary to complete this work would not have existed.

Acknowledgements

The author would like to acknowledge many people for their assistance (direct or indirect) to this research. First, I would like to thank my family and friends for all of their support and encouragement. I would also like to thank Yoann Goaer for his assistance on this research during the summer of 2008. Additional thanks to Dr. S.K. Gupta and Dr. George Dieter for their guidance and participation on my committee. And finally, to Dr. Linda Schmidt, whose superior guidance, advice, and collaboration have resulted in this both document and my two wonderful years of graduate study at the University of Maryland.

Table of Contents

List of Tables

List of Figures

Nomenclature

- **Build Time**- The amount of time (in minutes) it takes for the FDM machine to build a given component.
- **Component**- A part whose design was used in this research.
- **Guideline**- A proposed rule that is intended to improve a component for manufacture if applied by the designer.
- **Example Case**- A design project from the junior-level (ENME 371) or senior-level (ENME 472) design courses that was examined in this research.
- **Fused Deposition Modeling (FDM)**- A layered manufacturing process that extrudes a thin thermoplastic filament to build a three-dimensional component layer-by-layer.
- **File**- A computer file in *.STL format that is used by Catalyst™ to generate toolpaths for the Fused Deposition Modeling machine to follow to create a specific part or part assembly. Can be generated from most CAD packages.
- **Machine**- Used colloquially in this document to refer to the Fused Deposition Modeling machine itself.
- **Material Volume**- The amount of ABS and support material combined (in cubic inches) used by the FDM machine to manufacture a given component.
- **Repository**- The database compiled for this research that includes part files (in both CAD and .STL formats). Contains 65 components.

- **Simulated Build**- The simulation of the manufacture of a given component by FDM. This build is generated using Catalyst™ and gives the user various statistics related to the manufacture, such as build time and material volume.

Chapter 1: Introduction

1.1 Overview

Fused Deposition Modeling (FDM) is a manufacturing process that is becoming rapidly adapted for use in a wide variety of applications. Since its commercialization in 1990 by Stratasys, Inc., FDM has been a popular process for rapid prototyping due to its relatively low associate costs. In 2008, Stratasys manufactured 44% of all layered manufacturing systems installed worldwide, making it the market leader (1). Other popular rapid prototyping technologies include Stereolithography, Selective Laser Sintering, and Electron Beam Melting. As improvements in both material properties and part accuracy are made, FDM is becoming a viable method for small batch manufacturing and FDM eliminates the need for permanent (or investment) tooling costs for production. NASA has even placed an FDM machine in the International Space Station for use of making spare parts (2).

One such company employing FDM in this manner is Stratasys' own RedEye. This facility operates over 100 Fused Deposition Modeling machines (or Fused Deposition Modelers) for the sole purpose of Direct Digital Manufacturing (DDM). DDM is a new, Internet-enabled manufacturing paradigm that allows users to convert digital files to finished parts using a layered manufacturing process with no tooling. Because of the digital nature of the build files, a designer can send it electronically to a fabrication facility anywhere in the world instantly for manufacture. This flexibility and agility can be extremely desirable to the designer.

Improvements in material quality and cost allow FDM to replace standard manufacturing processes for small lot productions, highly complex parts, or components that require varying levels of customization (3). RedEye is now at the forefront of developing the newest materials and technologies in DDM, becoming the first company to employ the use of ULTEM plastic in DDM (4). ULTEM (Polyetherimide) is a plastic material with considerably strong mechanical properties (tensile strength of 475 kpsi) that can operate at temperatures up to 200 degrees Celsius. In this research, all studies were conducted with ABS plastic as the build material.

Stratasys has recently introduced the uPrint™ to make FDM technology more affordable for small organizations and in educational settings. This machine operates on the same FDM principles as other Stratasys machines, but can be available for purchase at under $15,000, due to its smaller build capacity. This increases the market size for FDM technology and will provide Stratasys with new categories of users and customers.

In its earliest use, prototyping, FDM was advantageous over other manufacturing technologies because of its short build time, ease of use, and low cost. In addition to this, the nature of rapid prototyping leads to only one or several parts built in each batch or each design iteration. This is fundamentally different from a standard manufacturing process, like injection molding, where many identical components are built for mass distribution or sale. As FDM replaces mature manufacturing technologies in an increasing number of applications, cost and build time become critical factors in process selection.

1.2 Need for Guidelines for FDM

A shift to a new manufacturing process is followed by a lag in time during which design engineers and manufacturing engineers discover how to process and design components to take full advantage of the new capabilities. Mature manufacturing processes that have been established for long periods of time have well-defined, standard design for manufacturing (DFM) guidelines. However, no such list of standard DFM rules has been generated for FDM. This interesting gap for DFM guidelines is due to several factors. First, this technology is relatively new, having been commercial for less than twenty years. Compared to a more established process like screw injection molding (developed in 1946), FDM has been in existence for a far shorter period of time. Perhaps equally illuminating is the fact that FDM was not initially developed as a standard manufacturing process. Because of its use as a prototyping method, there was not a need to "improve" a design for more efficient production with respect to reducing build time and cost. Prototyping is typically driven by convenience and flexibility, not by cost. The need for reducing cost and build time is becoming more established as more designers begin to consider FDM as a manufacturing method for some plastic components. As compatibility with other engineering materials is achieved with layered-manufacturing processes, their use as full-scale manufacturing methods becomes increasingly viable.

Another factor contributing to the current lack of design guidelines for FDM is its design flexibility. DFM guidelines for various processes stem from manufacturing infeasibility issues in the original engineering designs. Unlike competing manufacturing methods, FDM does not have process limitations that prevent making features such as overhangs or undercuts. Because there are few physical limitations to the FDM process and a large amount of design flexibility is available to the designer, the need for DFM rules is not driven by the need to ensure manufacturing feasibility. As such, it is necessary to intentionally develop any guidelines based on universal improvement metrics such as build time and cost.

Many studies have been conducted with respect to general improvement of rapid prototyping technologies. There are four major performance criteria used to evaluate FDM processes. They are strength, accuracy, build time, and build cost, where build cost is determined primarily by material required for the build and time to build the part in question. Improving the methods by which to select a rapid prototyping process is one area of existing research (5). Another area of current research seeks to improve physical qualities of products manufactured using rapid prototyping. Additional research has examined how to alter the design of large components (those exceeding the machine's capacity) for rapid prototyping feasibility (6). These characteristics include surface texture and geometric tolerance (7, 8). Further examination of these existing studies will be discussed in Chapter 2.

Most research in FDM has focused on the issues of the fabrication process itself. Only a few studies have looked to generate a set of design guidelines specifically applicable to FDM. The shortcomings of these studies will also be examined in Chapter 2. Research aimed to create design guidelines has generally focused on creating guidelines that improve the performance or tolerance of the finished product (9). In contrast, the goal of this thesis research is to examine DFM guidelines for FDM from the perspective of reducing cost and materials. This work will also demonstrate the ability to measure guideline effectiveness in a quantitative and statistical manner. In these areas specifically, this research is unique.

The emergence of FDM as a small volume manufacturing process (1000 units or less) and a lack of explicit rules for improving the efficiency of this process bring necessity to the development of design guidelines. To develop such a set of guidelines, candidate rules needed to be generated. Each candidate guideline can then be tested to determine its impact on important performance metrics such as build time and cost. By analyzing this data and comparing it with baseline performance, one can determine which guidelines may be suitable for adoption.

It should be noted that software packages have been developed for improving layered manufacturing process settings. These packages are not sold with FDM machines directly and tend to be costly. It is still useful to establish potential guidelines because doing so could prevent the designer from purchasing this third-party software. Empirical development and analysis of guidelines is also valuable so that the process of establishing guidelines can be understood and used by practitioners as FDM processes improve without reliance on build improvement software. This is further discussed in Chapter 4.

1.3 Research Questions

This study will answer three specific research questions. In an overall attempt to improve the design of components for manufacture by Fused Deposition Modeling, the following three critical research questions were identified:

1. What are the most critical metrics associated with Fused Deposition Modeling that directly dictate the feasibility of its use as a small-volume manufacturing process?

2. What guidelines or rules can be applied to all varieties of components to improve the defined metrics in a statistically significant manner?

3. Of the guidelines that significantly improve the defined metrics, which guidelines can be implemented without changing the functionality of the component?

The thesis is structured to ensure that these issues are addressed directly.

1.4 Organization of Thesis

This thesis begins with a discussion of existing literature with respect to Fused Deposition Modeling. Chapter 2 includes discussion on the development of the technology, research aiming to improve the technology, and the development of design guidelines for various layered manufacturing technologies. Additionally, Chapter 2 also discusses an overview of Design for Manufacturing (DFM) guidelines generated for any manufacturing process. A background of existing research on generating DFM guidelines for FDM and other layered manufacturing processes is included in this chapter.

The methodology of the entire study is described in depth in Chapter 3. This includes a discussion on the generation of the component repository, development of the proposed guidelines, and a presentation of the methods used conducting both the quantitative simulations and the qualitative case examinations. Chapter 4 discusses the development of the candidate guidelines.

From Chapter 5 and forward, an in-depth description of the quantitative portion of the research is presented. Chapter 5 includes a discussion on how the candidate guidelines were applied to each of the items in the repository, how simulations were conducted, what data were collected, and how a statistical analysis was completed. This section also includes an initial correlation study. Chapter 6 presents a discussion on the qualitative example cases. This includes an explanation of how information on various design projects was collected and how this information was analyzed. Chapter 7 summarizes the results of both the quantitative and qualitative aspects of the research. Chapter 8 is a conclusion that outlines the overall results of the research endeavor. This chapter also includes a presentation of areas of future work.

Chapter 2: FDM Process Description and Background

It is important to describe the fundamental operation of Fused Deposition Modeling (FDM) technology in order to discuss the application of guidelines to FDM. This includes both the physical operations of the equipment and the simulation software that prepares builds and provides the user with relevant build data. Section 2.1 discusses the background and operation of FDM along with an overview of the purpose of the companion Catalyst™ software and the useful information it produces. Full FDM process details from part design to manufacture are given at the end of this section

Section 2.2 gives an overview of DFM guidelines in general, discussing how they are developed for any manufacturing process and their usefulness to designers. Section 2.3 provides an overview of existing research related to the development of DFM guidelines for FDM and other emerging manufacturing technologies. This section also describes the gap in the literature and where this study contributes to the field.

2.1 Description of FDM Process and Simulation

2.1.1 Fused Deposition Modeling

Fused Deposition Modeling was commercialized by Stratasys Inc. in 1990. The process is a layered manufacturing technology that builds components using a thermoplastic material. Specifically, a thermoplastic filament is drawn into an extrusion head that heats the material just past its glass transition temperature. The material is extruded onto the work surface in which an initial two-dimensional cross-section is created by movement of the filament relative to the horizontal platform. Due to the material's temperature (set to a level just above glass transition) it solidifies instantly upon contact with the work piece. As the first two-dimensional cross-section is completed, the work piece (mounted on a platform that translates in the z-direction) shifts down a distance equal to the thickness of the first layer. The material laying process repeats as the second layer is deposited. The stacking of these layers eventually results in a solid, three-dimensional object (10). The machine diagram of an FDM machine can be seen in Figure 1. Figure 2 holds an image of the Stratasys Dimension FDM machine from the Product Innovation and Realization Laboratory Suite (PIRLS). The connection between PIRLS and this research is described in Chapter 3.

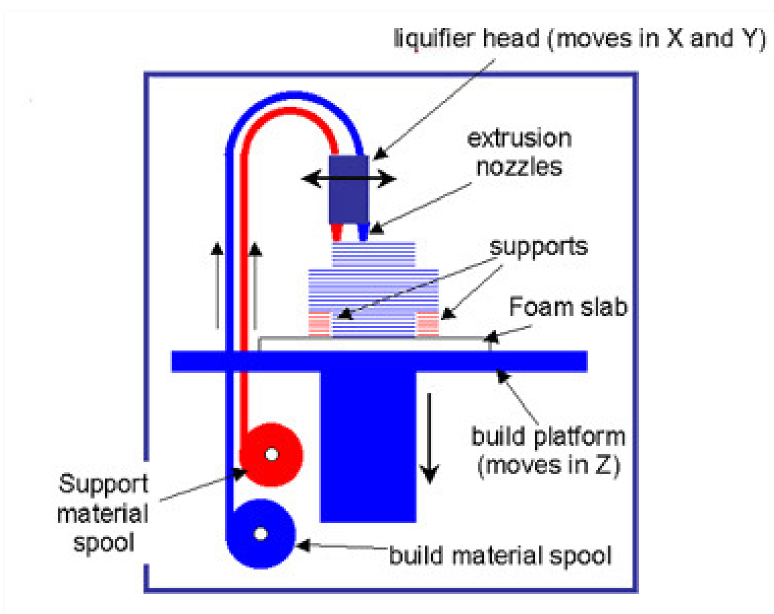


Figure 1. FDM Process Diagram (11)

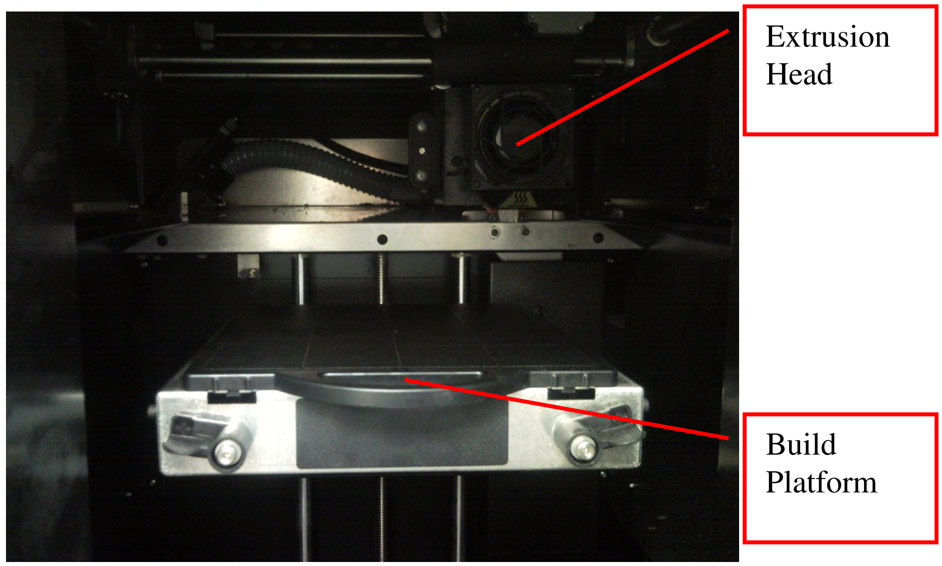


Figure 2. Interior of Stratasys Dimension (Note build platform in foreground and extrusion head at top right)

The ability to create overhanging or hollow features using FDM is based on the process of using a second support material. Because the material is extruded from the nozzle in a semi-solid state, it must be placed directly upon a preceding layer. For overhangs or hollow features, these underlying layers are built with a secondary, water-soluble material that will be removed during post-processing. These support structures are removed after the build is complete using either a chemical bath (using sodium hydroxide and water in an ultrasonic bath, to facilitate the support removal process) or through physical removal by hand, resulting in the desired final structure. If supports are removed by hand, some material may not always be removable, as is the case with certain hollow features. Figure 3 demonstrates the concept of support structures. Figure 4 shows an actual component built in a Stratasys Dimension machine with support structures intact.

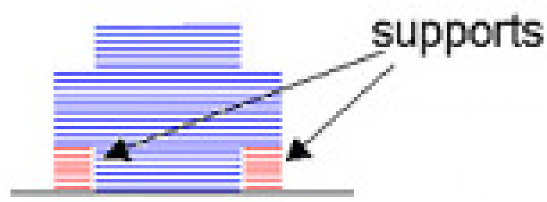


Figure 3. Support Structures (modified from 11)

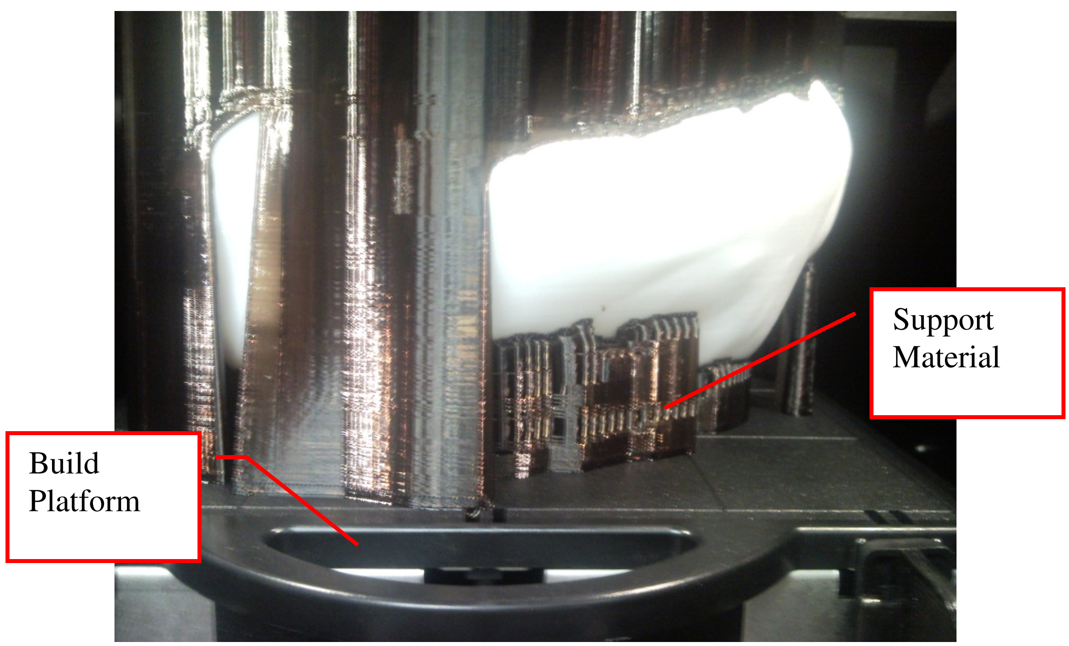


Figure 4. Support Structures on Actual Component

2.1.2 Catalyst™ Software

Catalyst™ is the standard software that is packaged with Stratasys FDM machines. Developed by Stratasys, this software has several functions. Primarily, this software takes the .STL file of a part or parts (generated from most CAD packages) and converts it to a .CMB file. In this conversion, the software takes the three-dimensional structure from the .STL file and slices it into two-dimensional cross-sections. These cross sections are offset from each other in the z-direction by a distance equal to that of the thickness of each layer deposited by the machine. A visualization of this process can be seen in Figures 5 and 6.

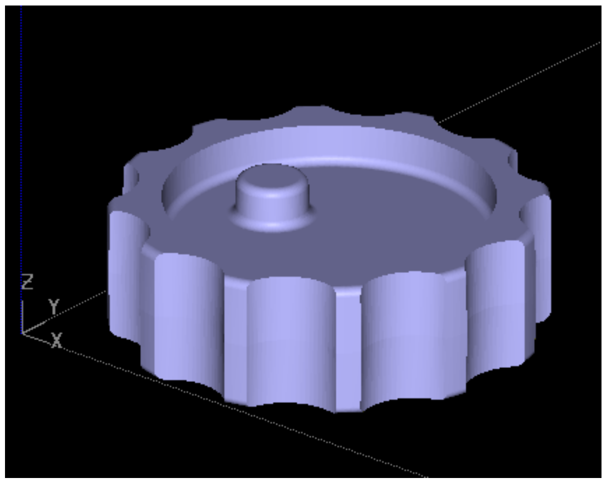


Figure 5. .STL File Represented in Catalyst™

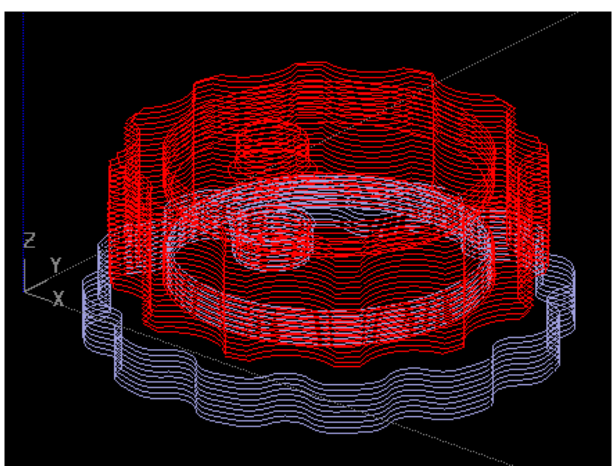


Figure 6. .CMB File Showing Cross-sectional Slices (note support material on bottom)

After this transition from three-dimensional model to a series of two-dimensional cross-sections, Catalyst™ generates the toolpaths which the extrusion head will follow to build the component. Catalyst™ is able to determine where support material is needed to support hollow features or overhangs. This is done without any input from the user. The user has considerable input into the build settings, such as part orientation and layer thickness. Altering these settings will result in a different toolpath that is sent to the FDM machine.

Catalyst™ not only creates the .CMB file to be sent to the machine, but can also provide the user with build data. This includes, but is not limited to, estimated build time and material usage estimates (both model and support). By accessing the build file, the user can obtain these data. The information that these data provide will be critical in quantitatively denoting improvement (or lack thereof) during the testing of the candidate guidelines.

2.1.3 FDM Process Description

To fully understand the FDM process, an example of a component's transformation from part design to manufacture is given. In this case, Part #28 from the repository created for this research is selected. To begin, this component was designed in a CAD package. Figure 7 shows this component modeled in SolidWorks.

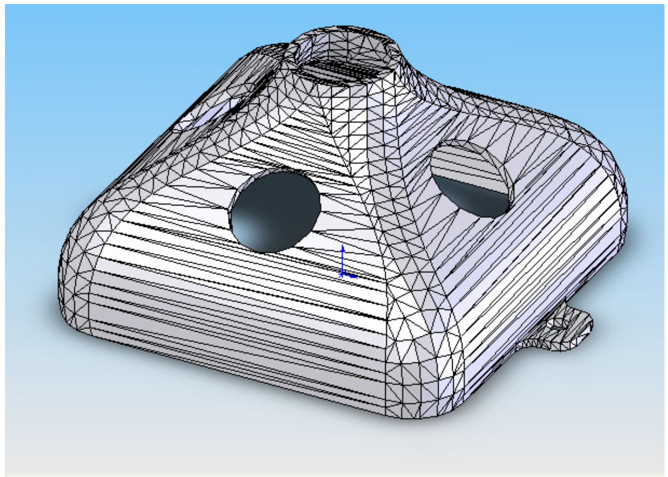


Figure 7. Part #28 from Repository Modeled in SolidWorks

From this point, the .STL file is sent to Catalyst™, where the software slices the file and generates toolpaths. Figure 8 shows this component after its Catalyst™ simulation, along with a top-view of a particular cross-section

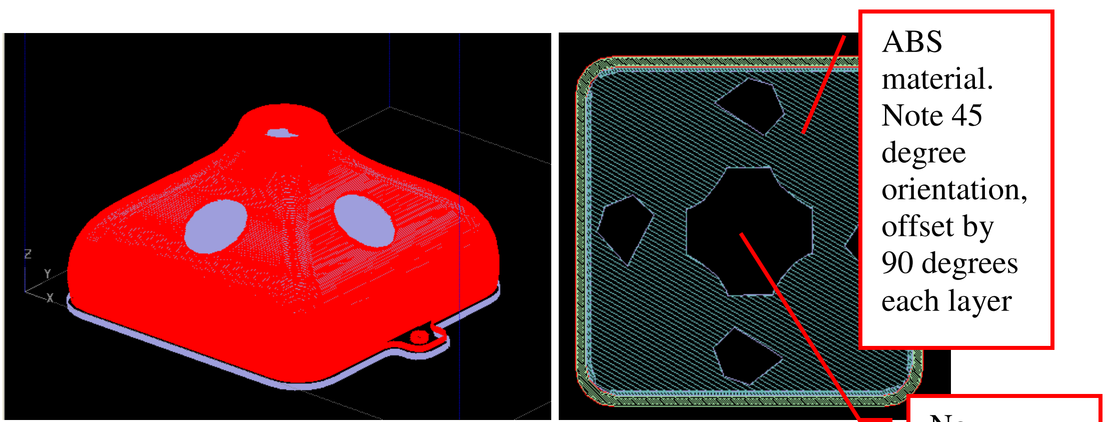


Figure 8. Part #28 from Repository Simulated in Catalyst™

With the simulation now complete, Part #28 is then sent to the Stratasys machine for building. After approximately 10 hours in the machine (8.83 cubic inches of material), Part #28 is removed from the machine and placed in the chemical bath. After dissolving the support material, the final Part #28 is complete.

2.2 Background of DFM Guidelines

To put this research into proper context, it is important to describe the background of Design for Manufacturing (DFM) guidelines and why they are critical in improving the design of a component. DFM focuses on altering the design of a component to improve its manufacturability with respect to a particular process. Therefore, different manufacturing processes generally have different DFM guidelines. This topic received considerable attention in the 1980s as the integration of concurrent engineering strategies occurred within many companies (12). DFM guidelines focus on both ensuring that a component can be manufactured using a particular process and reducing the costs and time associated with that process. Traditionally, DFM guidelines are empirically derived over many years of experience with the manufacturing process (12). For further detail on DFM, there are many texts that focus on this topic (for example, 13, 14).

A standard set of DFM guidelines generally has applicability to most manufacturing processes. Some of the guidelines generally considered to be universal include (12):

- Minimize total number of parts
- Standardize components
- Use common parts across product lines
- Standardize design features

- Aim to keep designs functional and simple
- Design parts to be multifunctional
- Design parts for ease of fabrication
- Avoid excessively tight tolerances
- Minimize secondary and finishing operations
- Utilize the special characteristics of a process

In addition to these standard guidelines, each specific manufacturing process tends to have a specific set of DFM guidelines. Because of the vast number of manufacturing processes available, it would not be feasible to list all such sets. Injection molding can be used to illustrate DFM guidelines. Entire texts are devoted to DFM for injection molding (for example, 15). However, for the purposes of brevity the following example provides one set of DFM guidelines for injection molding (16):

- Decrease maximum wall thickness
- Create uniform wall thickness
- Round corners
- Inner radii should be greater than or equal to wall thickness
- Apply draft angles to all walls parallel to parting direction
- Add ribs for structural support perpendicular to axis of bending
- Isolate bosses from corners and ensure thickness of no greater than 60% of main wall thickness
- Minimize undercuts

- Minimize number of side-action directions
- Orient threads perpendicular to parting direction

One can see that many of these injection molding rules are concerned with the moldability of the component. For example, the inclusion of draft angles ensures that the component can be ejected from the mold appropriately after cooling. Draft angles would not be required if this component was machined on a milling machine.

These guidelines help demonstrate the need for specific guidelines relevant to FDM. Returning to Part #28 in the repository discussed in section 2.1.3, it is interesting to note how the design might have to be changed to apply DFM guidelines for injection molding. In Figure 9 below, one can see that the four holes on the walls of the component would require side cores. As such, one would have to redesign the component to eliminate these features since the tooling costs associated with the side cores will be higher.

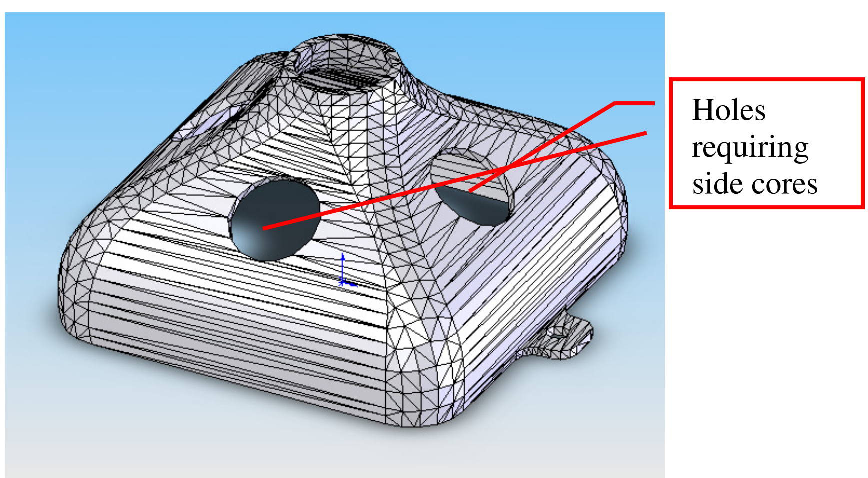


Figure 9. Part #28 from Repository

However, if this component was manufactured using FDM, these holes would not be an issue because there is no mold necessary for the FDM process. Therefore, the same component (Part #28) made with the same material (ABS, for example) would have a completely different set of design guidelines for two different manufacturing processes. As more designers choose to utilize FDM as a manufacturing process, the need for design guidelines specifically-applicable to FDM becomes increasingly apparent.

2.3 Existing Research on Guidelines for FDM and other Layered Manufacturing Processes.

With the need for FDM-specific design guidelines already established, it is necessary to examine research that has been done to develop such guidelines. One area of existing research takes a fundamentally opposite approach from that discussed up to this point. Rather than improve a component's design for a particular manufacturing process, Peres and Martin devised a method to select the best rapid prototyping process based upon a given component and its desired qualities (5).

Specifically, this work used a Quality Function Deployment (QFD) method to relate the main requirements desired of the manufacturing process to the processes themselves. Some of the requirements included ability to create new concepts, simplification of communication between user and machine, integration of component into environment, anticipation of fabrication problems, ease of testing components, forming parts as patterns, and directly manufacturing molds. The technologies considered in this QFD analysis included FDM along with seven other rapid prototyping processes. This study found that FDM rated the highest for its ability to create components for testing purposes. Although the method created in the study operates in a fundamentally opposite fashion to this work, it still gives a good example of existing research that aims to effectively mesh a component with a manufacturing method.

A majority of the other exiting studies on improving FDM focus on altering the design of the components themselves. One example is the study conducted by Medellin (6). The focus of that work was to improve the manufacturability of a component with a volume that exceeded the build capacity of the rapid prototyping machine with which it was intended to be manufactured. By dividing a component by an array of orthogonal planes, issues arise with the strength and accuracy of those components. Therefore, this study examined and noted many common problems and potential solutions to these problems. Though it did not develop a universal set of design guidelines, this study gives a relevant example of research that aims to create guidelines to improve the manufacturability using a layered manufacturing process.

A study similar to Medellin's was conducted by Dimitrov, Schreve, Taylor, and Vincent (17). Again, the aim of the research was to develop guidelines for improving the manufacture of components built in machines whose capacity was too small to build the desired part in one piece. However, Dmitrov et al. focused specifically on 3D printing, a rapid prototyping process different from FDM that was developed by Z Corporation (18). Their research primarily dealt with altering the designs to ensure strengthening of critical components and ensuring necessary support structures were present. Again, this is a relevant example of an attempt to create guidelines related to a process similar to FDM

Jee and Sachs conducted a study that aimed to improve the quality of components build using a layered manufacturing process. Specifically, this work focused on the creation of surface macro-textures (7). These are defined as a set of geometric, three-dimensional features integrated onto the surface of a component. Some examples of surface macro-textures include fins to increase heat transfer or treads of a tire. Jee and Sachs developed an automated method that examined the manufacturability of a given set of surface macro-textures. However, the design rules generated in their study were only based on the process limitations of the manufacturing process itself. For example, one design rule was to ensure that the component's overall size was less than that of the machine's capacity. Still, this research gives another relevant example of previous work that aimed to define guidelines for application to layered manufacturing processes, including FDM.

Sambu, Chen, and Rosen developed a method called "geometric tailoring" that created guidelines to apply to a prototyping process in order to manufacture a component with specific characteristics (8). The issue that their work addressed was using rapid prototyping processes to make molds. When molds are manufactured using rapid prototyping processes, the mold material differences (with respect to standard molds) tend to create differences in the final injection molded components. Therefore, the goal of the work was to create DFM rules that helped ensure similitude between components injected into standard molds and molds made using a rapid tooling process. By employing optimization techniques, the researchers were able to mitigate many of these issues. The result was yet again an example of creating DFM guidelines for layered manufacturing in a specific scenario.

In a study conducted by Thrimurthulu, Pandey, and Reddy, part orientation in FDM was examined (19). Their study employed the use of genetic algorithm optimization techniques to determine optimum part orientations with respect to minimizing build time and minimizing surface roughness. These authors created a tool to customize orientation for each individual part. However, this study did not generate any design guidelines and the optimization technique needs to be implemented on a case by case basis for each component to determine its unique orientation recommendation.

Cristofolini and Filipi are one of few researchers who have developed an explicit set of design guidelines for FDM (8, 20). In their work, they attempted to create a set of design guidelines that could be universally applied to components to improve manufacture using FDM. However, their initial set of guidelines consisted of only five rules. The proposed rules were tested only to ensure the build accuracy of the parts using a coordinate measuring machine (CMM). These dimensions were then compared to the exact dimensions of the CAD file provided to the machine. This is useful to the research presented in this study in that accuracy of built components does not need to be confirmed after application of such guidelines. While there are many limitations to this study with respect to ignoring factors such as material cost, this still provided useful insight on some candidate guidelines already posed in the literature. As will be discussed in Chapter 4, the Cristofolini and Filipi research was used to generate several of the candidate guidelines for this study.

In addition to the research described up to this point, there are various other emerging areas of study related to FDM. One example is a study by Han, Jafari, and Seyed focused on speeding up the deposition process (21). While the goal of their research is similar to one goal proposed in this study, it differs greatly. Han et al. focus on altering the FDM process to reduce idle time and increase the speed of the moving mechanisms within the machine itself rather than applying design guidelines to alter the components. Pandey, Reddy, and Dhande examined how to create an adaptive slicing technique within the toolpath generation software for FDM (22). This would allow for the increase of part quality and accuracy because the machine would be able to build the component in various planes depending on which surface was most critical at a given point on the component.

Another interesting study was conducted by Hopkinson and Dickens (23). Their work focused on determining the validity of FDM as a production process based on cost factors. These factors included material cost and labor cost (as a function of build time). While not directly related to the development of DFM guidelines for FDM, their worked helps confirm that FDM can be a contributing production process in certain manufacturing scenarios and provides support for the selection of build time and material volume as critical process metrics.

One additional study which aimed to apply DFM guidelines to FDM was conducted by Hague, Mansour, and Saleh (24). This work aimed to determine which DFM guidelines for injection molding still held true for FDM. However, they focused solely on eliminating the injection molding guidelines that were rooted on the molded nature of the manufacturing process. In doing so, there was no confirmation of the validity of the remaining guidelines. Additionally, no quantitative analysis was conducted to validate these guidelines.

2.4 Gap in Literature

This examination of the existing literature identifies several gaps where this research can make significant contributions. First and foremost, there is limited research on specifically developing design guidelines for application to FDM. As FDM becomes an increasingly more attractive production option in various scenarios, the development of a set of guidelines will become incredibly useful. While some research has been completed in this area, much of it focuses on improving the FDM process itself, rather than helping a designer improve his or her part to be most effectively produced using the FDM process in its current form

Additionally, the limited work that has focused on creating a set of guidelines has been both narrow in focus and lacks verification. As described previously in this section, many guidelines that have been suggested relate to a specific FDM issue or challenge, such as required surface quality or insufficient build capacity. The verification of proposed guidelines has been minimal, with very few quantitative studies completed. In addition to reviewing this literature, a paper to appear in ASME IDETC 2009 by the author of this thesis discusses the beginning of this research (25).

The goal of this thesis is to begin the development a universal set of guidelines that can be applied to all components using FDM, rather than only those components with a specific use or purpose. Additionally, this work aims to validate the effectiveness of the proposed guidelines. This will be done through both quantitative methods (simulation) and qualitative methods (study of example cases). Beyond laying down the groundwork in developing a set of guidelines, this work aims to outline necessary areas of further research. If these goals are achieved through this work, a significant gap in the research on FDM as a production process will have been filled.

Chapter 3: Methodology

One of the objectives of this work is to provide a rigorous process for qualifying a design guideline in the absence of years of manufacturing experience. This chapter outlines a mixed methods study to test FDM guidelines. Quantitative data will be collected on the effectiveness of each proposed FDM guideline by using the build simulation features of the Catalyst™ Software. Single-factor ANOVA will be used to make inferences about the data. Qualitative data will be gathered in a small exploratory study of the effectiveness of applying each candidate guideline to the components designed by junior and senior students in mechanical engineering design courses.

Developing the proposed FDM guidelines required a multi-step process. The methodology first describes the repository of components that will serve as the sample on which the guidelines will be individually tested. This repository is outlined in Section 3.1. Section 3.2 discusses the proposed set of initial guidelines (prior to their testing and statistical confirmation) and their origins. An overview of how the component designs and their FDM build settings were altered to apply each guideline is also provided. Section 3.3 discusses each the build of each component was simulated and how data were compiled. Additionally, the methods by which the data were analyzed are discussed. Section 3.4 outlines the qualitative portion of the research. This includes the information sheet that was developed to describe the student design tasks along with how these example cases were analyzed.

The data to be collected in the quantitative aspect of this study are the targeted performance metrics associated with the FDM process. Specifically, build time and material volume were selected as the critical characteristics due to their direct impact on the costs associated with FDM. Catalyst™ provides simulated values for these two metrics. The gathering of this simulated data from Catalyst™ along with an analysis of this data is outlined in Section 3.3.

It is important to note that there are two other common performance metrics related to layered manufacturing process in addition to build time and material volume. These are part strength and part accuracy. These were not measured in this study because they were considered constraints when minimizing cost and time. Because the goal of this study is to identify guidelines that will increase the feasibility of FDM as a niche manufacturing process, improving characteristics other than build time and material volume has less value. It is important, however, for the designer to ensure that all performance metrics sufficiently meet any manufacturing requirements prior to selecting FDM as the process of choice.

For the qualitative portion of the research, the data that were collected described the application of the candidate guidelines on a series of example cases. These example cases were reviewed to establish which candidate guidelines could be implemented without changing the functionality of the component. Results were examined to determine if any general conclusions could be made regarding infeasible guidelines.

Throughout this research, much information was used related to the author's experience as the Product Innovation and Realization Laboratory Suite (PIRLS) Lab

Manager. As manager of this lab from January 2007 to May 2009, the author has extensive experience in working with FDM and student design projects. Overall, the author has built over 150 components, ranging from under 1 cubic inch to over 100 cubic inches. These components have been as simplistic as a basic cube to as complex as a robotic arm interface. These components required a combined build time of over 1000 hours, including builds for research groups, private companies, and artists.

Because of the author's considerable experience and the large variety of components available through PIRLS, this laboratory's data are an extensive resource. The components examined in this study were originally built through PIRLS (see Section 3.1) and the author's experience was used as a source for several of the guidelines described in Chapter 4.

3.1 Design Repository

In order to test the statistical validity of any candidate guidelines for FDM, a set of sample components has to be defined. The laboratory in which the authors conduct research, the Product Innovation and Realization Laboratory Suite (PIRLS), is dedicated primarily for education of undergraduates in the Department of Mechanical Engineering at the University of Maryland[1]. PIRLS equipment includes a Stratasys Dimension SST machine along with Catalyst™ software (Version 4.0). Additionally, due to the nature of junior- and senior-level team projects each semester, a large database of components designed by the students is available.

[1] http://www.pirls.umd.edu

These files were compiled over two years (2007-2008) by the PIRLS Lab Manager. They varied in size from less than 1 cubic inch to over 55 cubic inches.

There are several advantages to using these component files as a database for an examination of the effectiveness of the candidate guidelines. First, the sheer quantity of files (94, prior to elimination of duplicates) will allow for statistical validity in any results. Additionally, the varying nature of the student projects produces a large variety of components, with respect to size and complexity. Lastly, because these files were created independently of this study, there is no concern of bias (beyond any limitations related to student projects).

The part repository for the guideline testing was finalized by eliminating repetitive component files and any component that would be too large for the equipment's capacity. In total, the final test set was composed of 65 components. Figure 10 displays a collection of various components from the repository.

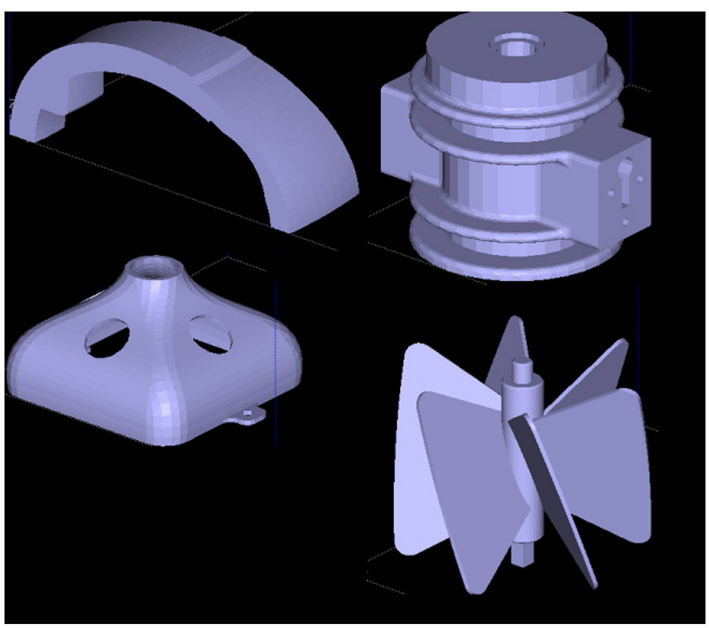


Figure 10. Sample Files from Repository

Figure 10 shows Parts (clockwise, from top left) 65, 58, 54, and 28. Note that these images have been scaled so that they appear to be approximately the same size. It is interesting to note the varying levels of part complexity. The characteristics for these components can be seen in Table 1.

Table 1. Sample Component Build Characteristics

Part Number	Build Time (minutes)	Material Volume (cubic inches)
28	736	8.83
54	414	4.78
58	1163	22.63
65	33	0.26

3.2 Guidelines

3.2.1 Developing Candidate Guidelines

An initial pool of candidate guidelines needed to be developed in order to test the validity of applying guidelines to FDM. Generally speaking, guidelines tend to be developed over long periods of time through heuristic methods. An increased level of comfort and experience with an established manufacturing technology leads to the development of "best practices" over time. Fused Deposition Modeling has only been commercially available since 1990. Therefore, its lack of maturity relative to more established manufacturing methods makes guidelines difficult to determine in this manner.

Two sources were used to compile an initial list of candidate guidelines. The first source was existing research literature. By examining recent work in the field, some proposed guidelines for FDM have already been identified. Since they have not been quantitatively tested to the extent of this study, they are well suited to be included as "candidate" guidelines here. As outlined in Chapter 4, several of these guidelines previously introduced in the literature were included in the initial set of candidate guidelines.

The experience of the author was relied upon to produce the remainder of the candidate guidelines. The author has considerable experience in manufacturing a variety of components using FDM because of the large amount of components manufactured through the PIRLS lab. As such, the author has identified heuristics that have had success. These guidelines were included in the initial iteration of the set of proposed guidelines.

With these two sources identified, an initial set of candidate guidelines was compiled. Through the methodology described in this section, a set of eight candidate guidelines were used in the quantitative study. Chapter 4 describes the list and its sources in detail.

3.2.2 Application of Candidate Guidelines

It is necessary to write a clear statement describing each candidate guideline in order to effectively apply them to the components in the test repository. In other words, the method by which to alter the design or build setup to achieve each guideline must be clearly stated. The methods by which to apply each guideline fell into two different categories. The application of some guidelines was achieved through physically altering the .STL file before processing it using the Catalyst™

software. This was noted as a “design change”. Other guidelines were applied by altering the build settings directly in the Catalyst™ software. This was described as a “build change”. These guidelines are discussed in further detail in Chapter 4.

Once the difference between a design rule or change and a build rule or change had been identified, standard practices for applying each rule needed to be outlined. This was completed for each candidate guideline in the initial set. The result was an explicit method for the application of each guideline to ensure that it was employed in a uniform manner for each component. Chapter 4 provides a detailed description of the methods by which each guideline is applied.

It should be noted that the guidelines examined in this study are currently build guidelines only, as no simulations (other than eliminating holes) required alterations to the design of the components themselves. As such, the statistical results of this research are only valid towards the application of these guidelines via changes to the build settings. However, as noted, many guidelines can be applied by either altering the design or changing the build settings of the FDM machine. Therefore, one would have reason to expect similar statistical validly in applying these guidelines through design changes.

3.3 Quantitative Analysis

Simulations in Catalyst™ were conducted to collect data on build time and material volume for each component in the study. Subsequently, the candidate guidelines were applied individually to each component in the repository and re-simulated, resulting in 8 new sets of performance data. Each of these data sets was then compared in a statistical manner to the baseline data. The results led to conclusions related to the effectiveness of each candidate guideline.

In this study, build time and material volume are the dependent variables. Their values are directly dependent on the geometric characteristics of the component. Because there are far too many individual geometric characteristics to list as independent variables, for the purpose of this study the independent variables are collectively referred to as the component geometry. An additional set of independent variables stems from the settings in Catalyst™ used to generate the toolpaths of the machine. By varying the component geometry (through design alteration) and the Catalyst™ settings, differing values of the dependent variables (build time and material volume) were generated. The last group of independent variables is the set of guidelines.

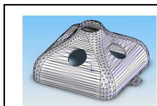
3.3.1 Simulation Method

Simulation of the FDM builds was conducted in the following manner. First, the builds of all components in the repository were simulated with no adjustments to determine the baseline characteristics of each component. The metrics that were tabulated were build time and material volume spent, both provided from the Catalyst™ simulation output. Then, each guideline was tested as a separate experiment. For each guideline, all components in the repository were altered to similarly apply the guideline. For those guidelines that were applied through altering the design, SolidWorks was used to modify the .STL file. This CAD package was chosen because of its ease of use in altering .STL files.

Several tests were conducted to determine simulation error in order to assure that the simulated build time was accurate with respect to the actual build time of a component. Physical components were built in the machine and actual build times were recorded. These build times were then compared to their simulated values. With parts of build times up to ten hours, the error in estimating the time was approximately one minute. As such, the simulated build time generated by the Catalyst™ software was deemed to be sufficiently accurate for this study.

Data on build time and material volume were again collected for each altered component. This was repeated for each of the candidate guidelines until nine sets of data were compiled. One data set was the baseline (or control value) for each component. Eight more data sets were generated, one for each of the eight guidelines. Table 2 below shows Part 28 with its nine simulated data sets. Each column gives the performance data after the application of a particular guideline. The first row lists the build time and the second row lists the material volume. For example, the application of G1 to Part 28 resulted in a 5% reduction in build time and a 2% reduction in material volume.

Table 2. Data Sets for Part 28

	**Base line**	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**	**G8**
Build Time (minutes)	736	700 -5%	596 -19%	596 -19%	596 -19%	643 -13%	596 -19%	526 -29%	730 - .5%
Material Volume (cubic inches)	8.83	8.68 -2%	8.18 -7%	8.18 -7%	8.18 -7%	7.66 -13%	8.18 -7%	9.8 +11%	8.82 0%

3.3.2 Data Analysis Methods

Statistical analyses were applied to the data to determine the significant improvements generated by a particular guideline using the nine sets of data generated in the manner described in Section 3.3.1. Those guidelines that proved to generate a significant reduction in build time and material volume spent would then be further tested qualitatively through case studies.

In order to determine the existence of significant improvements, two statistical studies were conducted. The first was the use of Single-Factor ANOVA. In this method, the data for each component's build time and material volume baseline values were compared to the respective values after a single guideline was applied. To normalize these results over all types of components, a percent change between the baseline data and altered simulation data was noted for each component. This was then repeated seven additional times for each guideline applied individually.

To determine if the application of an individual guideline provided a statistically significant improvement in reducing either build time or material volume, single-factor ANOVA analyses were conducted between the baseline and the data set corresponding to each guideline. The results of these analyses provided the user with insight on whether a significant improvement was measured. These applications and results are further discussed in more detail in Chapter 5.

The second quantitative method employed in this research was a correlation study between the guidelines. Each candidate guideline is treated as an independent variable in the first analysis. This is not always going to be the case with all components, so further study was required. Each set of data was compared to all other data sets generated by independently applying the candidate rule to calculate the Pearson correlation index. These indices would determine the presence of linear relationships between individual guidelines. These data would provide insight into whether or not applying two different guidelines at the same time provided similar results. Chapter 5 discusses this examination in further detail.

The third and final quantitative study examined relationships between the presence of design features and guideline effectiveness. This study was conducted with the use of two-factor ANOVA. In this case, the presence and magnitude of particular features was noted for each component in the repository. An initial study was conducted to see if the presence of curved features or overhangs had a significant impact on the level of improvement a particular guideline provided. Further details on this study along with initial results can be found in Chapter 5.

3.4 Exploratory Qualitative Analysis

3.4.1 Development of Prototype Information Sheet

Once the effectiveness of implementing each guideline was determined through the quantitative analyses provided by Catalyst™, it was important to determine the overall feasibility of implementing these guidelines for an actual design scenario. This is necessary because one guideline may be shown to have very positive effects on reducing build time and material volume, but might be infeasible for a designer to implement without sacrificing key component functionalities. For example, Part 28 as shown previously could not have holes eliminated without eliminating its functionality as a chimney to disperse heat.

Parts built for actual student projects were examined in an exploratory study into the feasibility of implementing the guidelines. Students in ENME371 (Product Engineering and Manufacturing) and ENME472 (Integrated Product and Process Development) at the University of Maryland, College Park were asked to fill out a "Prototyping Information Sheet" when preparing a part to be built using the FDM. These data were collected from September 2008 until December 2008. Student projects were selected because of the level of familiarity the author had with the design projects themselves. Therefore, the author could easily make judgments as to what alterations might be acceptable while maintaining functionality.

This information sheet required the student teams to describe the functionality of the device, its size, and loading scenarios that it would encounter in operation. Additionally, students were required to provide free-body diagrams and a screenshot of the CAD file of their component. In total, 11 information sheets were collected and each was examined through the method described in Section 3.6. These 11 were selected from the original pool of 13 prototypes built in Fall 2008. Two repetitive components eliminated. These 13 student teams chose to prototype using the FDM machine out of a total of 24 teams. Table 3 shows a sample Prototyping Sheet used in the research.

Table 3. Sample Prototyping Sheet

Prototyping Information Sheet

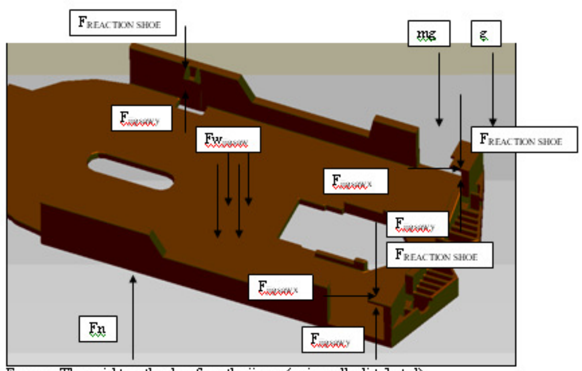
Brief Description of Prototype: Standard shoe from DEWALT jigsaw with an angled addition on the front to change the way air is blownout from the front of the shoe and to displace sawdust off to the side. The ribs reduce the stress in the shoe addition by 8 times.

Approximate Dimensions (inches): 3.2 wide x 6.5 long x 0.8 high (inches)

Description of critical functions:

- Protect cutting surfaces from metal shoe
- Absorb shock for metal shoe when tool is dropped
- Displace sawdust away from the front of the shoe opening
- Chemically resistant material to work in most any cutting conditions

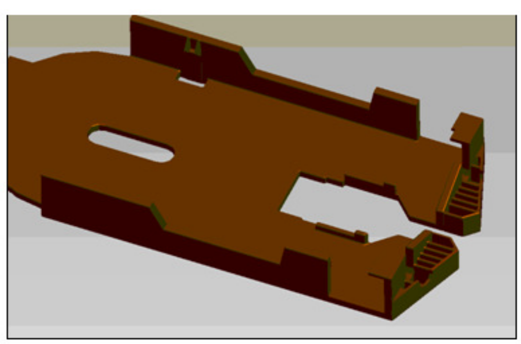
Sketch (including FBD, noting any critical loads):



Fw_{jigsaw}: The weight on the shoe from the jigsaw (universally distributed)
$F_{jigsaw\ y}$: The force on the clips of the shoe in the y direction from the metal shoe assembly
$F_{jigsaw\ x}$: The force on the clips of the shoe in the x direction from the metal shoe assembly
$F_{REACTION\ SHOE}$: The reaction forces of the shoe to the forces from the jigsaw
Fn: normal force acting on the shoe from the cutting surface

The reaction forces and the jigsaw forces in the x and y direction act as the clip to hold the shoe on the shoe assembly.

Screenshot image of CAD file:



Once the data from the example cases were collected, each information sheet was examined with respect to the eight guidelines to determine the functional feasibility of implementing each guideline. Using information provided in the information sheet and holding necessary discussion with the students, qualitative judgments on the feasibility of implementing each guideline were made. The method by which these judgments were made is discussed in Section 3.6.

3.4.2 Analysis of Sample Data

It was necessary to examine the level of feasibility of applying each candidate guideline to each component. If it was judged by the author that the application of a guideline would have minimal or no effect on the ability of the component to perform its desired function, then the guideline was deemed feasible in that case. However, if the implementation of a guideline on a given component resulted in a loss of functionality or an inability to interact with any related component or subsystem, then it that guideline was deemed infeasible to implement on that component. This approach was deemed reasonable due to the author's familiarity with the design projects of the students requesting the builds and the exploratory nature of this study.

Once data were collected related to the application of each guideline to each component independently, data were compiled to calculate the percentage of the components that allowed for the feasible application of a given guideline. Specifically, this was calculated as:

$$(\text{Number of possible applications}) / 11 * 100\%$$

In addition to this percentage of applicability success for each guideline, comments were made regarding factors that prohibited the feasible application of a guideline to particular components. The tabulation of this information allows for further elimination of inappropriate guidelines from the proposed list. This is due to the fact that some appear to be nearly universally infeasible to implement, despite their capability to reduce build time and material volume. The specific results of this component of the research are discussed in Section 5.

The final aspect of the qualitative study was to run a quantitative analysis on performance metrics after simultaneously applying all final guidelines to each of these example cases. Data on build time and material volume were collected in each case. This set of data was then compared to the baseline using a paired t-test. The results of this study would be used to determine if the simultaneous application of all proposed guidelines to a component would result in statistically significant reductions in the critical metrics.

Chapter 4: Proposed Guidelines

4.1 Development of Initial Guidelines

The list of proposed guidelines was developed through compiling guidelines proposed in existing literature and supplementing them based upon the authors' extensive experience in using the FDM equipment (discussed in Section 3.2). Table 4 displays the candidate list of eight guidelines along with their source.

It is important to separate these guidelines into two separate categories. Some are denoted as "build rules". These are guidelines that are applied through the alteration of build settings of the FDM machine itself. Examples of these settings include build orientation within the machine, material layer thickness, and part rotation around the z-axis. The second set of guidelines are denoted as "design rules". Their application is achieved through altering the design of the component itself, much like standard DFM rules. It is also important to note that the application of some guidelines can be conducted by either altering the build settings or changing the design of the component. The method(s) by which the guideline is applied is also noted in Table 4.

Table 4. Proposed Guidelines

Guideline	Source	Application	Code
Minimize Height along z-axis	Filippi and Cristofolini (8)	Design change or build change	G1
Minimize Form Ratio	Filippi and Cristofolini (8)	Design change or build change	G2
Minimize Number of Overhangs	Authors experience	Design change or build change	G3
Build Holes Facing Upward	Authors experience	Build Change	G4
Minimize Number of Holes	Authors experience	Design change	G5
Build Object with Largest Surface on Bottom	Authors experience	Build Change	G6
Maximize Layer Thickness	Filippi and Cristofolini (8)	Build Change	G7
Rotate build 45 degrees around z-axis	Authors experience	Build Change	G8

It should be noted that G1-4 are build alterations that are commonly found in third-party software packages developed for layered manufacturing processes. One example, Materialise's Magics RP, includes many of these features and makes decision automatically in an attempt to reduce metrics such as build time and material volume. However, these packages are not sold with FDM machines directly and tend to be relatively expensive (Magics RP retails for approximately $7,000). As such, it is still be very useful to the designer to establish how these guidelines should be applied, along with proving their validity. Doing so could prevent the designer from purchasing third-party software, again reducing the costs associated with manufacturing using FDM. Empirical development and analysis of guidelines is also valuable so that the process of establishing guidelines can be understood and used by practitioners as FDM processes improve without reliance on build improvement software.

Upon the finalization of this proposed set of guidelines, it was critical to outline the methodology by which to apply these guidelines through a standardized and clearly defined process.

4.2 Application of Guidelines

As outlined in Section 3.2.2, specific methods by which each guideline would be implemented were developed. This was to ensure standard and uniform application of a particular guideline on any type of component. Rigidly defining how each guideline should be implemented resulted in a valid assessment of the overall effectiveness of each guideline. The list below describes each guideline and its application method.

G1: Minimize Height: This was achieved by altering the orientation of the component within Catalyst™ to minimize the height in the z-direction. The logic behind this guideline is that minimizing the number of layers of the build will reduce the build time. This can be applied in any case where minimizing the height doesn’t cause the maximum x or y dimension to exceed the allowable 8”. This is illustrated in Figure 11.

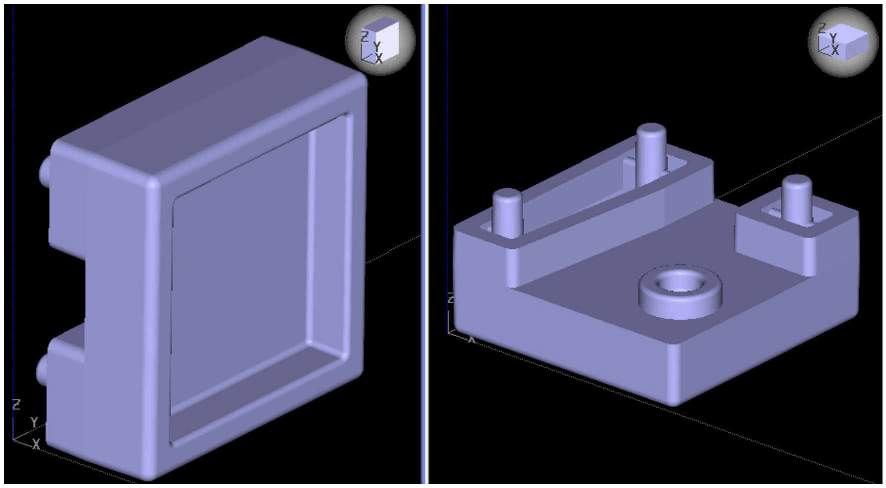


Figure 11. Minimizing Height (G1) with Part 47

G2: Minimize Form Ratio: This was achieved by altering the orientation of the component within Catalyst™ to minimize the form ratio of the part. The form ratio is defined as follows:

(Height along z-axis) / (length along x- or y-axis, whichever smaller)= Form Ratio

The logic behind this guideline is that minimizing the form ratio will also reduce the number of layers, likely resulting in a reduction in build time. Much like G1, this can be applied in any case where minimizing the height doesn't cause the maximum x or y dimension to exceed the allowable 8". The application of this guideline is illustrated in Figure 12.

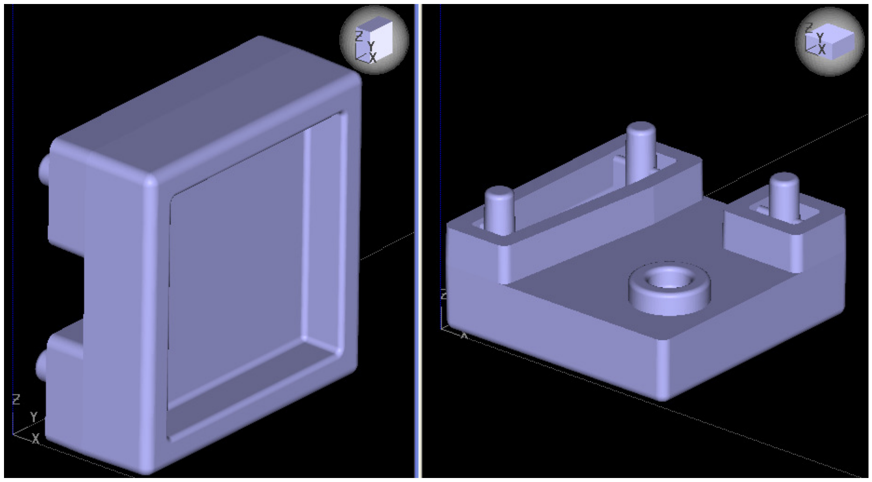


Figure 12. Minimizing Form Ratio with Part 47(G2)

G3: Minimize Number of Overhangs: This was achieved by altering the orientation of the component within Catalyst™ to minimize the overall number of overhanging features of the part. The logic behind this guideline is that minimizing the number of overhangs will reduce the amount of support material required. This can be accomplished by either altering the design using a CAD package or by orienting the component within Catalyst™. For the purposes of this study, the component was oriented within Catalyst™ to minimize the presence of these features, because simulation in Catalyst™ will not distinguish between the two methods of integrating G3. The application of this guideline is illustrated in Figure13.

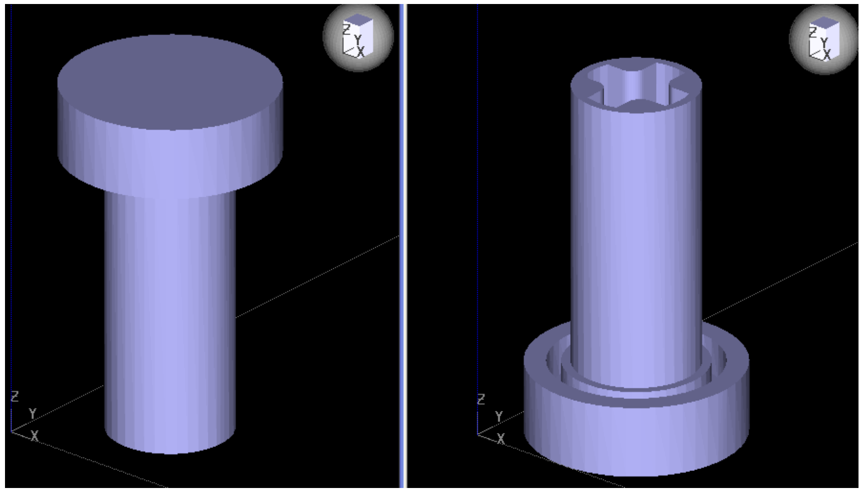


Figure 13. Minimizing Overhangs (G3) with Part 62

G4: Build Holes Facing Upward: This was achieved by altering the orientation of the component within Catalyst™ to ensure that the maximum number of holes was present on the top surface facing upward. The logic behind this guideline is that building holes facing upward will reduce the amount of support material needed. This can be applied in any case where holes are present in the component. The application of this guideline is illustrated in Figure 14.

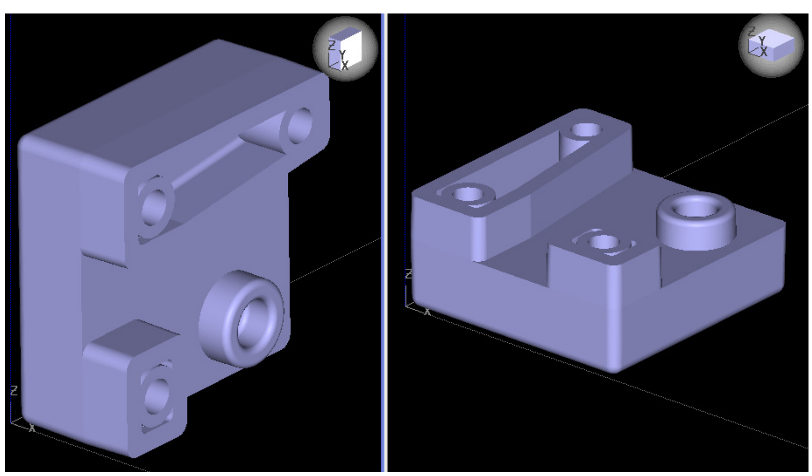


Figure 14. Build Holes Facing Upward (G4) with Part 46

G5: Minimize Number of Holes: This was achieved by altering the .STL file in SolidWorks and eliminating all holes within each component. The logic behind this guideline is that minimizing the number of holes will reduce the amount of support material needed. Another option would be for the designer to create the holes by drilling them during post-processing. Similar to G4, this guideline can be applied in any case where holes are present in the component. The application of this guideline is illustrated in Figure 15.

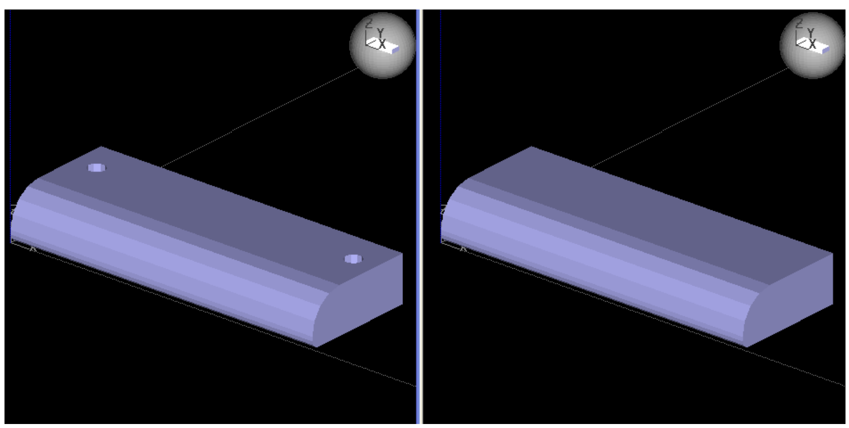


Figure 15. Build Holes Facing Upward (G5) with Part 29

G6: Build Objects with Largest Surface on Bottom (X-Y plane): This was achieved by altering the orientation of the component within Catalyst™ to place the largest surface on the x-y plane, in this case, directly on the build platform. The logic behind this guideline is that this will reduce the amount of support material needed.

This can be applied in any case where placing the largest surface on the x-y plane does not cause the component to exceed the 8” by 8” x-y boundary. The application of this guideline is illustrated in Figure 16.

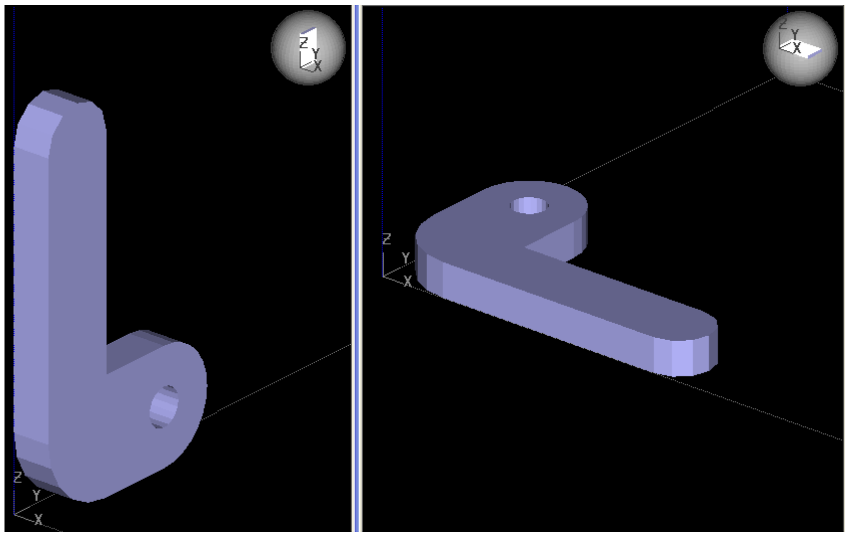


Figure 16. Build Objects with Largest Surface on Bottom (G6) with Part 45

G7: Maximize Layer Thickness: This was achieved by altering the build settings within Catalyst™ to maximize the layer thickness. The standard setting is 0.010”, but the application of this rule changed the thickness to 0.013”. The logic behind this guideline is that maximizing the layer thickness will reduce the number of layers of the part, therefore reducing build time. It can be applied to all components. The application of this guideline is illustrated in Figure 17.

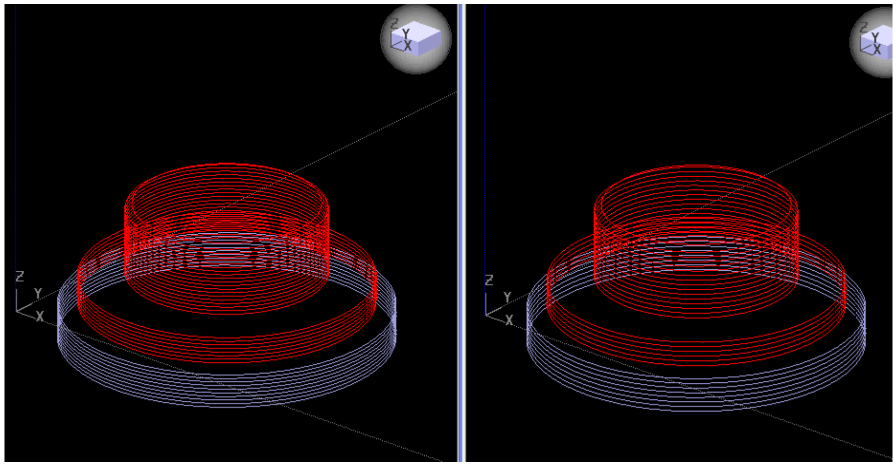


Figure 17. Maximize Layer Thickness (note 28 layers on left and 22 layers on right) (G7) With Part 17

G8: Rotate Build 45 degrees around z-axis: This was achieved by altering the orientation of the component within Catalyst™ to rotate the component 45 degrees around the z-axis. Through initial experimentation by the author, this was seen to have a significant impact on reducing the build time. It should be noted that applying this guideline could have a significant effect on the mechanical performance of a component if it were purposely designed to exploit the material deposition pattern. In many cases, the designer is unaware of the intricacies of the build process. For purposes of this study, it was assumed that part strength would be considered a constraint by the designer. This guideline can be applied in any case where rotating the component does not cause it to exceed the 8" by 8" x-y boundary. The application of this guideline is illustrated in Figure 18.

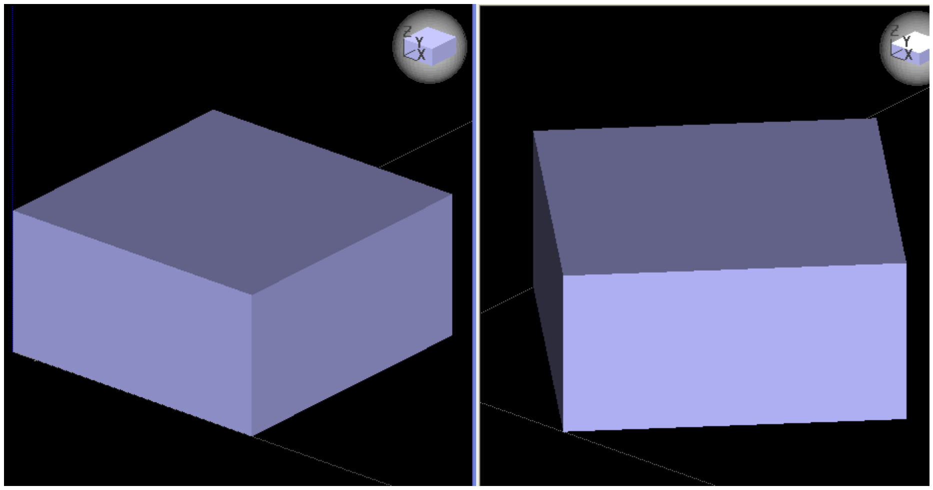


Figure 18. Rotate Build 45 degrees (G8) with Part 14

To explain the reasoning behind the addition of G8 as a candidate guideline, the toolpath creation within Catalyst™ should be further explained. Figure 19 shows the orientation of the toolpaths of a square part by default in Catalyst. One notices that by default, Catalyst orients the toolpaths +/- 45 degrees with respect to the x-axis, shown by angle θ in the left side image of Figure 19. By rotating the component 45 degrees around the z-axis, indicated by γ in the right side image of Figure 19, these =/- 45 degree angles become 0/90 degree angles with respect to the side of the part.

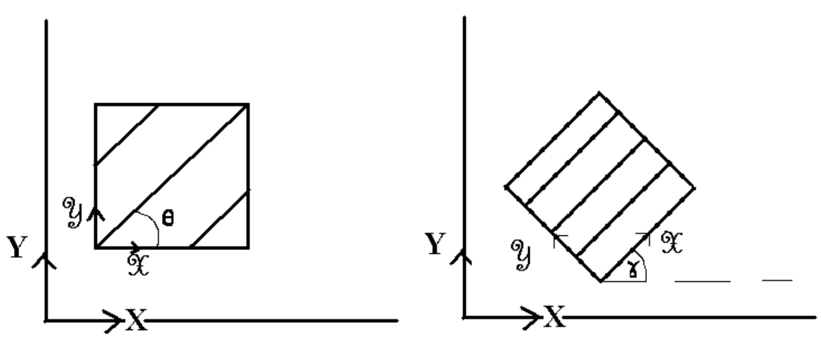


Figure 19. Toolpath Orientation

Figure 20 shows actual Catalyst toolpaths for a rectangular component. The toolpaths appear as dotted lines in Figure 20. Because the re-orientation of the toolpath angle (γ) from+/- 45 degrees (a) to 0/90 degrees (b), one can see that each pass has a longer length. Therefore, the nozzle has further time to speed up to its maximum velocity before being required to slow down to turn and make the next pass. It was hypothesized that this process would reduce the build time for a given component. Therefore, G8 was added to the candidate list of guidelines.

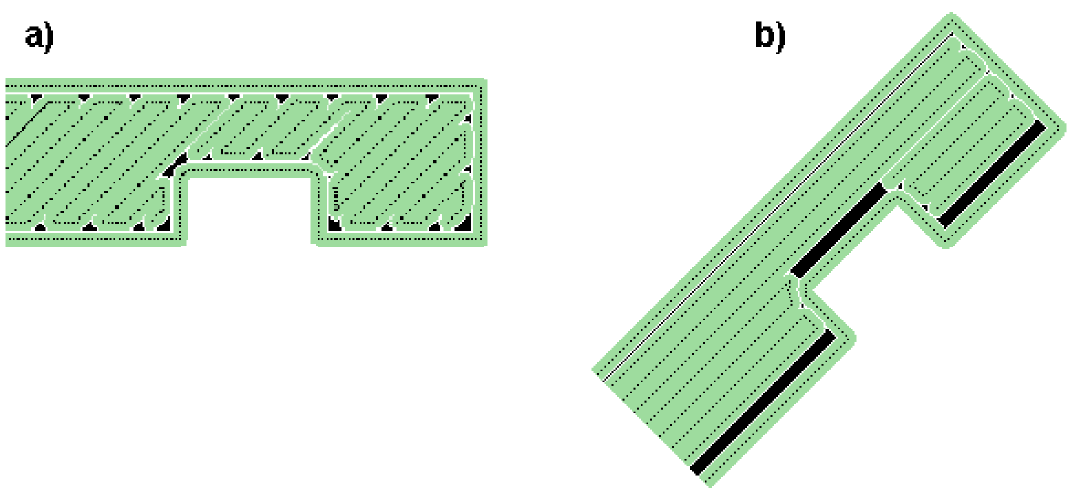


Figure 20. Increased Toolpath Length through Application of G8

Chapter 5: Quantitative Analysis through Simulations

5.1 Single-factor

The results for each guideline data set were compared to the baseline data to determine the effectiveness of each guideline. Each data set was comprised of the build time and material volume for the components subjected to the application of a single guideline. In order to normalize the data to facilitate comparison with the baseline, the build time and material volume spent were converted into percent change rather than actual values. Therefore, the data set for the baseline was the null set for both material volume spent and build time (i.e. 0% change). Each data set was converted to percent change with respect to the baseline values.

To determine any statistically significant impact that the application of each guideline might have, 16 single factor ANOVA tests (95% confidence level) were conducted. The null hypothesis in each case was that the application of the guideline had no impact on the build time and material volume for a given component. Each of the 16 tests compares one of the eight guideline data sets to the baseline data set with respect to a performance metric (either material volume or build time). Table 5 shows a sample ANOVA table from the study. The critical components of this table are the F- and P-values, along with the mean and standard deviation values. In this test, C1 is the baseline data and C2 is the data with the guideline applied

Table 5. Sample ANOVA Analysis

Guideline 1: Minimize Height

Results for: Build Time

One-way ANOVA: C1 versus C2

```
Source  DF     SS     MS      F      P
C2       1  16709  16709  39.71  0.000
Error   78  32820    421
Total   79  49530

S = 20.51   R-Sq = 33.74%   R-Sq(adj) = 32.89%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  -----+---------+---------+---------+----
1      40  28.90  29.01                         (----*----)
2      40   0.00   0.00  (----*----)
                         -----+---------+---------+---------+----
                              0        12        24        36

Pooled StDev = 20.51
```

Results for: Material Volume

One-way ANOVA: C1 versus C2

```
Source   DF     SS   MS     F      P
C2        1    691  691  4.34  0.039
Error   128  20368  159
Total   129  21059

S = 12.61   R-Sq = 3.28%   R-Sq(adj) = 2.52%


                        Individual 95% CIs For Mean Based on Pooled StDev
Level   N  Mean  StDev     +---------+---------+---------+---------
1      65  4.61  17.84                    (---------*----------)
2      65  0.00   0.00     (---------*---------)
                           +---------+---------+---------+---------
                        -3.0       0.0       3.0       6.0

Pooled StDev = 12.61
```

Table 6 displays the average percent reduction for the eight candidate guidelines for both build time and material volume spent. Column 3 lists the mean percent decrease in build time under the application of a particular guideline. Column 4 shows the standard deviation of this percent change. Column 5 gives the percent decrease in material volume under the application of a particular guideline. Column 6 shows the standard deviation of this percent change.

Table 6. Mean Percentage Improvement of Performance Metrics for Each Applied Guideline (negative values imply adverse effect)

		Build Time (minutes)		Material Volume (cubic inches)	
Guideline	**N**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
G1	40	17.79	26.71	4.61	17.84
G2	48	17.83	26.83	4.70	17.79
G3	36	16.93	25.97	8.61	13.79
G4	33	14.38	24.83	7.18	12.08
G5	37	12.57	17.82	0.86	12.11
G6	34	35.64	35.84	22.22	30.46
G7	65	32.36	4.16	-4.53	6.29
G8	61	5.63	4.89	1.55	2.85

Note that only G7 (maximize layer thickness) has 65 data points. The seven other guidelines had less than 65 samples. This is because some components needed no design or build change to apply a guideline. As such, the percent change in both metrics would be 0% for that component if it were re-simulated and included. Therefore, these components were ignored when this occurred.

Table 7 summarizes the results of the 16 statistical analyses. This table shows whether or not the improvement is seen for a given performance metric. Additionally, the f-value of this study is given. The extremely low p-values are not surprising given the vast difference in means seen in Table 6. For all cases where the null hypothesis was rejected (i.e. $p < 0.05$), reduction of the performance metrics occurred. The lone exception was the significant finding of G7 with respect to material volume, where the null hypothesis was rejected because there was a statistically significant *increase* in this metric. This is discussed further, along with other findings, in Chapter 7.

Table 7. Overview of Results from ANOVA Analyses

Guideline	Build Time (minutes)	Material Volume (cubic inches)
G1	P-value= 0.0 F-value= 39.71	P-value= 0.04 F-value= 4.34
G2	P-value=0.0 F-value= 33.95	P-value=0.035 F-value= 4.54
G3	P-value=0.0 F-value= 41.83	P-value=0.0 F-value= 25.31
G4	P-value=0.0 F-value= 32.04	P-value=0.0 F-value= 22.95
G5	P-value=0.0 F-value= 19.71	P-value=0.468 F-value= 0.53
G6	P-value=0.0 F-value= 30.46	P-value=0.0 F-value= 26.28
G7	P-value=0.0 F-value= 3935.83	P-value=0.0 F-value= 33.69
G8	P-value=0.0 F-value= 81.06	P-value=0.0 F-value= 17.88

5.2 Correlations between Guidelines

With the quantitative benefits of each guideline individually established, determining the correlations between each guideline was important. In other words, if two guidelines were found to be highly positively correlated, then it would be expected that the implementation of one leads to the similar results as the implementation of the other and one rule might dominate the impact of the other. Conversely, if two guidelines were found to be highly negatively correlated, then the implementation of one would lead to the opposite results of implementing the other.

To determine correlations between guidelines, Pearson correlation indices were calculated in Minitab. A correlation index of 1 means that the two guidelines have an exact positive linear relationship, whereas a correlation of -1 shows an exact negative linear relationship. A correlation index near zero shows that there is no linear relationship present between the two guidelines. Two correlation studies were conducted, one for correlations with respect to build time, and one for correlations with respect to material volume. Table 8 shows the results of the correlation study for build time. These results show the correlations values with their p-values below. Again the significance level was 95%. To read this table, correlation values can be seen between a given guideline column and the corresponding guideline row. Statistically significant results are in bold.

Table 8. Correlation Study for Build Time

	G1	G2	G3	G4	G5	G6	G7
G2	**0.999** **0.000**						
G3	**0.957** **0.000**	**0.953** **0.000**					
G4	**0.961** **0.000**	**0.955** **0.000**	**0.996** **0.000**				
G5	**0.751** **0.002**	**0.746** **0.002**	**0.788** **0.001**	**0.785** **0.001**			
G6	0.202 0.489	0.196 0.503	0.173 0.555	0.156 0.594	0.138 0.639		
G7	-0.208 0.475	-0.212 0.467	-0.264 0.361	-0.302 0.294	-0.113 0.699	0.489 0.076	
G8	0.527 0.053	0.547 0.053	0.429 0.126	0.405 0.151	0.063 0.830	0.537 0.057	0.316 0.271

Several interesting conclusions can be drawn from this table. First, one notes that with respect to build time, there are highly positive linear correlations for all combinations of G1, G2, G3, and G4. G5 also correlates significantly to G1, G2, and G3. No other significant conclusions can be drawn. This would imply that minimizing the height, minimizing the form ratio, minimizing overhangs, and building holes facing upward tend to require similar alterations. Because these can all be achieved through altering the build settings of the FDM machine, it is quite possible that the application of each of these guidelines independently would result in the same build orientation. Minimizing the number of holes also has a significant correlation, though not as linear.

Table 9 below shows the results of the correlation study for material volume. These results show the correlation values with their p-values below. It reads identical to Table 8. Statistically significant results are in bold.

Table 9. Correlation Study for Material Volume

	G1	G2	G3	G4	G5	G6	G7
G2	**0.995**						
	0.000						
G3	**0.826**	**0.810**					
	0.000	**0.000**					
G4	**0.827**	**0.812**	**0.992**				
	0.000	**0.000**	**0.000**				
G5	0.208	0.234	0.188	0.205			
	0.476	0.421	0.520	0.483			
G6	**0.827**	**0.813**	**0.993**	**0.999**	0.191		
	0.000	**0.000**	**0.000**	**0.000**	0.514		
G7	-0.151	-0.191	-0.226	-0.166	0.017	-0.172	
	0.607	0.513	0.436	0.571	0.953	0.557	
G8	0.010	0.013	0.021	-0.058	-0.416	-0.030	-0.255
	0.972	0.965	0.943	0.845	0.139	0.918	0.379

Several interesting conclusions can be drawn from this table. First, one notes that with respect to build time, there are highly positive linear correlations for all combinations of G1, G2, G3, and G6. No other significant conclusions can be drawn. This would imply that minimizing the height, minimizing the form ratio, minimizing overhangs, building holes facing upward, and building the object with the largest surface on the x-y plane tend to require similar alterations. Because these can all be achieved through altering the build settings of the FDM machine, it is quite possible that the application of each of these guidelines independently would result in the same build orientation.

Overall, these results would seem to imply that G7 (maximize layer thickness) and G8 (rotate part 45 degrees around z-axis) have very little relation to the other six guidelines. When examining alterations made to the design to apply these two guidelines, it is apparent that they are not applied in a manner similar to the other highly-correlated guidelines. The results of this study are interesting and appear to show that the application of G1, G2, G3, and G4 probably occur simultaneously by implementing the same alterations. The build time and material volume savings are not additive.

5.3 Initial Design Feature Impact Study

One additional area of study is related to the how the presence of individual design features might affect the benefits provided by applying a particular guideline. One such preliminary study has been examined. This analysis attempted to infer any significance in the presence of curved features or overhangs on the 45 degree rotation guideline (G8).

The prevalence of curved features and overhangs in the default orientation was noted for each component in repository to conduct a two-factor ANOVA. Two levels of prevalence were possible for each factor. A value of 0 denotes that the factor is not at all present in the part or has very little presence. A value of 1 denotes that the factor is widespread in the component. These values were intended to be subjective and were assigned to the components by the author. For example, a part with very few overhangs in comparison to the total material volume used, or without any overhang at all, will receive a 0 for the overhang factor. The following parts are examples of showing different levels of factors.

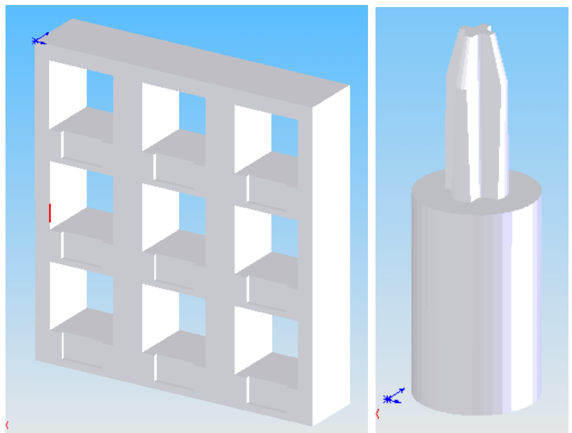


Figure 21. Part #9 from the repository with an overhang factor of 1 and a curve factor of 0 (Left) and Part #63 from the repository with an overhang factor of 0 and a curve factor of 1 (Right)

A two-factor ANOVA analysis was conducted, and the results can be seen in Table 10.

Table 10. 2-Factor ANOVA Analysis on the Effect of Curved Features and Overhangs on G8

Two-way ANOVA: % versus curve, overhang

Source	DF	SS	MS	F	P
curve	1	267.488	267.488	16.07	0.000
overhang	1	0.037	0.037	0.00	0.963
Error	25	416.099	16.644		
Total	27	683.623			

S = 4.080   R-Sq = 39.13%   R-Sq(adj) = 34.26%

```
                Individual 95% CIs For Mean Based on
                Pooled StDev
curve     Mean  -------+---------+---------+---------+--
0      9.22004                     (-------*------)
2      3.03841  (------*-------)
                -------+---------+---------+---------+--
                     3.0       6.0       9.0      12.0
```

```
                   Individual 95% CIs For Mean Based on
                   Pooled StDev
overhang     Mean  --------+---------+---------+---------+-
0         6.16542   (-----------------*------------------)
2         6.09303  (------------------*-----------------)
                   --------+---------+---------+---------+-
                         4.8       6.0       7.2       8.4
```

From Table 4, one can conclude that there is no significant evidence of a curve-overhang interaction effect or an overhang effect because of a p-value greater than the acceptable alpha value (0.05). However, the p-value for the curve factor of 0 is less than the alpha level of 0.05. Therefore, there is evidence that the presence of curved features has an effect on the reduction of build time for a given component. This is supported by a brief analysis of the raw data. Without curved features, the average reduction of build time is 9.2%, whereas only a 3 % reduction is seen in parts with curved features. Thus, one can conclude that the presence of more curved features in a part will result in less reduction in build time by making a 45° rotation. Similar studies to this one need to be conducted for a variety of features as related to all guidelines. The ability to determine important factors contributing to the performance of these guidelines will be critical in evaluating the feasibility of each potential guideline. Further discussion on these areas of future work is found in Chapter 8.

Chapter 6: Qualitative Analysis through Case Studies

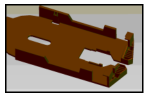
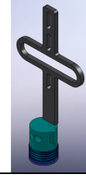
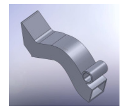
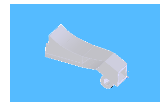
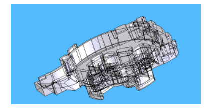
The quantitative study results of Chapter 5 determine the effectiveness of the candidate guidelines in reducing build time and material volume. These metrics represent critical characteristics in the use of FDM, but they are not the sole determining characteristics. Equally important is that these candidate guidelines must not impair the functionality of the component to which they are being applied. In order to make this determination, an exploratory qualitative analysis was needed. The purpose of conducting the qualitative study through example cases was to determine if any of the guidelines were infeasible to implement independent of their simulated performance as judged by Catalyst™. This is an initial exploration for the sole purpose of determining if there exist fundamental conflicts between the application of a particular guideline and the functionality of the component to which it is applied.

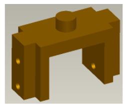
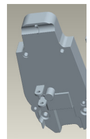
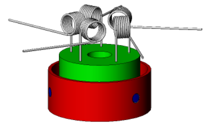
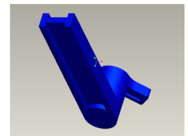
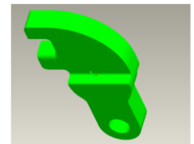
Each information sheet that was submitted as outlined in Section 3.4 was analyzed to determine if the implementation of each guideline would maintain the component's functionality and performance as intended by the designer. For example, the application of a particular guideline might be proven through a simulation study to have a very beneficial impact on build time and/or volume. However, one might find it impossible to implement that guideline in a real design scenario without significantly impacting the component's intended function.

The applicability of implementing each guideline independently on the described component was determined. For each sample component, several factors went into determining this applicability. These included build space (i.e. would applying a guideline not allow the component to fit into the 8" by 8" by 12" build space), loss of a critical function, elimination of a feature interacting with another component, and other various factors that were deemed by the author to diminish or eliminate the functionality or performance of the component in question.

For each prototyping information sheet, each guideline was marked as either "yes" or "no" with respect to the ability to feasibly implement that guideline on the described component. For cases in which it was determined to be infeasible, reasoning for its infeasibility was noted on the information sheet. A summary of the results from this qualitative examination can be seen in Table 11. Each column represents a component described on an information sheet. Each row lists whether or not a guideline could be feasibly applied to a given component.

Table 11. Feasibility of Implementing Each Guideline for 11 Case Studies

Guideline	Information Sheet					
	1 	2 	3 	4 	5 	6 
Minimize Height along z-axis	yes	yes	yes	yes	yes	yes
Minimize Form Ratio	yes	yes	yes	yes	yes	yes
Minimize Number of Overhangs	yes	yes	yes	yes	yes	yes
Build Holes Facing Upward	yes	yes	yes	yes	yes	yes
Minimize Number of Holes	no	no	no	no	no	no
Build Object with Largest Surface on Bottom	yes	yes	yes	yes	yes	yes
Maximize Layer Thickness	yes	yes	yes	yes	yes	yes
Rotate build 45 degrees around z-axis	yes	yes	yes	yes	yes	yes

Guideline	Information Sheet				
	7 	**8** 	**9** 	**10** 	**11** 
Minimize Height along z-axis	yes	yes	yes	yes	yes
Minimize Form Ratio	yes	yes	yes	yes	yes
Minimize Number of Overhangs	yes	yes	yes	yes	yes
Build Holes Facing Upward	yes	yes	yes	yes	yes
Minimize Number of Holes	no	no	no	no	no
Build Object with Largest Surface on Bottom	yes	yes	yes	yes	yes
Maximize Layer Thickness	yes	yes	yes	yes	yes
Rotate build 45 degrees around z-axis	yes	no	yes	yes	yes

By examining this data, one can determine the percentage of cases in which a particular guideline was feasible. Table 12 shows the percentage of successful applications for each guideline.

Table 12. Percentage of Successful Applications for Each Guideline

Guideline	Percentage Success
Minimize Height along z-axis	100.0
Minimize Form Ratio	100.0
Minimize Number of Overhangs	100.0
Build Holes Facing Upward	100.0
Minimize Number of Holes	0.0
Build Object with Largest Surface on Bottom	100.0
Maximize Layer Thickness	100.0
Rotate build 45 degrees around z-axis	90.9

These results imply several interesting conclusions. First, it is important to note that Guidelines 1, 2, 3, 4, 6, and 7 were feasible to apply on all eleven of the example cases. On the other extreme, Guideline 5 (eliminate holes) was infeasible on all 11 example cases. Guideline 8 had mixed feasibility. As hoped, this exploratory analysis was able to identify a definitive conflict between maintaining functionality and implementing a particular guideline. In this case, eliminating holes appears to be infeasible as a guideline, due to its universal degradation of component functionality. Chapter 7 will discuss potential reasons for why these results may have occurred in further detail.

The 11 example cases were next examined to determine the overall performance of applying the final set of proposed guidelines. The build of each example case was first simulated in Catalyst™ to determine baseline values for both build time and material volume. Then, all proposed guidelines (excluding G5 and G7 as previously explained) were simultaneously applied to each example case. This resulted in two sets of data for each case (one baseline, and one with guidelines applied). Two paired t-tests were then employed to determine if there existed significant reduction in either material volume or build time.

First, the baseline build times were compared to the set of data resulting from applying the guidelines simultaneously. The results of the paired t-test from Minitab can be seen below in Table 13. In this table, C1 is the baseline build time of the 11 example cases. C2 is the build time associated with the 11 components after all guidelines were simultaneously applied.

Table 13. Paired t-test Results from Minitab for Build Time

Paired T-Test and CI: C1, C2

```
Paired T for C1 - C2

             N   Mean  StDev  SE Mean
C1          11  161.8  174.2     52.5
C2          11  109.2  113.9     34.3
Difference  11   52.6   79.7     24.0


95% CI for mean difference: (-0.9, 106.2)
T-Test of mean difference = 0 (vs not = 0): T-Value = 2.19  P-Value = 0.053
```

The results of this show that the mean build time after guideline application (109.2 minutes) is much lower than the mean build time of the baseline (161.8 minutes). This is a 32.5% reduction. Additionally, the p-value of this test was equal to 0.053. Therefore, one can be more than 94% sure that these data show a statistically-significant reduction in build time after applying the guidelines. Because the sample size is very small (N=11), one would expect this to cross the 95% confidence level threshold with a few more samples if the results are typical.

An additional t-test was conducted to determine the level of significance in reducing the material volume of the example cases. Again, all six final proposed guidelines were applied simultaneously to the 11 example cases and material volume data was collected. Using the paired t-test, this data set was compared to the baseline simulations. The results of this test can be seen in Table 14 below. In this table, C1 is the baseline material volume of the 11 example cases. C2 is the material volume associated with the 11 components after all guidelines were simultaneously applied.

Table 14. Paired t-test Results from Minitab for Material Volume

Paired T-Test and CI: C4, C5

```
Paired T for C4 - C5

             N   Mean  StDev  SE Mean
C4          11  1.852  2.254    0.680
C5          11  1.597  1.979    0.597
Difference  11  0.255  0.469    0.141


95% CI for mean difference: (-0.060, 0.569)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1.80  P-Value = 0.102
```

The results of this show that the mean value for material volume after guideline application (1.597 cubic inches) is lower than the mean build time of the baseline (1.852 cubic inches). This is a 14% reduction. Additionally, the p-value of this test was equal to 0.102. Therefore, 90 out of every 100 experiments in which these guidelines are applied will result in a statistically-significant reduction in material volume. Again, because the sample size was only 11, it is expected that several more samples would allow the p-value to cross below the 0.05 threshold.

From this assessment of example cases in an exploratory qualitative manner, one can draw several conclusions. First, the list of qualifying guidelines after the quantitative analysis in Chapter 5 was examined with respect to actual design scenarios. The results of this study showed that an additional candidate guideline needed to be excluded from the final proposed list (that which does not include G5 or G7). The remaining candidate guidelines were then simultaneously applied to the set of example cases. The results of this study show that a reduction in build time and material volume were present at a fairly high confidence level. It would be useful to conduct a similar study with more samples to gather more information. Further discussion on these results can be seen in Chapter 7.

Chapter 7: Discussion of Results

7.1 Quantitative Data

The results of these statistical analyses are very interesting. First, one can see that minimizing height (G1), minimizing form ratio (G2), minimizing overhangs (G3), building holes facing upward (G4), building with the largest surface on bottom (G6), and rotating 45 degrees (G8) show statistically significant improvement both in reducing build time and material volume spent. As such, these can be added to the first iteration of the proposed guidelines for FDM.

Perhaps more interesting are the results stemming from minimizing the number of holes and maximizing the layer thickness. Chapter 5 showed that minimizing the number of holes provided a statistically significant improvement in reducing the build time. However, it did not provide any measurable improvement in reducing the material volume spent. This result is counter-intuitive for a novice FDM user. Yet, this is an expected result because FDM often places support material to fill in an empty region (such as a hole). Despite a lack of significant improvement, this would still appear to be a candidate for the first iteration of guidelines due to the lack of adverse impact. While it appears to qualify based on the quantitative results, it does not yet consider the impact of the qualitative study.

The effectiveness of G7, maximizing the layer thickness, is another interesting case. Much like minimizing the number of holes, maximizing the layer thickness resulted in a statistically significant reduction in build time. This is intuitive because few layers results in fewer nozzle passes. For example, the part shown in Figure 12 was built in six fewer layers. However, it also showed a statistically significant increase in material volume spent. The logic behind this is based on the fact that the minimum feature width that the machine is able to produce under these new settings is 0.013” rather than 0.01”. Therefore, for very small features, the machine is forced to lay down more material than the designer specified. Over the course of building an entire component, these minimal increases in material result in a component that is comprised of significantly more material. This was the only potential guideline of the eight tested that had an adverse impact on either metric, let alone a statistically significant change. Because of the presence of a significant negative effect, it would be difficult to include this guideline in the first iteration of the guidelines for FDM. However, it could be considered a conditional guideline which is only applied when lead time is the critical and dominant factor in dictating the use of FDM to manufacture a given component.

Correlations between the guidelines were also determined in Chapter 5. These showed that G7 (maximize layer thickness) and G8 (rotate part 45 degrees around z-axis) have very little relation to the other six guidelines. Additionally, the results appear to show that the application of G1, G2, G3, and G4 probably require the implementation of the same alterations.

After conducting the statistical analyses, the first iteration of guidelines for FDM is defined. This list is composed of all guidelines that had at least one statistically significant improvement of a performance metric and had no statistically significant adverse effects on either performance metric. After this initial study, only one candidate guideline was eliminated. Table 15 shows the surviving guideline list below:

Table 15. Candidate List of Guidelines after Quantitative Study Only

Guideline
1. Minimize Height
2. Minimize Form Ratio
3. Minimize Number of Overhangs
4. Build Holes Facing Upward
5. Eliminate Holes
6. Build Object with Largest Surface on Bottom
7. Rotate build 45 degrees

7.2 Qualitative Data

Much like the quantitative study employing simulations, the results of the qualitative analysis using example cases were very interesting. First, one notices that Guidelines 1, 2, 3, 4, 6, and 7 all had 100% applicability success rates. Examining these guidelines individually puts these results into context.

Guideline 1 is minimizing the build height in the z-direction. It seems logical that this would be feasible in all cases in which no dimension (x, y, or z) exceeded 8”. In other words, the only cases in which Guideline 1 could not be implemented would be when minimizing the z height resulted in either the x or y dimensions being larger than 8” (thus exceeding the x and/or y capacity of the machine).

Guideline 2 is minimizing the form ratio. Again, this is a build guideline that only alters the component’s orientation within the machine. The only case in which minimizing the form ratio would be infeasible would be when doing so causes an x or y dimension to be exceeded.

Guideline 3 asks the user to minimize the number of overhangs by altering the orientation of the component. The only cases in which this can't be applied are if there are no overhangs, or where there are an equal number of overhangs no matter what the build orientation of the component.

Guideline 4 asks the designer to build holes facing upward. This was applicable in all cases because doing so did not violate the geometry exceeding the 8" by 8" by 12" capacity.

Guideline 6 requires building the component with its largest surface on the x-y plane at z = 0". Like the other guidelines that were seen to have 100% applicability in this limited study, it is applicable on any component unless that bottom surface has an x or y dimension exceeding 8". In the case of these examples, no component exceeded this 8" by 8" limit.

Guideline 7, where layer thickness was maximized, was the final guideline with 100% applicability. As this is purely a build setting that does not alter the orientation of the component, it is applicable to any part. From the quantitative analysis, it was considered a conditional guideline to only be applied when lead time is paramount. However, it was still examined in the qualitative analysis to determine it's applicability in these conditional scenarios.

Examining the two guidelines that had less success provides more interesting insight. Guideline 5, eliminate holes, was applicable on zero of the 11 example cases. Because it requires the user to eliminate all holes, functional feasibility was a very large concern. In all 11 example cases, the holes present in the component were integral to the functionality of the device. In other words, eliminating the holes in these components would result in a part that might not perform its function as intended by the designer. This study did not consider the possibility that these holes could be drilled during post-processing to allow for full functionality. Further studies would have to be conducted to determine the feasibility, time, and accuracy issues with creating the holes in this manner. It is interesting to note that this was the only guideline that had significant feasibility issues.

Guideline 8, rotate part 45 degrees around z-axis, was the only remaining guideline that lacked 100% applicability in the 11 example cases. In the one case of infeasibility, it occurred because doing so caused the component to exceed 8" in the x-direction. Consequently, the rule could not be applied. However, there do not appear to be any fundamental conflicts between applying this guideline and maintaining component functionality.

From this qualitative study, it can be seen that six of the seven candidate guidelines (not considering the conditional G7) proved to be feasible with respect to implementation for the 11 example cases. However, Guideline 5 (eliminate holes) proved to be infeasible in every case. As such, it seems reasonable to eliminate this guideline from the candidate list. Although it was shown to reduce the build time of components in a statistically significant manner, this initial qualitative study shows that it most likely has feasibility issues with respect to implementation.

This final set of six guidelines was then applied simultaneously to each of the 11 example cases. The two sets of data relating to build time and material volume were then compared to the baseline using paired t-tests. These analyses showed promising data that can lead one to conclude that applying the final proposed set of guidelines simultaneously will reduce the build time and material volume of a given component.

7.3 Final Candidate List

From the results of both the quantitative and qualitative aspects of this research, it is imperative to re-examine the initial candidate list and see which guidelines have been shown to be beneficial and feasible, and which guidelines should be eliminated from the candidate list. The results of the quantitative analysis showed that minimizing height, minimizing form ratio, minimizing overhangs, building holes facing upward, building with the largest surface on bottom, and rotating 45 degrees all showed statistical improvement in both categories. Additionally, none of these guidelines had implementation problems in the 11 example cases.

The quantitative simulation study also found that minimizing the number of holes only had an impact on reducing the build time of the component. Additionally, the implementation of this guideline in the 11 example cases proved to be completely infeasible. Therefore, it would seem logical to eliminate this guideline from the final candidate list.

The guideline yet to be discussed is that of maximizing the layer thickness. The quantitative study showed its application to have a significant improvement on build time. However, it also determined that it had a statistically negative impact on material volume. In the qualitative portion of the research, there were no feasibility issues with its implementation. However, it was noted that parts requiring a fine surface quality or containing very small features would have issues in maximizing the layer thickness. As such, it would only seem logical to implement this guideline when build time is critical and no small features are present. Additionally, surface quality must also not be a critical factor. Due to the fact that there are limited cases in which this guideline would be both beneficial and feasible, it was not included in the final candidate list. With all eight original candidates examined, the final candidate list can be seen in Table 16.

Table 16. Final List of Proposed Guidelines

Proposed Guideline
1. Minimize Height
2. Minimize Form Ratio
3. Minimize Number of Overhangs
4. Build Holes Facing Upward
5. Build Object with Largest Surface on Bottom
6. Rotate build 45 degrees

Chapter 8: Conclusions and Future Work

As FDM becomes a more attractive production option in various scenarios, the development of a set of guidelines will become increasingly useful. While some existing research has been completed in this area, much of it focuses on improving the FDM process itself, rather than helping a designer improve his or her part to be most effectively produced using the FDM process in its current form

An initial set of proposed guidelines for FDM has been based upon the analysis of the data collected from the simulations and from a qualitative examination of example cases. The initial candidate list has been narrowed down two six guidelines by determining the quantitative impact that these guidelines had on performance metrics along with their qualitative feasibility. Research suggests that the implementation of these guidelines should result in a reduction in build time and material volume spent on most components manufactured using FDM. However, the two candidate guidelines withheld from the proposed list (maximize layer thickness and eliminate holes) may warrant further in-depth examination. The application of the six final proposed guidelines should be possible in almost all scenarios.

8.1 Contributions

The contributions of this work can be established by re-examining the research questions posed in Chapter 1.

What are the most critical metrics associated with Fused Deposition Modeling that directly dictate the feasibility of its use as a small-volume manufacturing process?

Through the literature review in Chapter 2, it was determined that FDM is becoming a feasible technology for use in the manufacture of plastic components in small volumes. The driving factor is that unlike a process like injection molding, there are no tooling costs associated with FDM. Because decreasing the costs of FDM should correlate with an increase in its use as a manufacturing process, metrics directly related to cost were identified. Material volume and build time are critical factors that were identified in this study for assessing the effectiveness of the guidelines. In addition, because these values could be simulated within Catalyst™, changes in these values could be determined through simulation.

What guidelines or rules can be applied to all varieties of components to improve the defined metrics in a statistically significant manner?

Chapter 4 introduced a candidate set of guidelines that was developed by both the author's extensive experience with FDM and through guidelines proposed in existing literature. Once this candidate list was created, each guideline was systematically applied to a large and varied set of components. By simulating a baseline set of build data and eight sets of data (one pertaining to each guideline) in Catalyst™, information on build time and material volume was gathered.

From this point, ANOVA analyses were conducted to determine if there were significant changes in either build time or material volume used. Those candidate guidelines which provided a statistically significant improvement in one or both categories (while showing no statistically significant negative impact in either) comprise an initial list that responds to this second research question. Additionally, correlations between the applications of each guideline were determined.

Of the guidelines that significantly improve the defined metrics, which guidelines can be implemented without changing the functionality of the component?

With seven guidelines showing universal improvement with respect to the two established metrics, an exploratory qualitative analysis was undertaken to determine whether or not these guidelines could be applied to components without altering their functionality. By gathering example cases of actual design projects, the candidate guidelines could be examined in actual design scenarios. Qualitative judgments were made by the author (based on familiarity with the design projects themselves) as to whether or not a particular candidate guideline could be applied without sacrificing functionality. The result was the determination that G5, minimizing holes, could not be implemented in any of the example cases without losing some level of functionality. As such, it was eliminated from the final list.

The result of all aspects of this research is a set of six proposed guidelines that displayed quantitative improvement in critical FDM performance metrics while maintaining component functionality. The application of the final entire set of proposed guidelines simultaneously to the example cases showed promising data that material volume and build time can be significantly reduced by implementing the set of proposed guidelines

From the results of this work, it is suggested that these proposed guidelines be implemented in practice. By introducing build managers of FDM systems to these proposed guidelines, their success can be tested in-situ. Because they have been shown initially to offer significant improvement without sacrificing performance, implementation should be universally beneficial. Additionally, introducing these guidelines to designers or students in design classes will help integrate the proposed guidelines into practice. With these potential guidelines identified in a systematic manner with established benefit, the probability of successful implementation is reasonable.

8.2 Future Work

Future work lies in several areas. First and foremost, further guidelines need to be identified. One would not expect the proposed guidelines from this study to be an all-encompassing list. As new candidate guidelines are identified, they can be validated by the methodology developed in this study

Another area of future work should further examine the interactions that may be present between guidelines. As discussed in Section 4.2, conducting further correlation studies is an crucial area in which further research needs top be conducted. The brief study conducted in Section 4.2 shows that the presence of curved features has a significant impact on the amount of build time reduced by applying Guideline 8. There are many other interactions between certain design features and the effectiveness of applying a particular guideline that need to be identified. The determination of these correlations and interactions can play a significant role in the refinement of the list of guidelines, or in the conditions under which certain combinations should be avoided.

Another possible concern is that two different guidelines are fundamentally incompatible to the point at which it would be impossible to simultaneously apply both to one design. If this is determined to be an issue between particular sets of guidelines, one will have to further examine which conflicting guideline is most beneficial. Further iterations of the set of guidelines should list any potential conflicts along with an order of preference between conflicting guidelines.

With many further areas of research defined, the refining of the set of guidelines for FDM is a non-trivial task. Eventually, this area of research should result in a robust set of rules that can fundamentally reduce the costs associated with FDM and can assist its ascent as a feasible full-scale manufacturing process.

Appendix 1: ANOVA Results

Guideline 1: Minimize Height

Results for: Build Time

One-way ANOVA: C1 versus C2

```
Source  DF     SS     MS      F      P
C2       1  16709  16709  39.71  0.000
Error   78  32820    421
Total   79  49530

S = 20.51   R-Sq = 33.74%   R-Sq(adj) = 32.89%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  -----+---------+---------+---------+----
1      40  28.90  29.01                          (----*----)
2      40   0.00   0.00  (----*----)
                         -----+---------+---------+---------+----
                              0        12        24        36

Pooled StDev = 20.51
```

Results for: Material Volume

One-way ANOVA: C1 versus C2

```
Source   DF     SS   MS     F      P
C2        1    691  691  4.34  0.039
Error   128  20368  159
Total   129  21059

S = 12.61   R-Sq = 3.28%   R-Sq(adj) = 2.52%


                        Individual 95% CIs For Mean Based on Pooled StDev
Level   N  Mean  StDev     +---------+---------+---------+---------
1      40  4.61  17.84                    (---------*----------)
2      40  0.00   0.00     (---------*---------)
                           +---------+---------+---------+---------
                        -3.0       0.0       3.0       6.0

Pooled StDev = 12.61
```

Guideline 2: Minimize Form Ratio

Results for: Build Time

One-way ANOVA: C1 versus C2

```
Source  DF     SS     MS      F      P
C2       1  13997  13997  33.95  0.000
Error   94  38751    412
Total   95  52749

S = 20.30   R-Sq = 26.54%   R-Sq(adj) = 25.75%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ------+---------+---------+---------+---
1      48  24.15  28.71                         (-----*-----)
2      48   0.00   0.00  (-----*-----)
                         ------+---------+---------+---------+---
                               0        10        20        30

Pooled StDev = 20.30
```

Results for: Material Volume

One-way ANOVA: C1 versus C2

```
Source   DF     SS   MS     F      P
C2        1    718  718  4.54  0.035
Error   128  20251  158
Total   129  20969

S = 12.58   R-Sq = 3.42%   R-Sq(adj) = 2.67%


                        Individual 95% CIs For Mean Based on Pooled StDev
Level   N  Mean  StDev     +---------+---------+---------+---------
1      48  4.70  17.79                    (----------*---------)
2      48  0.00   0.00     (---------*---------)
                           +---------+---------+---------+---------
                        -3.0       0.0       3.0       6.0
```

Guideline 3: Minimize Number of Overhangs

Results for: Build Time

One-way ANOVA: C1 versus C2

```
Source  DF     SS     MS      F      P
C2       1  16816  16816  41.83  0.000
Error   70  28144    402
Total   71  44960

S = 20.05   R-Sq = 37.40%   R-Sq(adj) = 36.51%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ------+---------+---------+---------+---
1      36  30.57  28.36                             (----*-----)
2      36   0.00   0.00  (-----*-----)
                         ------+---------+---------+---------+---
                               0        12        24        36

Pooled StDev = 20.05
```

Results for: Material Volume

One-way ANOVA: C1 versus C2

```
Source   DF       SS      MS      F      P
C2        1   2406.7  2406.7  25.31  0.000
Error   128  12173.4    95.1
Total   129  14580.1

S = 9.752   R-Sq = 16.51%   R-Sq(adj) = 15.85%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N   Mean   StDev  -------+---------+---------+---------+--
1      36  8.605  13.792                              (------*-----)
2      36  0.000   0.000  (------*------)
                          -------+---------+---------+---------+--
                               0.0       3.5       7.0      10.5

Pooled StDev = 9.752
```

Guideline 4: Build Holes Facing Upward

Results for: Build Time

One-way ANOVA: C1 versus C2

```
Source  DF     SS     MS      F      P
C2       1  13230  13230  32.04  0.000
Error   64  26431    413
Total   65  39661

S = 20.32   R-Sq = 33.36%   R-Sq(adj) = 32.32%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ------+---------+---------+---------+---
1      33  28.32  28.74                         (-----*----)
2      33   0.00   0.00  (-----*-----)
                         ------+---------+---------+---------+---
                               0        12        24        36

Pooled StDev = 20.32
```

Results for: Material Volume

One-way ANOVA: C1 versus C2

```
Source   DF       SS      MS      F      P
C2        1   1675.6  1675.6  22.95  0.000
Error   128   9343.4    73.0
Total   129  11019.0

S = 8.544   R-Sq = 15.21%   R-Sq(adj) = 14.54%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N   Mean   StDev  -------+---------+---------+---------+--
1      33  7.180  12.083                          (------*------)
2      33  0.000   0.000  (------*------)
                          -------+---------+---------+---------+--
                               0.0       3.0       6.0       9.0

Pooled StDev = 8.544
```

Guideline 5: Minimize Number of Holes

Results for: Build Time

One-way ANOVA: C1 versus C2

```
Source  DF     SS    MS      F      P
C2       1   3415  3415  19.71  0.000
Error   72  12474   173
Total   73  15889

S = 13.16   R-Sq = 21.49%   R-Sq(adj) = 20.40%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  -------+---------+---------+---------+--
1      37  13.59  18.61                        (-------*------)
2      37   0.00   0.00  (------*------)
                         -------+---------+---------+---------+--
                              0.0       6.0      12.0      18.0

Pooled StDev = 13.16
```

Results for: Material Volume

One-way ANOVA: C1 versus C2

```
Source  DF      SS    MS     F      P
C2       1    42.1  42.1  0.53  0.468
Error   72  5697.6  79.1
Total   73  5739.7

S = 8.896   R-Sq = 0.73%   R-Sq(adj) = 0.00%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N   Mean   StDev  -----+---------+---------+---------+----
1      37  1.508  12.580          (--------------*-------------)
2      37  0.000   0.000  (--------------*--------------)
                          -----+---------+---------+---------+----
                            -2.0       0.0       2.0       4.0

Pooled StDev = 8.896
```

Guideline 6: Build Object with Largest Surface on Bottom

Results for: Build Time

```
Source  DF     SS     MS      F      P
C2       1  13389  13389  30.46  0.000
Error   66  29013    440
Total   67  42402

S = 20.97   R-Sq = 31.58%   R-Sq(adj) = 30.54%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ------+---------+---------+---------+---
1      34  28.06  29.65                        (-----*-----)
2      34   0.00   0.00  (-----*-----)
                         ------+---------+---------+---------+---
                               0        12        24        36

Pooled StDev = 20.97
```

Results for: Material Voume

One-way ANOVA: C1 versus C2

```
Source  DF     SS    MS      F      P
C2       1   2903  2903  26.28  0.000
Error   66   7291   110
Total   67  10194

S = 10.51   R-Sq = 28.48%   R-Sq(adj) = 27.40%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ------+---------+---------+---------+---
1      34  13.07  14.86                       (-----*-----)
2      34   0.00   0.00  (-----*-----)
                         ------+---------+---------+---------+---
                             0.0       6.0      12.0      18.0

Pooled StDev = 10.51
```

Guideline 7: Maximize Layer Thickness

Results for: Build Time

One-way ANOVA: C1 versus C2

```
Source    DF        SS        MS        F      P
C2         1  34026.22  34026.22  3935.83  0.000
Error    128   1106.59      8.65
Total    129  35132.81

S = 2.940   R-Sq = 96.85%   R-Sq(adj) = 96.83%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  -+---------+---------+---------+--------
1      65  32.357  4.158                                 *)
2      65   0.000  0.000  (*)
                          -+---------+---------+---------+--------
                           0        10        20        30

Pooled StDev = 2.940
```

Results for: Material Volume

One-way ANOVA: C1 versus C2

```
Source    DF      SS     MS      F      P
C2         1   667.2  667.2  33.69  0.000
Error    128  2535.4   19.8
Total    129  3202.6

S = 4.451   R-Sq = 20.83%   R-Sq(adj) = 20.22%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  --------+---------+---------+---------+-
1      65  -4.531  6.294  (----*-----)
2      65   0.000  0.000                         (----*----)
                          --------+---------+---------+---------+-
                               -4.0      -2.0       0.0       2.0

Pooled StDev = 4.451
```

Guideline 8: Rotate 45 degrees

Results for: Build Time

One-way ANOVA: C1 versus C2

```
Source   DF      SS     MS      F      P
C2        1   968.4  968.4  81.06  0.000
Error   120  1433.5   11.9
Total   121  2401.8

S = 3.456   R-Sq = 40.32%   R-Sq(adj) = 39.82%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ----+---------+---------+---------+-----
1      61  5.635  4.888                             (---*----)
2      61  0.000  0.000  (---*---)
                         ----+---------+---------+---------+-----
                           0.0       2.0       4.0       6.0

Pooled StDev = 3.456
```

Results for: Material Volume

One-way ANOVA: C1 versus C2

```
Source   DF      SS     MS      F      P
C2        1   71.64  71.64  17.88  0.000
Error   122  488.70   4.01
Total   123  560.34

S = 2.001   R-Sq = 12.79%   R-Sq(adj) = 12.07%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  -------+---------+---------+---------+--
1      61  1.520  2.830                       (------*------)
2      61  0.000  0.000  (------*------)
                         -------+---------+---------+---------+--
                              0.00      0.70      1.40      2.10

Pooled StDev = 2.001
```

Bibliography

1. Wohlers, T. 2008. *Wohlers Report 2008 - State of the Industry Annual Worldwide Progress Report*, Wohlers Associates Inc.
2. Watson, K., D. Peterson, and R. Crockett, "Application of Solid Freeform Fabrication Technolody to NASA exploration missions", 1999, Proceedings from the SFF Symposium, Austin, Texas, pp. 857-864.
3. Czajkiewicz, Z., 2008, "Direct Digital Manufacturing- New Product Development and Production Technology", ORGMASZ, **2**(2), pp. 29-37.
4. http://finance.yahoo.com/news/RedEye-On-Demand-is-First-bw-14255281.html
5. Peres, F. and C. Martin, 1999, "Design Methods Applied to the Selection of a Rapid Prototyping Resource", IEEE Symposium on Emerging Technologies and Factory Automation. **1**, pp. 417-422.
6. Medellin, H., T. Lim, J. Corney, J.M. Ritchie, and J.B.C. Davies, 2005, "Automatic Decomposition and Refinement of Oversized Components for Rapid Prototyping", Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. **2**(B), pp. 1283-1293.
7. Jee, H. and E. Sachs, 2000, "Surface Macro-texture Design for Rapid Prototyping", Rapid Prototyping Journal. **6**(1), pp. 50-59.

8. Sambu, S.,Y. Chen, and D. Rosen., 2004, "Geometric Tailoring: A Design for Manufacturing Method for Rapid Prototyping and Rapid Tooling", Journal of Mechanical Design, **126**, pp. 571-580.
9. Filippi, S. and I. Cristofolini, 2007, "The Design Guidelines (DGLs), a Knowledge-based System for Industrial Design Developed Accordingly to ISO-GPS (Geometrical Product Specifications) Concepts", Research in Engineering Design. **18**(1), pp. 1-19.
10. Yan, X. and P. Gu, 1996, "A Review of Rapid Prototyping Technologies and Systems", Computer-Aided Design. **21**(3), pp. 307-318.
11. CADCAMNET, http://www.cadcamnet.com
12. Dieter G. E. and L. C. Schmidt, *Engineering Design*, 4th ed., McGraw-Hill, New York, 2009, pp.558-665.
13. Bralla, J.R. *Design for Manufacturability Handbook*, 2nd ed., McGraw-Hill, New York, 1999.
14. Anderson, D.M., *Design for Manufacturability*, 2nd ed., CIM Press, Cambria, CA, 2001.
15. Malloy, *Plastic Part Design for Injection Molding*, Hanser Publishers, New York, 1994.
16. CustomPartNet, http://www.custompartnet.com/wu/InjectionMolding#design_rules
17. Dimitrov, D., K. Schreve, A. Taylor, and B. Vincent, 2007, "Rapid Prototyping Driven Design and Realization of Large Components", Rapid Prototyping Journal, **13**(2), pp. 85-91

18. Z Corporation 3D Printing Technology http://www.zcorp.com/documents/108_3D%20Printing%20White%20Paper%20FINAL.pdf

19. Thrimurthulu, K., P. Pandey, and N. Reddy, 2004, “Optimum Part Deposition Orientation in Fused Deposition Modeling”, International Journal of Machine Tools and Manufacture, 44, pp. 585-594.

20. Cristofolini, I., S. Filippi, and C. Bandera, 2006, “How Rapid Prototype Processing Parameters could affect the Product Design Phase: A KBS Approach”, Proceedings of 2006 ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, September 10-13 2006, Philadelphia, PA.

21. Han, W., M. Jafari, and K. Seyed, 2003, “Process Speeding up via Deposition Planning in Fused Deposition-Based Layered Manufacturing Processes”, Rapid Prototyping Journal, **9**(4), pp. 212-218.

22. Pandey, P.M., N.V. Reddy, and S.G. Dhande, 2003, “Real Time Adaptive Slicing for Fused Deposition Modelling”, International Journal of Machine Tools and Manufacture, 43, pp. 61-71.

23. Hopkinson, N. and P. Dickens, 2002, “Analysis of Rapid Manufacturing-Using Layer Manufacturing Processes for Production”, Institution of Mechanical Engineers Journal of Mechanical Engineering Science, **217**(C), pp. 31-39.

24. Hague, R. S. Mansour, and N. Saleh, 2004, "Material and Design Considerations for Rapid Manufacturing" International Journal of Production Research, **42**(22), pp. 4691-4708.

25. Teitelbaum, G., Y. Goear, and L. Schmidt, 2009, "Examining Potential Design Guidelines for use in Fused Deposition Modeling to Reduce Build Time and Material Volume", to appear in ASME IDETC 2009. Accepted April 12, 2009.