

**ENHANCING AWARENESS OF ADDITIVE AND SUBTRACTIVE
MANUFACTURABILITY WITH VIRTUALIZED VOXEL-BASED
SIMULATIONS**

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by

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To the students of ME2110

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SUMMARY

Manufacturing challenges are often introduced during the design process, and designers must be capable of designing components in such a way to minimize these challenges. Frequently, mechanical engineering students are too inexperienced to consider the limitations that manufacturing processes impose upon design, and they often design parts that are either difficult or impossible to manufacture. Students must be competent in design-for-manufacturability to be able to design parts that are readily realizable. Students often turn to additive manufacturing processes when they need to make a part for any application, which is not always the best choice. The goal of this work is to develop a framework to rapidly provide students with the knowledge they need to fluidly move between mindsets for additive and subtractive manufacturing processes. This thesis presents the design, implementation and analysis of a system for educating undergraduate students about manufacturability considerations; groups of students were given training in a software package that provides visualizations of the turning process and trained on the operation of CNC machine tools. Knowledge assessments were given to the students to measure their understanding of a variety of topics in manufacturability. A control group, who also completed the knowledge assessments, was not provided with access to the visualization software and only completed manual machining training. Analysis of the survey results indicates that student understanding of geometrical limitations in turning can be dramatically improved by employing such visualizations; however, students' choice of a manufacturing process for a given part was mostly unaffected.

1 INTRODUCTION

Engineering students are frequently unaware of the challenges and part design considerations imposed by the choice of a manufacturing process. Due to the ease of implementation of an additive manufacturing (AM) process, students tend to gravitate to AM when they need to manufacture a part for any application. This can be problematic for many parts, such as those that require high strength or good surface finish, as the AM processes available to students are usually incapable of producing satisfactory parts that conform to these requirements. Even when a subtractive manufacturing (SM) process, such as machining, could produce a given part with superior characteristics to an additively-manufactured version, students frequently still choose AM. While AM processes are ideal in some situations, SM processes are equally valid in other scenarios. It has been found that a large percentage of undergraduate students prefer AM processes because they are unfamiliar with SM; however, for students to be effective designers and engineers as they move into the workforce, they must be equally comfortable with both AM and SM processes. This thesis presents methodologies that rely on computer-based simulations to increase student understanding of both additive and subtractive manufacturing processes; these simulations were performed using a voxel-based software package for computer-aided manufacturing (CAM) known as SculptPrint that enables video game-like visualization of a manufacturing process for various part and tooling geometries. Case studies were performed in a sophomore-level mechanical engineering course that evaluated the improvement in student understanding of AM and SM. Experimental groups of students from the course were selected to receive both experience with the voxel-based CAM

software and training on computer-numerical control (CNC) machine tools, while the remaining students in the course did not receive such treatment. Additionally, process planning for SM operations was introduced using the software, and students in the experimental groups designed and created multi-part assemblies using CNC machine tools. Online surveys were deployed to compare the level of understanding of AM and SM processes between the students that did and did not receive exposure to the CAM software.

This thesis is laid out as follows: in the Background section, relevant information on educational approaches, design and build courses, computer-aided manufacturing software and statistical analysis approaches is presented; in the Methods section, all of the deployed assessment instruments and the training protocol for two implementations of the study are described in detail; in the Results section, a quantitative analysis of the survey results from before and after machining training, in addition to qualitative observations on student text responses is presented; finally, in the Discussion and Conclusions section, the results are discussed and recommendations for future studies are presented.

2 BACKGROUND

Many factors must be considered during the development of a manufacturing process, and often consideration of such factors is out of reach for engineering students with little to no experience in manufacturing. Undergraduate engineering curricula include courses in both design and manufacturing, but many students still struggle with synthesizing knowledge gained from the two into a concept known as design-for-manufacturability (DFM). DFM is the practice of design such that manufacturing considerations are taken into account during the design process. DFM is an essential skill for any designer, as it is essential for the efficient realization of engineered systems. This section describes the current practice of design and manufacturing education, coupled with approaches used by engineering education researchers to improve the effectiveness of teaching both manufacturing and DFM. Additionally, the tools used in this thesis to realize visualized simulations of manufacturing are discussed. Finally, methodologies to analyze student understanding of manufacturability are described.

2.1 DESIGN EDUCATION

The ability to design systems and components is an absolute necessity for any engineering graduate, and thus design education is an indispensable part of any engineering curriculum. Design education occupies a distinct part in a curriculum that is removed from typical analysis courses that are normally associated with engineering education. The science of design, which has both qualitative and quantitative aspects, bridges the gap between artistic creativity and classical engineering analysis. Oftentimes, there is not a single answer to a

design problem; this characteristic of the science of design is what makes it challenging to practice and even more challenging to teach [1].

One of the primary factors to be considered during the design process is the physical realization of a system or component. Designers must be able to understand the limitations of the currently available suite of manufacturing processes when they design a part; while design engineering and manufacturing engineering are distinct fields, designers will not be effective in their work if they have no understanding of manufacturing [2].

2.2 MANUFACTURING EDUCATION

Although the understanding of manufacturing is an essential skill in engineering practice, it is not heavily emphasized in the majority of engineering curricula [3]. Typically, a university will provide one required course in manufacturing processes and may provide others as electives [4]. Although manufacturing education is lacking, students are still expected to be capable of fabricating components and devices they create; for example, engineering curricula are required to include a capstone design course, and engineering students must design and build a physical device to succeed in the course. Many Bachelor's programs provide students with a course that focuses on the theory supporting analysis of manufacturing processes, but the students are frequently not taught to actually implement the processes discussed in the course. This can be attributed, in part, to the fact that teaching implementation of manufacturing processes requires extensive capital expenditure to develop a functional manufacturing shop floor [5]. Without experience in implementation, students can only learn the design implications of various manufacturing operations once they are practicing engineers.

2.2.1 ADDITIVE AND SUBTRACTIVE MANUFACTURING

As a result of students' inadequate preparation in the implementation of physical devices, they are frequently unaware of design constraints that are imposed by a particular choice of manufacturing process. These students frequently turn to additive manufacturing (AM) as the best option for any part they want to make, regardless of the part's application [6]. AM processes are typically simple to implement and place a relatively low number of geometric constraints on part design; however, they can suffer from poor dimensional accuracy and low-strength parts [7], [8]. Subtractive manufacturing (SM), on the other hand, is the range of processes where a part is manufactured by cutting material away from a larger blank. SM processes, also called machining processes, are performed using a cutting tool such as an endmill, single point cutting tool or broach. In contrast to AM, SM processes allow for the rapid creation of parts from a variety of materials. However, additional limitations on part geometry exist in the realm of SM processes [9]. As SM accounts for a large percentage of all manufacturing that is performed today, students must be comfortable with both AM and SM if they are to be effective mechanical engineers [10].

SM is generally performed using a machine tool, which is a piece of equipment that can create controlled movements of a cutting tool to generate desired geometry on a workpiece. A machine tool can be operated manually, where a machinist uses handwheels to control tool movement; or, tool movements can be created using a computerized motion control system with servomotors and a programmable controller. Such a machine is referred to as a computer numerical control (CNC) machine tool, and accounts for the vast majority of machine tools used worldwide [11]. CNC machine tools enable creation of parts that are far more complex than are possible with manual machine tools, but programming them can

be a challenge [12]. Programming a CNC machine is typically accomplished using G-Code, which is a standardized way of describing tool movements in the machine's coordinate system. Education in AM and SM processes is usually accomplished through both traditional lecture-based courses and design-build courses. Students learn to mathematically analyze a given process in a lecture-based course, and then implement that process in a design-build course. However, little treatment is given to the implementation of CNC machining processes at the undergraduate level [13].

2.2.2 UNIVERSITY MAKERSPACES

Many universities have begun to establish so-called “makerspaces” on campus, where students can fabricate parts with university-owned equipment [14]. These makerspaces arose from the popular “maker” movement, in which people from all professions practice creating parts, assemblies and systems that would traditionally have only been realizable by someone with an engineering background. The rise of affordable AM hardware has greatly accelerated the pace of the movement, to the extent that students in middle and high schools are using 3D printers to fabricate parts [15], [16]. University makerspaces afford students with the resources they need to learn how to physically realize many of the concepts that are taught in engineering courses, and have contributed to students' familiarity with both AM and SM. One notable makerspace is Georgia Tech's Invention Studio, where student volunteers assist classmates in 3D printing on a range of AM equipment [17]. The Invention Studio is quite popular amongst both undergraduate and graduate students, and remains busy throughout the semester.

2.3 EDUCATIONAL APPROACHES

2.3.1 PROJECT-BASED LEARNING

Project-based learning (PBL) is a teaching strategy that provides students with treatment of real-world, complex problems. Instead of giving students problems from a textbook, they are given a problem description and a set of constraints with which to frame the solution [18]. This teaching strategy can be challenging to implement, however, as it requires different instruction and assessment practices than students are used to [19], [20]. PBL is the typical approach taken in culminating capstone design courses, as it is a realistic approach to problem solving that students will encounter in engineering practice [21].

2.3.2 SIMULATION-BASED LEARNING

Simulation-based learning (SBL) is a technique to replace real-world experiences with artificial ones for training purposes. It has been applied to numerous fields previously, such as medicine, aviation and the military to provide trainees with accurate experiences in the respective field [22]. SBL can be implemented using actors, props or games. It is frequently applied in professional education settings, where the efficiency of teaching real-world skills is of utmost importance [23]. SBL is an ideal strategy for manufacturing education, as it does not require the physical operation of expensive and often hazardous manufacturing equipment. Additionally, SBL allows for the development of intuition that may be difficult to teach in a traditional classroom setting [24].

2.3.3 COMPUTER-ASSISTED LEARNING

Computer-assisted learning (CAL) is a teaching strategy in which students work through training materials with the help of a computer. CAL allows for a large number of students

to access a learning resource simultaneously without the help of an instructor, and is useful in visualizing complex concepts [25]. CAL has been shown to improve knowledge retention when compared to typical face-to-face instruction [26], [27]. CAL can be applied in conjunction with SBL to create simulation-based computer-assisted learning (SBCAL); in this strategy, students carry out simulations of concepts with the help of a computer in an effort to aid their understanding [28]. The use of SBCAL is becoming more common, and is frequently implemented with games or virtual worlds [29]. Computer simulations allow for complex and immersive visualization of a given process that would be difficult to realize in the physical world.

2.4 SBL AND CAL IN ENGINEERING EDUCATION

The use of computer-based simulations in engineering education is commonly implemented using computer-aided design (CAD) software in introductory courses. CAD allows students to create digital models of parts and assemblies without actually manufacturing them. Additionally, students can use computer-aided engineering (CAE) software to perform simulations of physics in complex systems. Ebner and Holzinger performed a study with civil engineering students in which a computer game was used to educate students about the theoretical aspects of designing structures with concrete [30]. While the goal of the game was simply to provide an alternative to traditional teaching approaches, the researchers found that students subjected to the experimental protocol scored far higher on user empowerment and fun factor indices than students in the control group. Gillet, Ngoc and Rekik deployed a web-based flexible learning system to allow students to perform simulated experiments in biomechanics, fluid mechanics and automatic control [31]. The students were also provided with a collaborative workspace in which they

could solve problems together; this study showed that engineering students are generally receptive to computer-assisted learning practices. Some researchers have also begun to apply computer-aided manufacturing (CAM) software in the classroom to help educate students about concepts in manufacturing. CAM has been shown to accelerate the pace of teaching students about subtractive manufacturing concepts [32], [33]. Koh, et al developed interactive simulations to teach students how to operate milling, turning and drilling machines; results from a post-training exercise demonstrated that students exposed to the computer simulations of machine tools had a superior grasp on the operation of those machines than students who were simply lectured on those machine tools [34].

2.5 COMPUTER-AIDED MANUFACTURING

Computer-aided manufacturing (CAM) software is an essential tool for realizing toolpaths for computer-numerical control (CNC) machine tools. The purpose of CAM software is both to give visual feedback to the user on the machining process of a particular part and to generate movement instructions for the machine. These movement instructions are most frequently realized using G-Code, which is a text-based programming language for CNC machines. While G-Code can be written manually, it may be difficult for inexperienced programmers to mentally visualize the path of a cutting tool without using CAM. The ability of a CAM software package to provide visual feedback on the machining process is invaluable in an educational setting.

2.5.1 PARAMETRIC APPROACHES TO CAM

The user interface for CAM software is similar to CAD software in that it allows a user to work with a digital part model. The user imports (or, in some CAM systems, creates) a

three-dimensional model of a part in the software and then creates toolpaths and process plans to manufacture the part. Most CAM software packages employ parametric part models, where surfaces and features are described mathematically with continuous functions [35]. The use of parametric models enables the user to resize models without a loss of fidelity, similar to the way that vector graphics can be scaled without loss of resolution. For relatively simple geometry, parametric models are ideal, as they require a small amount of space to store and are capable of accurately representing many of the features that would be present on a machined part [36]. However, for very complex geometry, the orders of functions that define parametric models become prohibitively high [37]. As a result, discretized part models must be used to represent geometry of sufficient complexity.

2.5.2 VOXEL-BASED APPROACHES TO CAM

Numerous methods to describe a discretized part model exist, but one notable example is the voxel model. A voxel is the three-dimensional equivalent of a two-dimensional pixel in an image; thus, instead of being a square as a pixel is, a voxel is a cube [38]. By arranging a collection of voxels into the shape of a part volume, a voxel model of the part can be created. This process is referred to as voxelization. Voxel models offer a number of distinct advantages over traditional parametric models; most importantly, the geometry represented by a voxel model can be significantly more complex than that of a parametric model, as a voxel model is effectively just a three-dimensional array [39]. Voxel models can be employed in CAM software to enable path planning for extremely complex parts that would be unachievable with the usual approach to CAM [40]. Additionally, the use of a voxel model in a CAM package allows for complex, in-process visualization of a

machining operation as voxel locations in the voxel model array need only to be turned off to simulate the effect of material removal [41]. This thesis makes use of SculptPrint, a voxel-based CAM system for turning and milling. SculptPrint can create toolpaths for many types of machining operations with minimal user input, including simultaneous 5-axis machining, and also provides a user-friendly visualization interface to simulate material removal throughout the machining process [42], [43].

2.5.3 ACCESSIBILITY OF CAM

It is undeniable that CAM software, both parametric and voxelized, is indispensable in the creation of G-Code for machining operations of varying complexity. However, CAM software requires a powerful workstation to use efficiently. This can be a limitation in an education setting, as the instructors must provide students with an individual workstation on which to use the CAM software [44]. An alternative to this approach is the establishment of virtual machines (VMs), which students can access using an Internet connection. Virtualization is a technique used to emulate certain aspects of computing; for example, a virtual machine is an emulated computer that provides the functionality of a local machine although the hardware is hosted remotely. Use of a VM enables users to access workstation-grade hardware using a client, which could be a laptop or other mobile device. As a result, users do not need to actually possess powerful and expensive computing hardware in order to efficiently operate a CAM system. For this study, a virtual machine setup was developed to allow up to 10 simultaneous students to access SculptPrint from both Windows and Macintosh clients [45].

2.6 GEORGIA TECH'S UNDERGRADUATE COURSES IN CAD AND MANUFACTURING

For the purposes of this thesis, there are two courses at Georgia Tech (GT) that provide students with the relevant knowledge to understand manufacturing and DFM. While students are introduced to more advanced topics in manufacturing after their sophomore year, the study described in this thesis was performed with second-year students; as a result, only the courses that students take during their first and second years are of relevance. These two courses, ME1770 and ME2110, are mechanical engineering (ME) courses that each ME student must pass before moving to more advanced topics in design and manufacturing.

2.6.1 ME1770

Georgia Tech's (GT) undergraduate students get their first formal introduction to CAD tools in the course titled ME1770: Introduction to Engineering Graphics and Visualization. ME1770 is a freshman-level course that is required for all students in Mechanical, Civil and Aerospace Engineering. They begin by learning the fundamentals of engineering drawing on paper, and gradually progress to two-dimensional and three-dimensional CAD. Ultimately, the students in the course learn to operate a commercial CAD system, such as Dassault SolidWorks or Autodesk Inventor, to create models and drawings of parts both from engineering prints and physical prototypes. Aside from modelling individual parts, the students also learn to create assemblies of varying complexity. The students must perform a team final project for the course, where they choose an assembly and create various animations to demonstrate their mastery of the CAD system they learned. The

students are also introduced to AM in the form of fused deposition modelling (FDM), which is the most common and easily implementable AM process. In the course, the students use FDM equipment to create physical versions of the parts they model in the CAD system. The students' use of both CAD and FDM in this course is expected to provide them with a foundational understanding of 3D visualization in the context of engineering [46].

2.6.2 ME2110

ME2110: Creative Decisions and Design is a sophomore-level design and build course at GT that is the next step in the course chain for ME students after ME1770. Once again, ME2110 is required for all undergraduate students seeking a degree in Mechanical Engineering. This course serves as students' first formal introduction to the realization of a functional device. ME2110 is a lab-based course, and as a result, each student's grade is derived from his or her performance on lab reports and projects. In ME2110, the lab sections are referred to as "studios" and each section is assigned a unique timeslot for their weekly studio session. There are no midterms or final exams in ME2110; rather, emphasis is placed on the actual practice of engineering design and manufacturing. Due to this grading strategy, ME2110 is a course that inherently makes use of PBL. This serves as a welcome reprieve for many students, who much prefer to be evaluated on their performance in design and construction of engineered systems rather than their ability to operate a calculator. The course is composed of three major projects: the structure project, the introductory project and the major project [47]. Both the structure project and the introductory project provide students with experience in physical realization and presentation of a structure or system they designed; this experience is then used in the

completion of the major project. The major project is a device that teams of students design and build to participate in a final, course-wide competition. Students design the device to complete a series of provided tasks within a limited amount of time. These tasks, such as the deposition of ping-pong balls into a tube or the retrieval of rubber dog bones, would be simple for a human to complete; however, the challenge to the students is that these tasks must be completed autonomously by their machines. The students are provided with a mechatronics kit, which consists of various actuators and a control system that they can program to allow their machine to function.

In addition to the mechatronics kit, the students are provided with a bin of scrap material from past competitions. This scrap consists mainly of wood, although some plastics and metals can also be found in the bin. The students can scavenge the materials they need to build their machines, or they can purchase materials within a budget. For many students, ME2110 is the first time they are exposed to hands-on work with tools or fabrication equipment. However, some students arrive in ME2110 with already functional knowledge of how to use a screwdriver; some arrive with experience in CNC machining; and yet others arrive without having ever seen a socket set. In order to normalize the population of the course so that each student has working knowledge of how to actually build something, each student is required to undergo machining training in the machine shop that is dedicated for use with ME2110. The machine shop, which is shown in Figure 1, contains numerous manual machine tools: there are approximately 10 manual milling and turning machines in the shop, in addition to various hand tools, a band saw, a drill press and a miter saw. The students are taught to operate all of this equipment in a safe way so that they can fabricate parts for their machines. In fact, one of the graded assignments for the course is



Figure 1. ME2110 Student Machine Shop

the machining of both a turned plastic shaft coupler and a milled plastic motor mounting bracket.

In addition to the manual machining equipment in the ME2110 shop, the students are permitted to fabricate their parts outside of the classroom. Some students may have an extensive collection of tools in their dorm rooms and thus may choose to fabricate everything on their own without spending time to walk to campus during the open lab hours; however, these students are in the minority. Most students choose to use the Invention Studio to fabricate whatever they cannot make in the 2110 shop. Most of the time, the students will employ FDM equipment to create the custom parts that they need for their machines. While FDM is acceptable for some parts, and sometimes the only option for others, it is common for students to print simple parts that they could have machined in a fraction of the time. For example, the pulley shown in the left of Figure 2 was printed by a student for use on his machine. For those familiar with turning, the manufacture of this part using a lathe would have taken a fraction of the time that it took to print it. The superior machined pulley is shown on the right in the Figure.



Figure 2. Printed and Machined Pulleys

However students choose to manufacture the parts for their machines, they must consider the reliability and robustness of the entire assembly if the machine is to be competitive when competing against other students' machines. The final competition, which takes place at the end of the course, is where the students are given the opportunity to demonstrate their capability to design and construct a working electromechanical system. Similar to a sport event, the student teams are bracketed according to their performance in qualifying rounds before the competition. The competition then proceeds until a winning team is able to beat all of its competitors. Frequently, the teams that perform well or even win the competition are those who spent significant time building, testing and debugging their machines in order to make them more reliable. This implies not only that the parts the students fabricated for their devices were robust enough to withstand the punishment of the competition, but also that the students were able to recognize the most effective manufacturing processes to employ for a given part.

2.7 ANALYSIS TOOLS

2.7.1 QUALTRICS

Evaluation of student performance in this study was performed using a variety of assessment instruments specifically developed to gauge students' understanding of manufacturing and DFM concepts. To automate both data collection and analysis, the surveys were deployed using the Qualtrics platform. Qualtrics is a web-based data collection tool that supports creation of custom surveys that incorporate different question types, interactive graphics and text-based response analysis [48]. The use of Qualtrics enabled more thorough data collection than would be reasonable with paper-based surveys; additionally, it provided a convenient means of exporting collected data.

2.7.2 STUDENT'S T-TEST

The Student's *t*-test is a statistical hypothesis test which is used to determine if two samples are different from one another. For example, a two-sample *t*-test can determine if the means of two separate samples differ significantly. A two-sample *t*-test is performed by first calculating the *t*-statistic, which is given by Equation 1,

$$t = \frac{\bar{X}_1 - \bar{X}_2}{s_p \sqrt{\frac{2}{n}}} \quad (1)$$

where *t* is the *t*-statistic; \bar{x}_1 and \bar{x}_2 are the means of samples 1 and 2, respectively; s_p is the pooled standard deviation; and *n* is the number of participants in each group. s_p is the pooled standard deviation, which is given by Equation 2,

$$s_p = \sqrt{\frac{s_{X_1}^2 + s_{X_2}^2}{2}} \quad (2)$$

where $s_{x_1}^2$ and $s_{x_2}^2$ are the unbiased estimators of the variances between two samples [49].

The use of Equation 1 necessitates that the two sample sizes are equivalent; often, this is not the case. Equation 3 is used to calculate a t -statistic for two samples with unequal size,

$$t = \frac{\overline{X}_1 - \overline{X}_2}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (3)$$

where s_p is an estimate of the pooled standard deviation; n_1 is the size of the first sample; and n_2 is the size of the second sample. s_p is given by Equation 4,

$$s_p = \sqrt{\frac{(n_1 - 1)s_{x_1}^2 + (n_2 - 1)s_{x_2}^2}{n_1 + n_2 - 2}} \quad (4)$$

The main assumption of Equations 3 and 4 is that the variances of the two samples are equivalent; often, this is not the case. To test whether or not two populations have equal means without assuming that the variances of the populations are equal, a Welch's t -test is employed. In this test, the t statistic is given by Equation 5,

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \quad (5)$$

where s_1^2 and s_2^2 are the sample variances of the first and second samples, respectively.

For this thesis, the sample sizes being tested were not equivalent and the variances were not assumed to be equal, as both groups underwent different training protocols; thus, Equation 5 was used to test the differences in means between groups. The result of the t -score can be used in a lookup table to determine a p -value given the degrees of freedom

(df) of the data set. The p -value indicates the probability that the null hypothesis is correct. For a t -test, the null hypothesis states that no difference exists between the means of two samples. It is customary to assume a significance level, α , of 0.05; a p -value less than α indicates that the probability that the null hypothesis is incorrect is greater than $1 - \alpha$ [49]. For example, suppose that a t -test was performed and yielded a p -value of 0.05; in this case, there is a 95% chance that the difference in means between the two samples used for the t -test is not due to random chance.

2.8 GOALS OF THIS THESIS

The work presented in this thesis aims to develop a framework to better equip undergraduate students with the skills they need to think more effectively about design and manufacturing. Students must be able to consider a multitude of factors when designing a part, including functional requirements, cost and manufacturing time. Additionally, many students may go on to be manufacturing engineers in their careers, in which case they must be thoroughly capable of considering the range of manufacturing processes available to them when choosing how to make a given part. Whether ME students decide to become designers, manufacturing engineers or specialize in another subfield of mechanical engineering, it is undeniable that they will be forced to consider manufacturing and manufacturability at some time during their engineering practice.

This work describes the development and implementation of a collaborative, computer-assisted simulation-based learning approach to manufacturing education that makes use of computer-aided manufacturing software. This thesis addresses the following research questions:

1. How does exposure to computer simulations of manufacturing *or* manual machining training affect students' ability to geometrically analyze the turning process?
2. How is a student's choice of a manufacturing process for a certain part influenced by exposure to computer simulations?
3. How does students' prior experience in manufacturing impact the effectiveness of the SBL approach?

The ultimate vision of this work is to develop an efficient procedure to rapidly educate the current generation of engineers about the what they need to consider when designing a part or a manufacturing process. The procedure in question will allow students to visualize the AM and SM processes that they will most frequently come in contact with. For the purposes of this thesis, the developed manufacturability education framework revolves around the use of voxelized simulations of manufacturing processes using SculptPrint to help students build intuition in DFM. Each of the previously mentioned research questions will be addressed using the findings from this study. The training approach is described in detail in the Method section, and results and relevant findings from the deployment of assessment instruments are presented in the Results section. A qualitative discussion of results is presented in the Discussion section, followed by conclusions and recommendations for future work.

3 METHOD

The manufacturability training approach presented in this thesis relies on the use of SculptPrint to provide undergraduate students with visualized simulations of a turning process. These undergraduates were selected from GT's ME2110 course, as the lab-based format of the course allowed for implementation of the training approach alongside the traditional training protocol that has been used in the course in previous years. Two implementations of the training approach are presented in this thesis. The first implementation was performed in the Spring of 2016 with a small group of students to evaluate the feasibility of the following two cornerstones of this work: first of all, the use of the virtualized CAM software in an educational environment had yet to be validated before this study began; concerns over performance of the system when subjected to multiple simultaneous users had to be addressed to enable an improvement in the reliability of the system. Secondly, training students in CNC machine operation and part production was also unproven, and had to be demonstrated as possible in the short time frame allotted for the study. Upon the completion of the pilot implementation of the study, improvements were made to the training protocol to enable a larger-scale deployment. The second implementation of the study, from which the majority of the data analyzed in this work were drawn, was performed in the Fall of 2016 with a larger sample of students.

Both the pilot study and the second implementation made use of control and treatment groups of students; these disparate groups were analyzed to determine the effectiveness of employing CAM software as a tool for manufacturability education. The control groups were subjected to the traditional approach to machining and manufacturability training that

has been used in ME2110 previously; the treatment groups were trained on and allowed to make use of the CAM software to study simulations of a machining process. Due to technical constraints in both the virtualization of the CAM software and the availability of CNC machine tools, students in the treatment group only received simulations of the turning process. Milling was not considered for the treatment group. Upon completion of training and use of the CAM software, the treatment groups were trained on and allowed to operate a 2-axis CNC turning center to produce parts from toolpaths that they created using the CAM software. Meanwhile, the treatment group produced a different set of parts using manual machining equipment in the ME2110 machine shop. Throughout the machining training for both groups in the lab sessions of ME2110, participants were asked to complete a variety of assessments designed to measure their understanding of concepts in machining and DFM. In the pilot study, these assessments were on paper; in the second implementation, the assessments were provided as online questionnaires using Qualtrics.

3.1 TRADITIONAL TRAINING APPROACH: MANUAL MACHINING

In the traditional training approach that has been employed in ME2110 in previous years, students are taught the implementation of manual machining on miniature lathes and milling machines. The traditional training approach provides no treatment of metal cutting theory, as it is not necessary to allow students to fabricate the simple parts that they need for their machines. Additionally, the traditional approach offers no introduction to CNC machining or other manufacturing processes. In this approach, students are taught first to safely operate the manual machining equipment in the 2110 shop after hands-on demonstrations by the teaching assistants (TAs) for the course. The students are then

required to machine two simple parts: a shaft coupler and a motor mounting bracket. An example of the shaft coupler is shown in Figure 3. These two parts can be used by the



Figure 3. Training Part for Control Group

students on their final machines for the competition. Once they finish machining the parts, dimensional accuracy is checked by the TAs. If they are not able to finish in the allotted time for the studio section, they can continue working during open lab hours. The students are given a week and a half to completely machine both parts. Once they have proven that they are capable of operating the manual equipment to make those parts, they are free to make use of the 2110 shop during open lab hours to fabricate other parts for their machines.

3.2 FIRST SCULPTPRINT IMPLEMENTATION: PILOT STUDY

The first implementation of the voxelized CAM software in ME2110 was performed in the Spring of 2016. In contrast to the typical training on manual machine tools, groups of students were allowed to use the CAM software to create toolpaths for parts that were later machined on a 2-axis turning center; this allowed for a study of the effectiveness of the CAM software in teaching concepts in DFM to students. The first implementation of the study was conducted using control and treatment groups as follows: first, two sections of

the course were selected to participate in the study; next, groups of four students from each section were selected as the experimental groups and the remainder of the section served as the control groups. The experimental group received training on the CAM software and the CNC lathe, while the control group received the typical training on manual machining equipment. A set of surveys was developed to gauge the students' understanding of DFM concepts before and after training, and results of the surveys were compared between groups.

3.2.1 COMPOSITION OF CONTROL AND TREATMENT GROUPS IN PILOT STUDY

The first implementation of this study was performed in the Spring of 2016 with two separate sections in ME2110. The study was performed over a four-week period, coinciding with the original time allotment for machining training in ME2110. Four students from each section were selected to comprise the treatment group; the remaining students in the section comprised the control group. The makeup of the control and treatment groups is shown in Table 1. Although each ME2110 section contains

Table 1. Control and Treatment Populations for First Implementation

	Control	Treatment
<i>Sample Size</i>	21	7

approximately 20 students, a number of them did not provide consent for their data to be published; as a result, they were removed from the count of sample size for whichever group they were assigned to. All of the students in the two sections of the course were given an initial questionnaire at the beginning of the course to record their prior experience. Students were asked to simply indicate whether or not they had previous experience with

manual machining, CNC machining or both. The results from this questionnaire are given in the Results section.

3.2.2 LEARNING ASSESSMENT

After the completion of the initial questionnaire, each of the students participating in the study was given a paper-based set of assessment questions to gauge their knowledge of DFM concepts. These questions covered a variety of topics related to DFM, but were all focused on turning operations. For this implementation, the simple turning process was deemed acceptable to prove the effectiveness of the approach, and milling was not considered. The general subject areas of these questions are shown in Table 2, and the

Table 2. Assessment Question Categories

Type	Assessment Question
<i>Machine Capability</i>	Which, if any, of the features shown are impossible to create on a 2-axis lathe?
<i>Fixturing</i>	Where would you fixture this part to reach all the features?
<i>Tooling</i>	What is the smallest number of available tools needed to make this part?
<i>Planning</i>	Are there any additional features of a lathe that could be useful in minimizing deflection?

complete questionnaire is presented in APPENDIX A [10]. The completed assessments were then graded blindly by an expert and separated between the control and treatment groups. Once the students had completed the assessments, both the control and treatment groups underwent their respective training procedures. At the conclusion of training for both groups, each student was asked to complete the same assessment again to study the change in their scores. The scores of the students in the control and treatment groups were then compared to determine which group demonstrated a larger score increase.

3.2.3 TRAINING PROTOCOL

Machining training for both groups began once the initial assessments had been completed. For the control group, the training consisted the usual hands-on demonstrations of manual machining equipment, followed by the manufacture of the two simple parts described in Section 3.1. The experimental group, meanwhile, was separated from the control group and provided with training in the voxelized CAM software. This training spanned two weeks, or a combined six hours of studio time. During the first week of the training, the students in the treatment group were given an informal lecture on the turning process in a separate classroom from the control group. The students were also shown examples of CNC machine tools, the workholding and axis configurations of various machines and parts that were made using CNC machine tools. Additionally, they were walked through the operation of the CAM software and used it to make a toolpath for the pawg shown in Figure 4a. Finally, they were instructed on the operation of an Okuma Genos L250 2-axis turning



a. Pawn Model



b. Machined Pawn

Figure 4. Pawn Model and Resulting Part Machined by Student

center and used the toolpaths they created to machine the pawns from 1-inch diameter round acetal rod. The students were taught to upload a G-Code file to the machine, clamp the stock in the lathe's chuck, set the work offset and run the G-Code they made with

SculptPrint. They were also taught about the various settings on the machine, such as rapid speed and federate override. An example of a pawn machined by a student in the treatment group is shown in Figure 4b. Unlike the students in the control group, students in the treatment group did not receive any training on manual machining.

During the second training session, the students in the treatment group once again used SculptPrint to create a process plan and the resulting G-Code for the pulley shown in Figure



Figure 5. Pulley Model and Resulting Part Machine by Student

5a. Once the process planning was complete and before machining the pulleys, the students were allowed to use the CAM system's cutting simulation feature to visualize the effect of different tools on the turning process. They were shown interactive visualizations of the pulley turning process using both right- and left-handed 35° turning tools. The goal of this exercise was to show the students how the geometry of a cutting tool influences the types of part geometry it can create; an example of the pulley cutting simulation for a 35° right-handed neutral lead cutting insert is shown in Figure 6 [10]. After the simulation exercise, the students were taken to a machine tool to deploy the G-Code they created. Each student

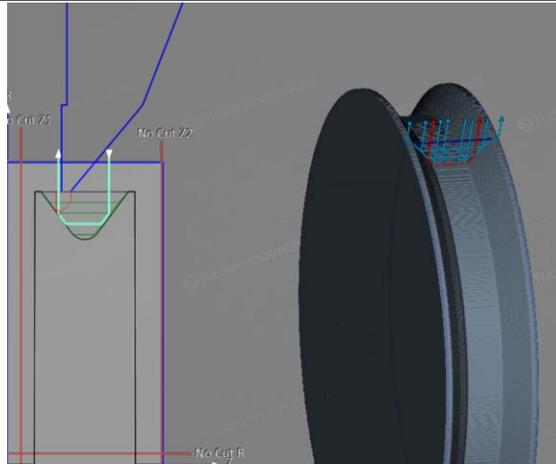


Figure 6. Simulation of Turning Process

was allowed to run his or her own G-Code using the Okuma turning center to create a pulley.

The training procedure, in addition to student operation of the 2-axis turning center, is shown in Figure 7. This hands-on demonstration and close interaction with the instructor allowed students to ask questions and gain insight into the intricacies of CNC machining.



Figure 7. Treatment Group Students using 2-axis Turning Center

The majority of students in the treatment group was receptive to the specialized training they were receiving, although a small minority of students was completely uninterested. Completion of SculptPrint and CNC training for the treatment group coincided with the completion of manual machining training for the control group. At that point, the students in both the treatment and control sections were asked to complete the same learning assessment they did before the training. The results and analysis of those data are presented in Section 4.

3.3 SECOND SCULPTPRINT IMPLEMENTATION: ENTIRE COURSE

After success with the pilot study, the materials for both training and assessment were revamped to be deployed to the entire population of ME2110 in the Fall of 2016. The original, paper-based surveys were completely redone and ported to an online system, Qualtrics, to enable more efficient data collection. Qualtrics is a web-based survey tool that not only allows for large-scale distribution of tests and assessments, but also enables the easy exportation of collected data. Many more survey questions were added to address a wider range of topics in manufacturing and DFM. As was the case with the pilot study, groups of students were selected to serve in the control and treatment groups for the second implementation of the study. The training for the control group remained the same as it was in the pilot study, but the training for the treatment group was modified substantially. The students still created toolpaths with SculptPrint, but instead of making two disparate parts, they created a two-piece assembly. Additionally, they were trained on and used both a 2-axis turning center and a 4-axis millturn machine.

3.3.1 STUDENT POPULATIONS FOR SECOND IMPLEMENTATION

The sample sizes of the control and treatment groups were increased substantially for the second implementation enable more thorough data analysis: the treatment group consisted of two entire sections of the course, rather than four students from two sections as was the case with the pilot study; and the control group consisted of every student in the other, non-treatment sections. Two of the thirteen sections were selected as treatment groups, while the remainder of the course served as the control group. The section populations for each of these groups is summarized in Table 3. In total, there were 15 students in the treatment

Table 3. Student Populations for Second Implementation

Section	Size	Classification	Group Size	Percent of Population
A	12			
B	11			
C	12			
D	10			
E	14			
F	10	Control	132	89.8%
I	14			
J	12			
K	15			
L	12			
M	10			
G	9	Treatment	15	10.2%
H	6			
Total	147			

group and 132 students in the control group, after data were removed for students that did not give consent for their data to be published.

3.3.2 TRAINING AND ASSESSMENT INSTRUMENTS

In total, 5 surveys were given to both treatment and control groups for the second trial; four of the surveys were understanding assessments and one was initial data collection on prior experience. The assessments were named according to their content and when they were administered: the Preassessment (PA) surveyed students on their prior experience; the Pretest (PreT) contained a range of questions on simple machining concepts; the Process Questions (PQ) required students to pick from a list of manufacturing processes for how to best make a group of parts; the Posttest (PostT) contained a range of more detailed questions on machining; and the Process Questions Post (PQP) was a repetition of the original PQ assessment. Additionally, the treatment group completed one additional assignment, the SculptPrint Exercises (SPE), which walked them through the machining visualizations in SculptPrint. The timing of when each assessment was given was carefully designed such that some were given before any machining training and the others were given after both treatment and control groups had completed their respective training exercises. The schedule of the ME2110 lectures, surveys and machining training for both groups is described in Table 4. For the assessments that coincide with pertinent lecture

Table 4. Schedule of Training and Assessment Instrument Deployment

<i>Week of Study</i>	<i>Week 1</i>	<i>Week 2</i>	<i>Weeks 3-5</i>	<i>Week 6</i>
Lecture	Design/Communication	Machining	Safety, QA	DFM
Studio	Intro Project		Machining	Open
Assessment	PA	PreT, PQ	SPE ¹	PostT, PQP

¹ Given to treatment group only

materials on the same week, students were only given access to the surveys after the lecture was complete.

3.3.2.1 Survey Distribution

As was the case in the pilot study, participants were asked by a third party to complete a consent form that indicated whether or not they would allow their data to be published. This consent form was given on paper and the collected responses were scanned and used to filter out student survey results. Unlike the pilot study, the surveys in the second implementation of the study were distributed through Qualtrics. This not only allowed for easier analysis after the study, as data could simply be downloaded into a suitable analysis package, but it also eased the distribution requirements and allowed for better control over which groups were able to access the surveys. All of the assessments were created and deployed to Qualtrics before the start of the study, but were only unlocked once students had completed the necessary prerequisites. For example, the surveys that were given after machining training (PostT and PQP) were only opened for responses once every section had completed their respective training. Although the assessments were not graded for correctness, students did receive a small percentage of their grade for submitting a completed survey. A student who completed the survey and answered every question correctly received the same credit on the assignment as another student that completed the assessment but answered every question incorrectly. Although this was not done in the pilot study, it was deemed necessary in the second implementation to provide an incentive to the students to complete the surveys. Because every student in the course was asked to complete the surveys, there was not an issue of one group being treated more fairly than another.

It was of utmost importance that the surveys designed to be completed before machining training were not submitted after training had already begun. As a result, students were given deadlines for the completion of each assessment. The response collection of the

surveys was closed after the deadline to prevent students from submitting them late; for those who did not complete a given survey by the deadline, no credit for that survey was given. Upon the completion of a survey, the student names and indication of completeness was provided to the section TAs so that the appropriate credit could be assigned to each student. The TAs were not provided with the answers submitted on the surveys to avoid tainting their judgment of an individual student. A detailed description of the chronology of the training and assessment instrument deployment is given below, and the full text of the assessments is presented in the appendices.

3.3.2.2 Preassessment

The Preassessment (PA), given in the first week of the study, was designed simply to gather data on prior experience of the students in a range of manufacturing processes. Students were asked about their previous experience in additive manufacturing, manual milling, manual turning, CNC machining, welding and laser cutting. They were also asked which of these processes they were most comfortable with and why. Additionally, they were provided with images of both a prismatic part and an axisymmetric part and asked which process would be best for each of those parts. With the exception of the question that asked students why they were most comfortable with the process they chose, all questions on the PA were multiple choice. Data gathered from the PA allowed for filtration of later survey results by prior experience for analysis of responses from different subsets of students. The full Preassessment is shown in APPENDIX B.

3.3.2.3 Pretest

Table 5. Pretest Question Types

Question Type	Assessment Question Example
<i>Process Fundamentals</i>	Is turning an additive or subtractive operation?
<i>Machine Capability</i>	In a lathe, does the tool spin or does the part spin?
<i>Fixturing</i>	Should a vise be used on a lathe or a mill?

The Pretest (PreT), which was given immediately after the machining section in the lecture but before actual hands-on machining training in the studio, was designed to gauge students’ understanding of fundamental concepts in additive and subtractive manufacturing. Students were asked basic technical questions about AM and SM equipment, such as questions about fixturing and workholding. The types of questions asked in the Pretest are shown in Table 5. The entire Pretest is shown in APPENDIX C. Unlike the PA, the PreT contained free response questions that asked students to explain their thought process for a given multiple choice question in a text box below the question. This allowed for further insight into the reasons why students chose incorrect answers for some questions.

3.3.2.4 Process Questions

The Process Questions (PQ) assessment, which was given at the same time as the Pretest, contained questions relating to the manufacturability of photos of different parts. Some parts were prismatic, some were axisymmetric and others had complex geometry that were obvious candidates for an AM process. As an example, the plastic pawn that was made in the first implementation of the study was shown and students were asked to pick which



a. Turned Part



b. Milled Part [52]



c. Milled Part [53]



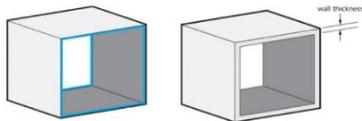
d. Millturned Part [53]



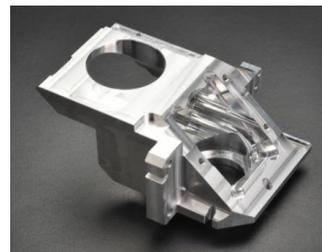
e. Printed Part [54]



f. Turned Part [55]



g. Printed Part [56]



g. Multi-Setup Milled Part [57]

Figure 8. Part Images for Process Questions

process would be best to make the part. Figure 8 shows the part images that were used for the eight questions in this assessment. For the eighth question, the students were asked if

the part was manufacturable on a 3-axis machining center or 2-axis lathe in a single setup. Although the training protocol used in the second implementation of the study did not explicitly address choice of a manufacturing process for a given part, the deployment of the PQ provided valuable feedback students' understanding of manufacturing and their thought process when choosing one to make a part. The complete PQ assessment is shown in APPENDIX D.

3.3.2.5 Machining Training

Training for the control group again consisted of the manufacture of the shaft coupler and motor mount as described in Section 3.1. Training for the treatment group in the second implementation followed a similar approach as was done in the pilot study, although the content of the training was different. First, the students were given a brief lecture on the intricacies of the turning operation; this included explanations of workholding and tooling geometry. Additionally, they were shown videos of different configurations of CNC machine tools and the differences between them were verbally explained. In contrast to the pilot study, where the lecture was performed in a separate classroom, this lecture was delivered by a machining expert to the entire section in the actual 2110 studio. This allowed for the use of a projector in a typical classroom setting. Students were provided with a variety of turning tools of different geometries and given explanations for where the different types of tools are most useful.

In preparation for the training studio, students were asked to design a simple part using CAD software and bring the resulting model to class. The part they were asked to design was one half of a yoyo; an example of the part is shown in Figure 9. This part was chosen

because the geometry is axisymmetric and it provided students with a memorable part that would enable fond reminiscing on their experience with the study.

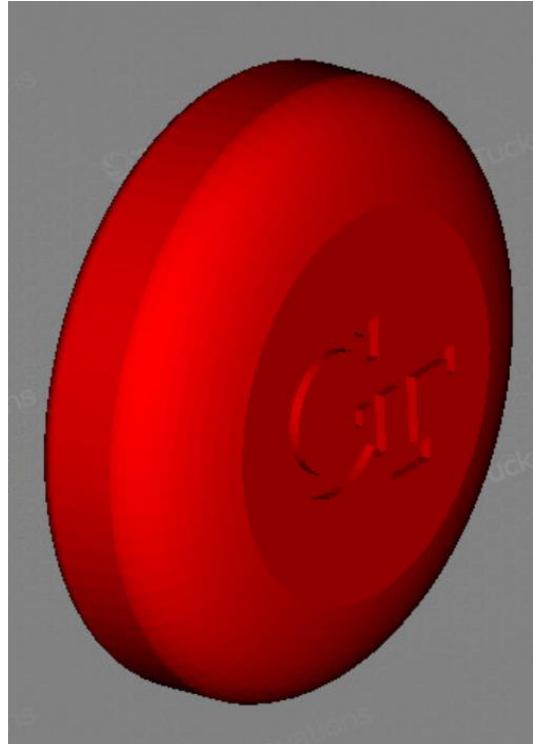


Figure 9. Yoyo Half Used for Machining Training

3.3.2.5.1 Yoyo Design

In order to design the yoyo half, the students were provided a set of instructions and a drawing that contained dimensional limits for the part. The complete set of instructions for the yoyo design that were given to the students is shown in APPENDIX E. Additionally, students were provided with a set of operating instructions for the machine tools used in this implementation as reference material. Figure 10 presents the relevant dimensional constraints that were provided. The outer diameter of the yoyo was chosen to be 63mm for two reasons: first of all, it enabled the manufacture of a yoyo that was of a reasonable size

and shape; secondly, 63.5mm (2.5”) material is readily available, and it is common practice to turn a small amount of material from the outer diameter of a blank to clean up the surface.

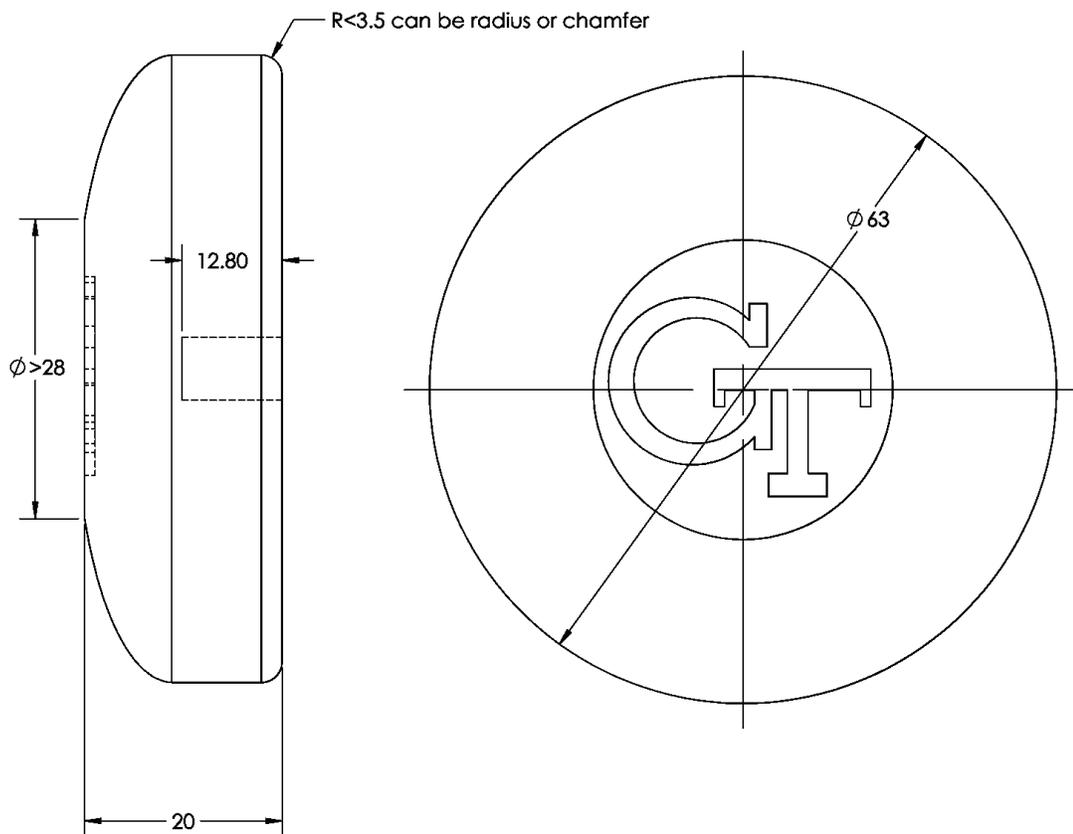


Figure 10. Yoyo Design Constraints

In order to increase both the safety and efficiency of the operation, it was determined that the students machining the yoyos should not be allowed to set the work offset for each part; rather, students would be provided with a blank and allowed to use a special fixture to hold the part in the lathe. Because the part needed to be machined on both sides, constraints were placed on the maximum radius or chamfer on the back of the part. A custom set of softjaws was machined with a 5mm deep shoulder to clamp on the outer diameter of the blank. The bottom face of the shoulder was used to set the work offset on the machine

before machining any of the parts. The set of softjaws made by the author for this project are shown in Figure 11. As the machining of the part was a light operation, it was deemed



Figure 11. Softjaws for Yoyo Machining

acceptable for the softjaws to only clamp on 1.5mm of the part's outer diameter, the remaining cylindrical portion of the blank after the back radius had been machined.

3.3.2.5.2 Process Planning for the Yoyo

This part required a number of different machining operations in two separate setups, and the manufacture of a total of eighty parts for the two treatment sections posed a challenge given the allotted time for the study. The following operations had to be performed for each part: face the back of blank to the correct axial dimension; turn the radius on the back; centerdrill, drill and chamfer the dowel pin hole on the back; flip the part over; face the front of the blank to the correct axial dimension; turn the outer diameter of the blank; turn the curve on the front; and load the almost-finished part into a millturn machine and

engrave the front pattern. As this was a relatively complex procedure for students never exposed to CNC machining, they were given an overview of process planning for turning

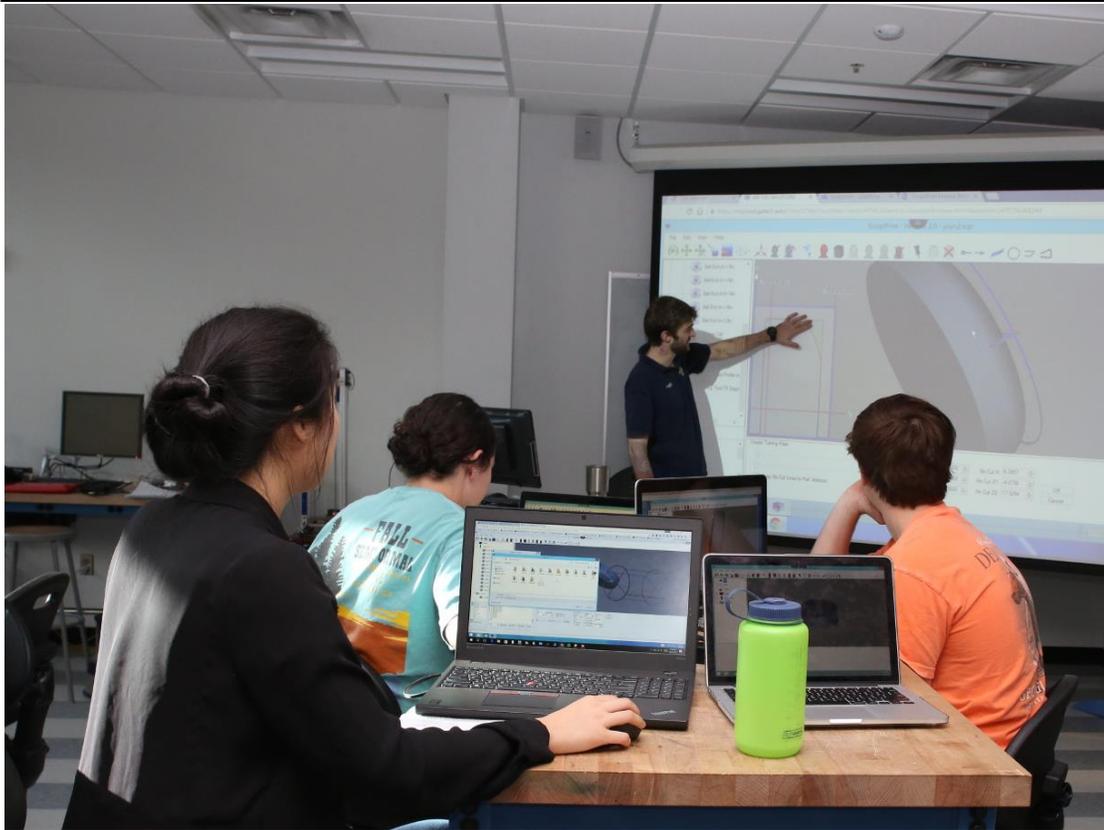


Figure 12. Interactive Training Procedure during Second Implementation

and walked through the procedure for creating separate toolpaths for the front and back of the part. The students were allowed to use their personal laptops to follow along with the instructor during the SculptPrint training and process planning stage. The students were also provided with a written set of example procedures that could be followed to make different parts in SculptPrint, namely the pawn and pulley from the pilot study, as a reference when they were creating the yoyo. Figure 12 shows the training procedure for one of the treatment sections. After the instructor-led training procedure, students were asked to volunteer to explain to the class how they did the process planning for their yoyo

designs. As each student had a separate design for the yoyo half, this provided the other students in the class not only with crowdsourced lectures, but also with a peer's explanation for their choices during the process planning phase.

3.3.2.5.3 Yoyo Machining and Assembly

Once the SculptPrint training had been completed, the students in the treatment group were brought to the Montgomery Machining Mall to create the yoyos. In order to ensure the safety, repeatability and efficiency of yoyo manufacture, the students were not permitted to run the G-Code they created for the yoyos they designed. Instead, they were provided with G-Code written by the author that performed all operations to make the turned features on the front and back of the part in a single program. The work offset for the provided blank size was hardcoded into the program; additionally, the program contained an optional stop in the middle to allow the students to manually flip the part over. During the machining procedure, operation of the Okuma Genos L250 2-axis turning center was explained to the students. The students each ran two parts each and were allowed to control the speed of the machine during the process.

Once all of the turned features had been completed on a part, the students were allowed to transfer the part to the Okuma Spaceturn LB2000EX 4-axis millturn machine to engrave the front pattern. To both avoid setting the work offset on the millturn machine and to provide axial alignment of the part and the machine's spindle, the students used the rig



Figure 13. Alignment Rig for Millturn Machine

shown in Figure 13 to place the part into the machine's collet chuck. The students were provided with two G-Code programs with which to engrave the front of the yoyo half: one of the programs engraved a Georgia Tech logo and the other engraved an image of Georgia Tech's yellow jacket mascot. Each of these programs used a 6.35mm-diameter chamfer mill to create a 0.3mm deep engraving. Students were allowed to choose which, if either, of the engravings they wanted on each of their halves of the yoyo. The yoyo halves were then assembled by the students by pressing a dowel pin into one half of the yoyo using an arbor press; the remaining half of the yoyo was then pressed onto the dowel pin and a shim

was used between the halves to ensure consistency between parts. An engraved and assembled yoyo is shown in Figure 14. For this particular yoyo, a Sharpie was used to



Figure 14. Finished Student Yoyo

enhance the engraving.

3.3.2.6 *SculptPrint Exercises*

After machining training, the treatment group was given an additional assessment that was not provided to the control group. This assessment, known as the SculptPrint Exercises (SPE) was meant to demonstrate the effects of tooling geometry on the turning process. The students were provided with an axisymmetric part, shown in Figure 15, which required

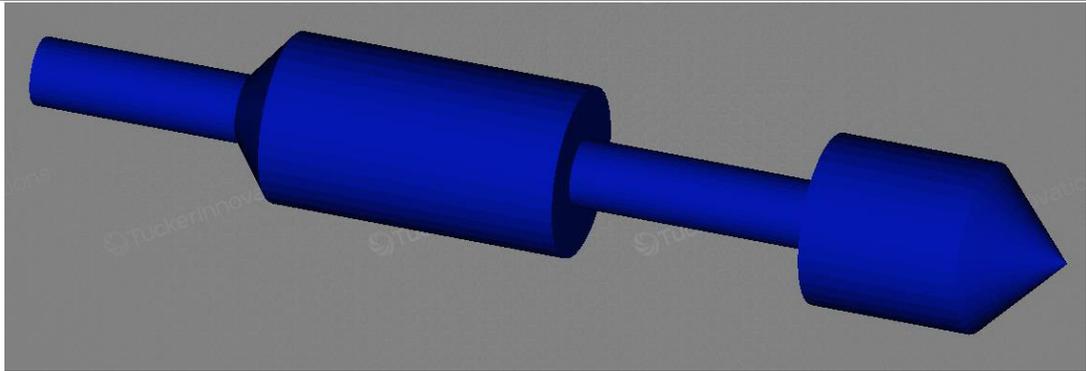
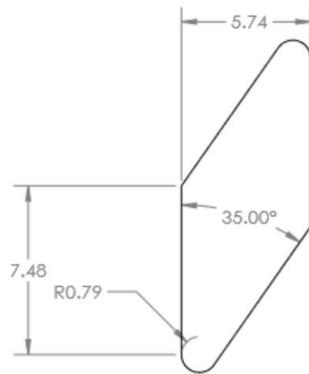
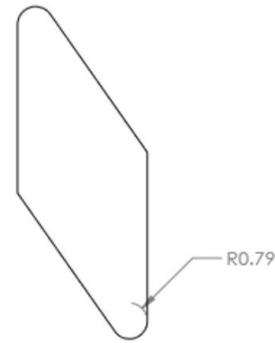


Figure 15. Example Part for SculptPrint Exercises

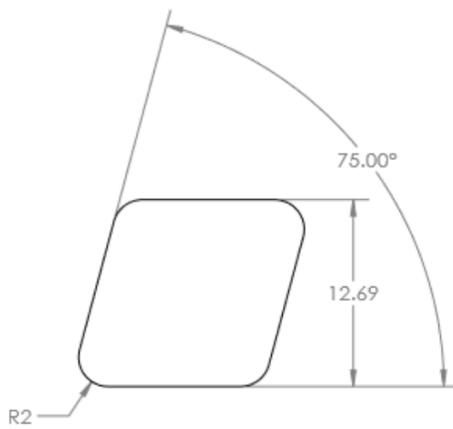
careful consideration of tooling to reach all the features on the part. Students needed to pick multiple tools from a provided tool catalog to completely manufacture the part. This assessment was given using Qualtrics, and students completed it outside of the class using the VMs that had been set up for the study. The geometry of the tool catalog that was provided during the assessment is shown in Figure 16.



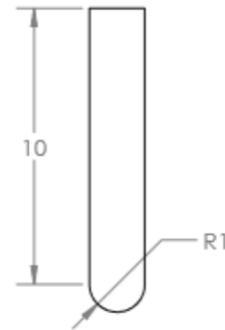
a. Neutral-Lead 35° Right-Handed Insert



b. Neutral-Lead 35° Left-Handed Insert



c. 15°-Lead 75° Right-Handed Insert



d. R.1mm Straight Profiling Insert

Figure 16. Tools Provided for SculptPrint Exercises

The goal of this assignment was to teach the control group about the principles of volumetric subtraction in a turning operation using visualizations. The students were provided with a total of four virtual cutting tools for this assignment: a 35° right-handed tool, a 35° left-handed tool, a 75° right handed tool and a straight profiling tool. Starting

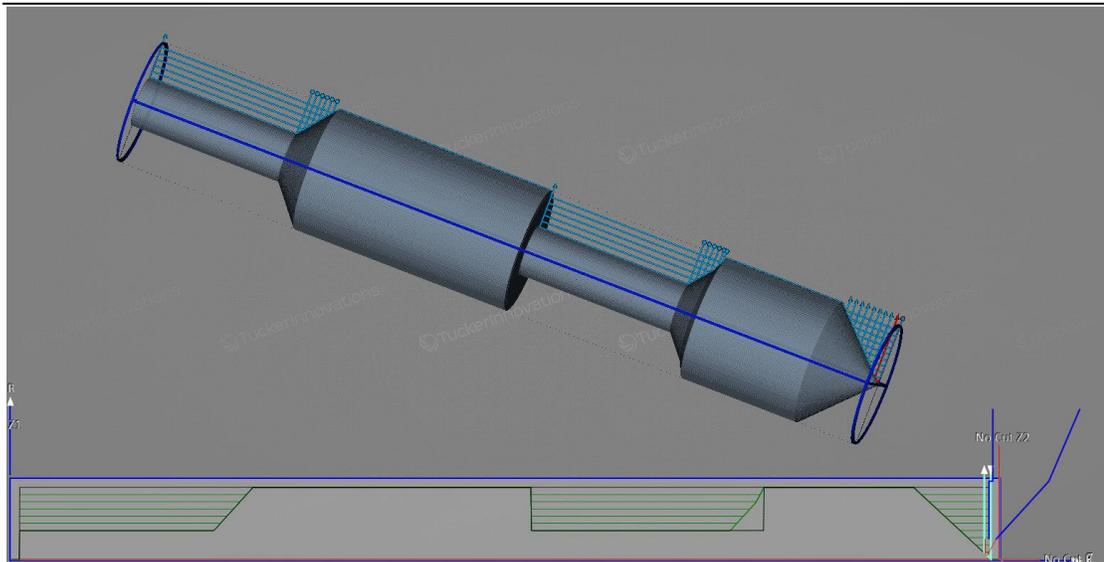


Figure 17. Resulting Part After Turning with 35 Degree Right-Handed Tool

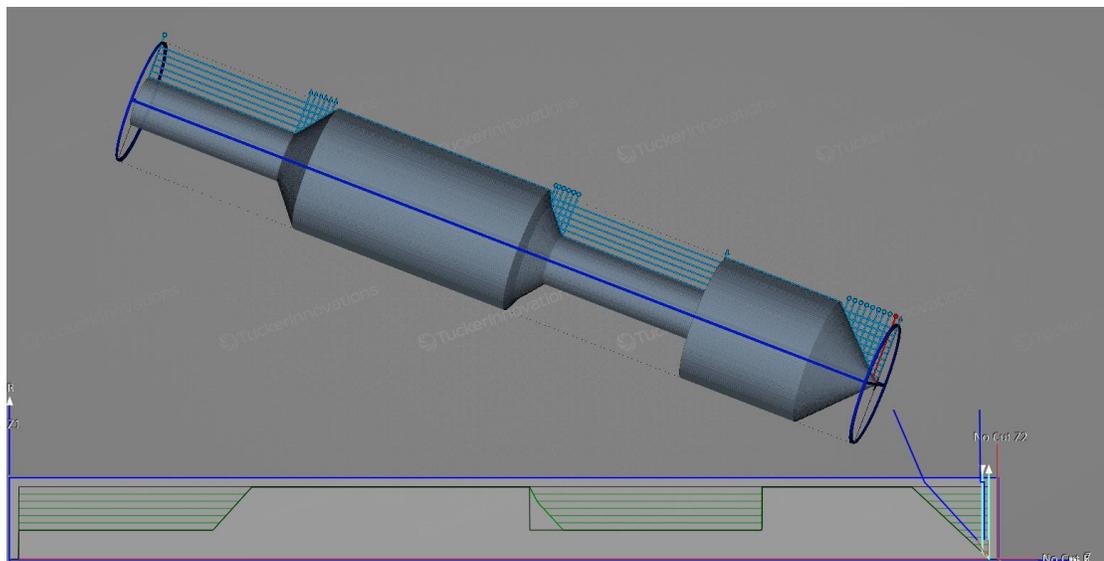


Figure 18. Resulting Part After Turning with 35 Degree Left-Handed Tool

with a cylindrical blank in SculptPrint, they were asked to create a turning pass with each of the provided tools and compare the resulting part after machining simulation to the target part geometry. Figure 17 demonstrates the machining simulation for the 35° right-handed tool (shown in Figure 16a); Figure 18 demonstrates the machining simulation for the 35°

left-handed tool (shown in Figure 16b); Figure 19 demonstrates the machining simulation for the 75° right-handed tool (shown in Figure 16c); and Figure 20 demonstrates the machining simulation for the straight profiling tool (shown in Figure 16d). The resulting volume of the part after turning is shown in grey in the top portion of each Figure, and the

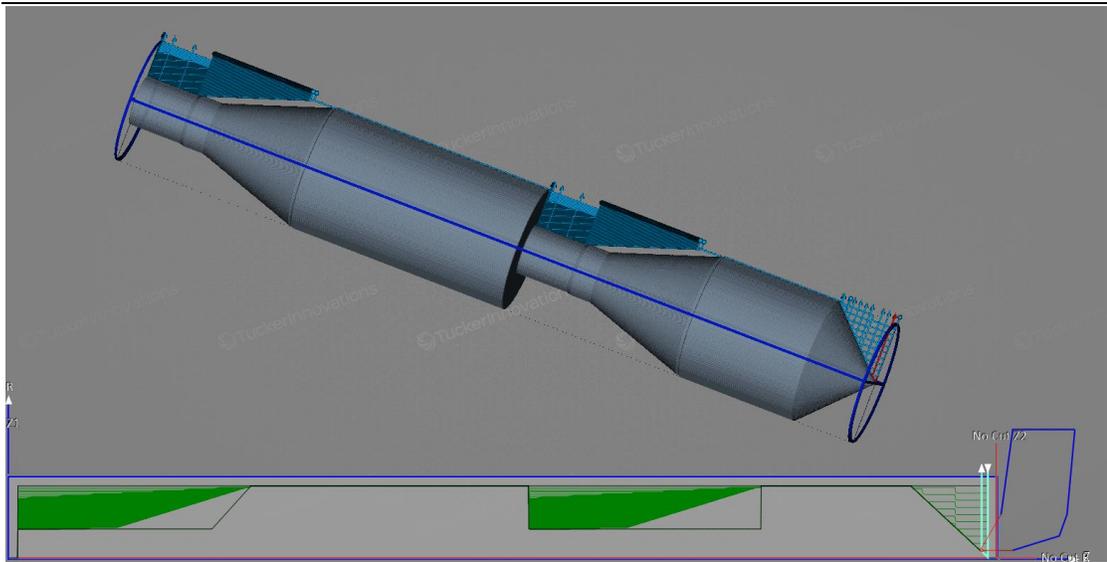


Figure 19. Resulting Part After Turning with 75 Degree Right-Handed Tool

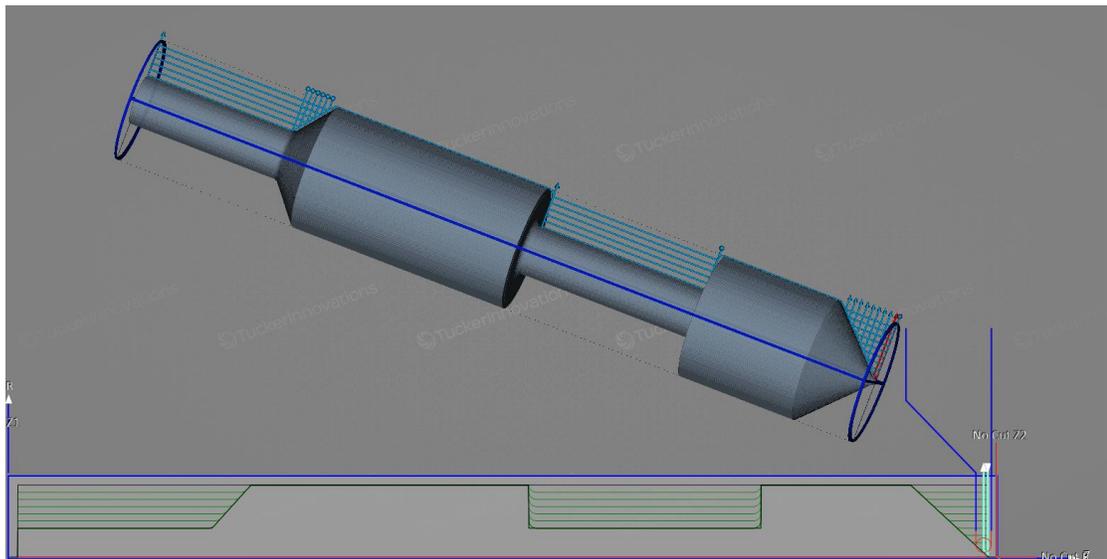


Figure 20. Resulting Part After Turning with Straight Profiling Tool

outline of the cylindrical stock is shown as blue lines around the part volume. The proposed toolpath is shown in two dimensions at the bottom of each Figure. Green lines denote the path of the tip of the nose radius of the selected cutting tool, for which the outline of the cutting insert is shown in red.

From these simulations, it is clear that both right- and left-handed tools can cut the chamfer at the front of the part, but the reliefs between the inner and outer diameters of the part present problems. The right-handed tooling can cut straight reliefs in the negative axial direction, and the left handed tooling can cut straight reliefs in the positive axial direction. The profiling tool can cut all of the reliefs, but large internal radii are left in the corners. Additionally, attention must be paid to the geometry of the insert holder, which is shown in blue in each Figure. Students were asked to drag a slider that allowed for an interactive animation of the cutting process; this showed them how the tool first progresses axially along the part during the cutting process and then steps further downward in the radial direction until the desired dimension is achieved. After performing each of the simulations, the students were asked to describe the differences they observed between the resulting parts and the target part geometry. The complete SPE survey is presented in APPENDIX F.

3.3.2.7 Post Test

The Post Test (PostT), which was given simultaneously with the second deployment of the Process Questions, was the most in-depth assessment that was given to the students. The questions on the PostT were designed to gauge how effective the visualization of the turning process was in helping the students learn about subtractive manufacturability; as a

Table 6. Question Types in the Post-Test

Question Type	Assessment Question Example
<i>Machine Capability</i>	Should a lathe or mill be used for an asymmetric part?
<i>Volumetric Subtraction</i>	Why would a left-handed tool be used instead of a right-handed tool?
<i>Process Selection</i>	Should machining or 3D printing be used to make a part that must withstand a substantial amount of force?
<i>Process Design</i>	In what order should the following turning operations be done to minimize the number of setups?

result, a large portion of the questions in the PostT focused on finer geometric details of the turning process. Table 6 summarizes the types of questions that were asked in the PostT.

The entire Post Test is shown in APPENDIX G.

Additionally, some of the questions in the PostT asked the students to sketch the result of a turning operation given a certain tool. As was the case with the SculptPrint Exercises, the students were provided with a drawing of the tooling that was available in a particular machine. They were also provided with a drawing of a part to be made, which was similar to the one used in the SculptPrint Exercises. However, the part given to the students in the PostT had a number of distinct differences; namely, it had additional diameters, fillets and

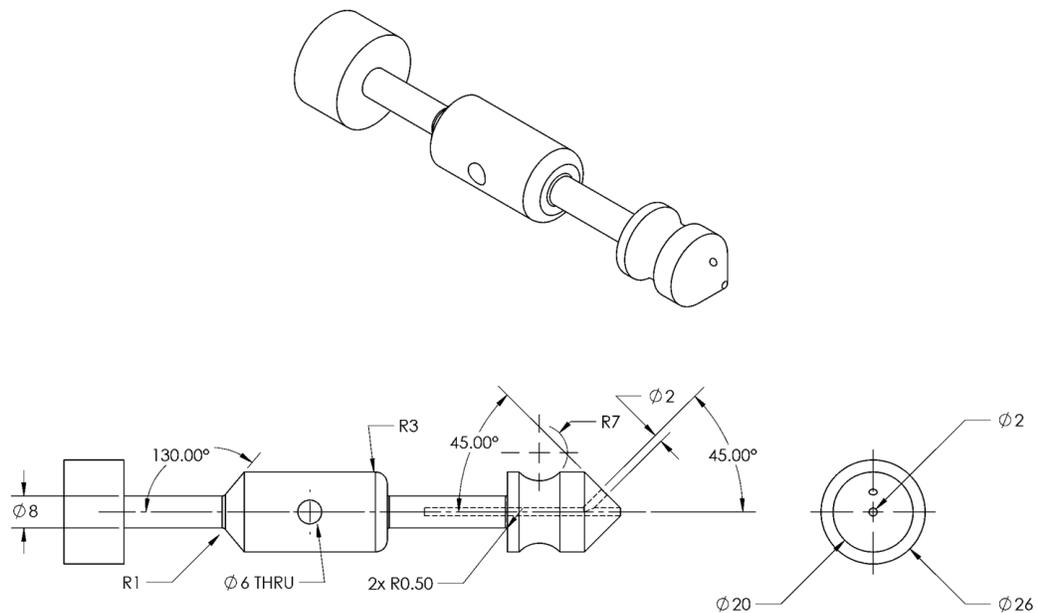


Figure 21. Part Print Provided for Post-Test

holes that were not present in the part they were provided with during the SPE. Figure 21 shows the drawing of the part that was provided to the students for the PostT. The students were able to sketch using the Signature question type that was provided by Qualtrics; the resulting sketches were saved as images and downloaded after completion of the survey for analysis.

3.3.2.8 *Process Questions Post*

The Process Questions assessment was repeated in an identical form after machining training for both groups to study differences in how the students thought about manufacturing process choice after being exposed to their respective training protocols. This assessment was referred to as the Process Questions Post (PQP) assessment. Comparison of the scores between the PQ and PQP gives some insight into the effectiveness of the training procedures in educating students about the most efficient choice for a manufacturing process given a certain part.

3.3.2.9 *Data Cleaning*

Upon student completion of all the deployed surveys and receipt from the TAs of indication of which students were given credit for each assignment, all collected data were exported from Qualtrics and cleaned of unusable records. Incomplete student responses were removed from the data set, as were duplicate responses. Occasionally, students would submit a response to the same survey multiple times; for consistency, only the first received response was retained. Additionally, to allow for a complete comparison of the students across all assessments, participants who did not complete each assessment fully were

Table 7. Summary of Data Loss from Both Groups

	Percent Loss
<i>Control</i>	35.92%
<i>Treatment</i>	59.46%
Total	39.50%

removed from the population, as were the students who did not provide consent for their data to be published. This was performed by intersecting a list of unique identifiers tied to

each student for each assessment. Once cleaning of the data was complete, a total of 147 records remained. This number is in contrast to the course enrollment of 243 students, which indicates that 39.5% of the data set was lost. Table 7 shows the loss of data for both the control and treatment groups.

4 RESULTS

The data gathered from assessments designed to measure student understanding of design for manufacturability are analyzed in this chapter. Both the data from the pilot study and the larger second implementation are presented and analyzed. This section presents the results from each assessment in the order in which it was deployed. The scores on the assessments are broken into the treatment and control groups, and statistical analysis is performed to determine the significance of the differences observed between the two groups. The results are discussed and relevant qualitative findings are also presented with each assessment. In order to control for variability that could arise with responses coming from students with varying amounts of understanding, filtered results that only came from students with minimal experience are presented when they were found to be significantly different from the results from the entire population.

4.1 PILOT STUDY

The pilot study of using SculptPrint to enhance student understanding of manufacturability was performed in the Spring of 2016. Before any training began, the students participating

Table 8. Prior Experience of Students in Pilot Study

	Number of Students	Percentage of Population
<i>Manual Experience</i>	9	32.1%
<i>CNC Experience</i>	1	3.6%

in the study were verbally surveyed on their prior experience in manufacturing. Of the 28 students participating in the study, 9 of them indicated that they had prior manual machining experience, and one indicated prior CNC experience. These results are

summarized in Table 8. The population was then divided into control ($n = 21$) and treatment ($n = 7$) groups. After creation of the groups, 2 students with prior manual machining experience and 1 with prior CNC experience were in the treatment group.

4.1.1 BEFORE AND AFTER SCORES

The students participating in the study were given the same assessment before and after machining training to study the score differences between the control and treatment groups. The scores on this assessment for both control and treatment groups before and after training is shown in Table 9 [10]. The mean difference between scores before and after

Table 9. Score Statistics for Pre- and Post-Assessments in Pilot Study

	Before Training		After Training		$\Delta\mu$
	μ	σ	μ	σ	
<i>Control</i>	1.86	1.31	2.88	1.86	0.76
<i>Treatment</i>	1.29	1.50	4.66	2.34	3.17

training, $\Delta\mu$ was calculated using Equation 6,

$$\Delta\mu = \mu_{i,\text{Before}} - \mu_{i,\text{After}} \quad (6)$$

where $\mu_{i,\text{Before}}$ and $\mu_{i,\text{After}}$ are the before and after training scores, respectively, for either the control or treatment group i . Although the sample sizes are small, the treatment group demonstrated an improvement in mean score over that of the control group. This result suggested that the visualizations performed by the treatment group were successful in increasing their understanding of the turning process.

4.1.2 LESSONS FROM PILOT STUDY

Two main observations were made during the pilot study that subsequently formed the basis for the design of the second implementation. First of all, the assessments in the pilot study were deployed on paper and consisted of only free response questions; this required human grading of the assessments. Although this was acceptable for a small sample size and a small number of surveys, it would be unrealistic for larger-scale data collection. The second observation was that the population size used in the pilot study was much too small to provide reliable results. As a result, the second implementation utilized a larger population in conjunction with computer-based surveys.

4.2 SECOND IMPLEMENTATION

The second implementation of this study built on the work done in the pilot study and incorporated changes to reflect the relevant observations from the pilot study.

4.2.1 STUDENTS' PRIOR EXPERIENCE IN MANUFACTURING

The goal of the Preassessment, which was the first assessment given to the students, was to gather data on students' prior experience with a range of manufacturing processes; this

Table 10. Prior Experience by Section

Section	3D Printing Experience	CNC Experience	Laser Cutter Experience	Lathe Experience	Mill Experience	Welding Experience
<i>A</i>	9	3	2	8	7	2
<i>B</i>	8	1	2	4	6	5
<i>C</i>	8	2	3	3	2	3
<i>D</i>	6	2	2	2	4	1
<i>E</i>	12	2	6	4	4	3
<i>F</i>	8		2	4	4	2
<i>G</i>	5	1	1		1	4
<i>H</i>	5	3	4	1		
<i>I</i>	11			3	6	2
<i>J</i>	8	3	4	5	6	3
<i>K</i>	14	2	3	4	4	3
<i>L</i>	10	5	4	4	3	3
<i>M</i>	7	3	3	1	3	1
Total	111	27	36	43	50	32
Percent	75.5%	18.4%	24.5%	23.2%	34.0%	21.8%

allowed for filtration of the data from later assessments as a function of prior experience and familiarity with manufacturing. The prior experience reported by all of the students in the population is summarized in Table 10. Not surprisingly, the highest percent of students surveyed had prior experience with 3D printing (75.5%), while the lowest percentage of students had experience in CNC machining (18.4%). The percentages in Table 10 were calculated using Equation 7,

$$\text{Percent} = \frac{\text{Experience}_i}{n} \% \quad (7)$$

where Experience_i is the total number of students indicating experience with a given process and n is the size of the sample, which was 147 students in this case. Students were

allowed to select multiple areas of prior experience for this question. The students' prior experience in 3D printing can be attributed to the fact that Mechanical Engineering students at Georgia Tech are required to enroll in ME1770, the introductory CAD course, before enrolling in ME2110; while in ME1770, the students are required to 3D print parts for their projects. Additionally, non-ME students are allowed to enroll in ME2110, and those students may be from the Business school and have no prior experience with any manufacturing process.

As explained in Section 3, only sections G and H were exposed to the modified training procedure, while the remainder of the sections were subjected to the typical manual machining training. Grouping the sections into the control and treatment groups enables

Table 11. Prior Experience by Group

Group	3D Printing	CNC	Laser Cutter	Lathe	Mill	Welding
Control	101	23	31	42	49	28
Percent	76.5%	17.4%	23.5%	31.8%	37.1%	21.2%
Treatment	10	4	5	1	1	4
Percent	66.7%	26.7%	33.3%	6.7%	6.7%	26.7%

better analysis of whether the experimental group was at an unfair advantage due to prior experience. For the remainder of this section, results will always be reported by group, rather than section, as the various sections of the control and treatment groups are irrelevant. Table 11 shows the results of the prior experience survey for both control and experimental groups. The percentages were calculated according to Equation 8,

$$\text{Percent} = \frac{\text{Experience}_i}{n_i} \% \quad (8)$$

where n_i is size of either the control or treatment group. These data are displayed graphically in Figure 22.

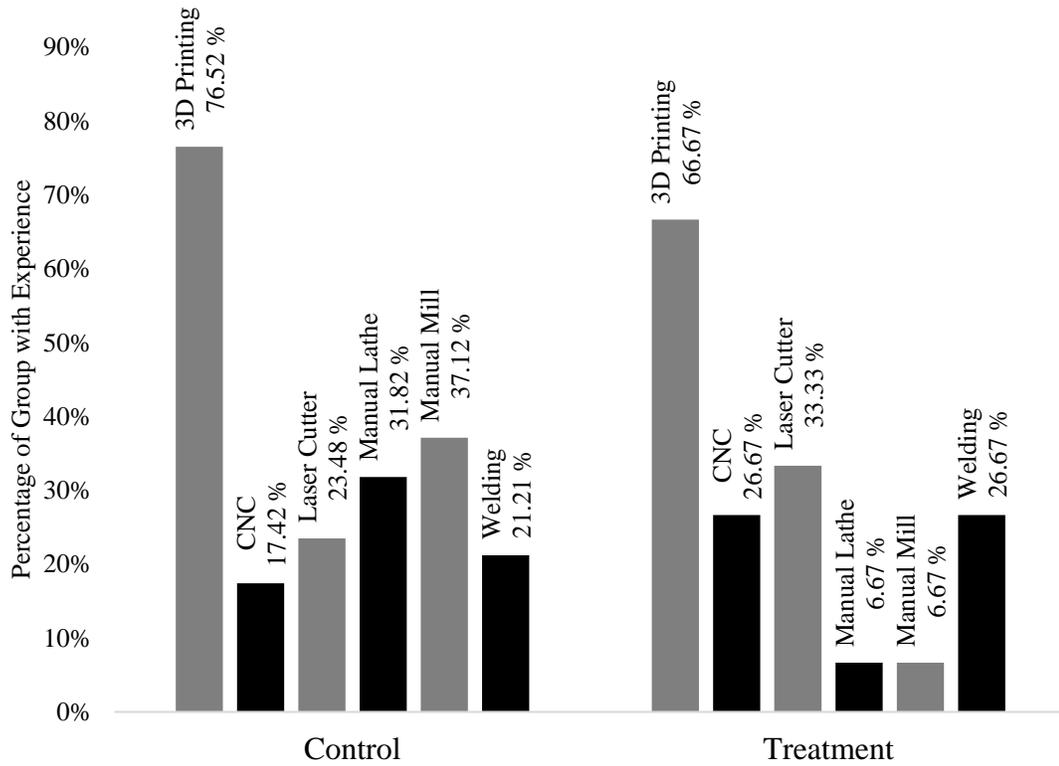


Figure 22. Percentage of Prior Experience by Group

4.2.1.1 Manufacturing Processes with Which Students Are Most Comfortable

Table 12. Students' Indication of Which Process They Are Most Comfortable With

Group	3D Printing	CNC	Laser Cutter	Lathe	Mill	Welding	None
Control	53	3	9	11	11	10	35
Percent	40.2%	2.3%	6.8%	8.3%	8.3%	7.58%	26.52%
Treatment	8	0	3	0	0	0	4
Percent	53.3%	0%	8.16%	0%	0%	0%	26.67%

Due to students' prior experience with 3D printing as a result of enrollment in ME1770, it was theorized that they would report 3D printing as the manufacturing process they were most comfortable with during the Preassessment. Table 12 presents the students' indication of which manufacturing process they were most comfortable with. The possible answer

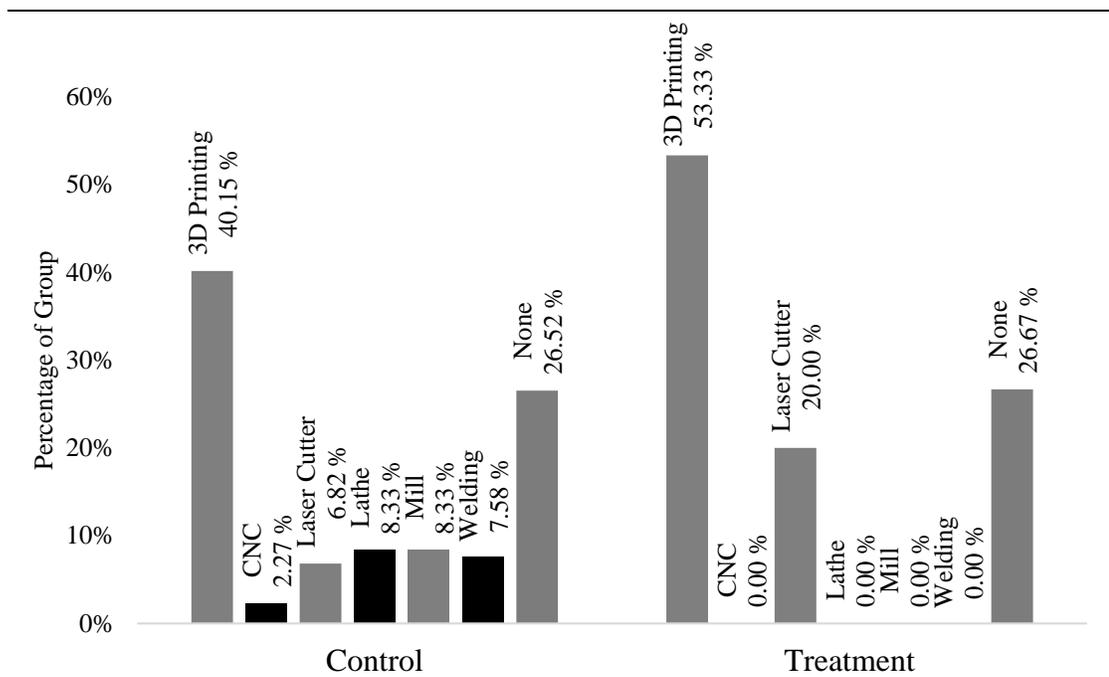


Figure 23. Percentage of Most Comfortable Process by Group

choices for this question were: 3D printing, CNC machining, manual turning, manual milling, welding, laser cutting and none of the above. Figure 23 shows the percentage of students by group for each of the possible process choices.

4.2.2 GENERAL MANUFACTURING QUESTIONS BEFORE MACHINING TRAINING

To allow for analysis of differences between the control and treatment groups before they underwent their respective training protocols, all students in the population were asked to complete the PreTest before any of them participated in any training. The questions on the PreTest were designed to simply gauge students' familiarity with additive and subtractive processes and to allow for comparison between students' reported familiarity with AM and SM and their answers to a collection of AM and SM questions. The students were actually exposed to all of the material they would need to answer these questions by the time the assessment was deployed, as it was addressed in the Intro to Machining lecture that was given to the entire class during the third week of the study. The answers to these questions serve not only to highlight differences between the control and treatment groups before training, but also to provide insight into areas where SM training for undergraduates can be improved in future courses.

4.2.2.1 *Questions Concerning Differences Between Additive and Subtractive Manufacturing Processes*

The PreTest contained two distinct questions that asked students explicitly about differences between AM and SM processes. The first of these questions asked if turning

was an additive or subtractive operation. Because the implementation of this study was

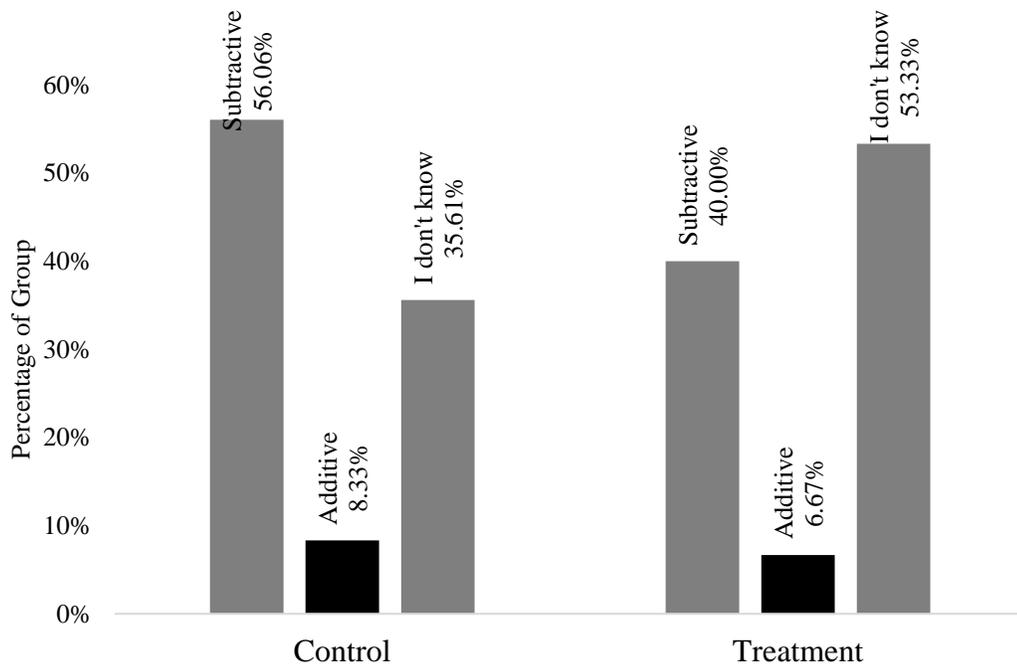


Figure 24. Student Responses to Whether Turning is an Additive or Subtractive Operation

focused on turning, rather than milling, it was important to understand if students knew what turning was before participating in the training procedures. Figure 24 shows the distribution of student responses to this question. Although the students were explicitly told that turning is a subtractive operation in the lecture, it is clear that many of them were either absent or not paying attention. Interestingly, even after removal of all students that did not have prior machining experience before the study, some still did not know the difference between additive and subtractive manufacturing in regards to turning. Figure 25 shows the answer distribution for this question for only the students that already had experience in both milling and turning. As shown in Table 11, no students in the treatment group reported previous experience in both milling and turning, so only students from the control group

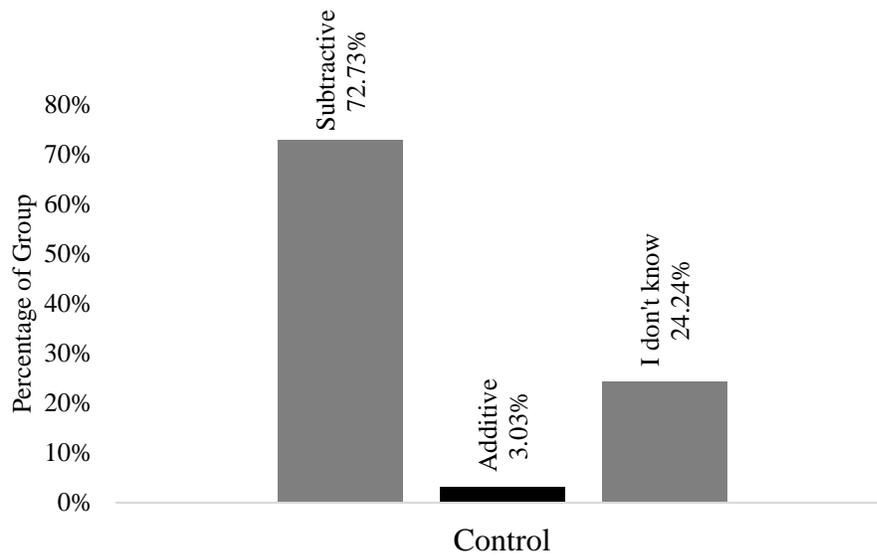


Figure 25. Student Responses to Whether Turning is an Additive or Subtractive Operation for Students with Both Milling and Turning Experience

are shown in Figure 25. It is clear from this result that vocabulary and terminology of

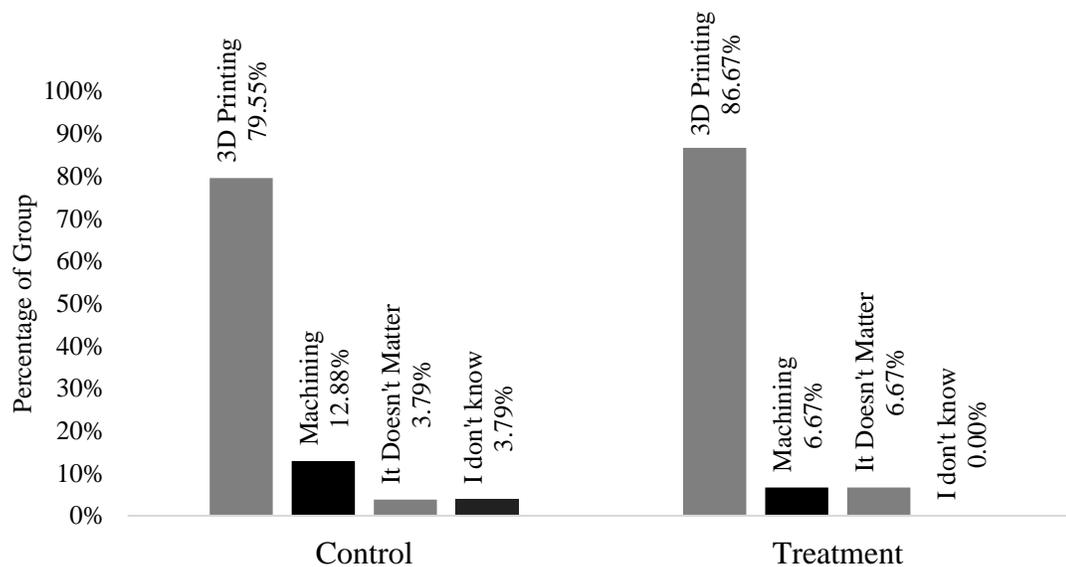


Figure 26. Student Indication of Which Process Should be Used to Quickly One-Off a Part to Check Rough Sizing

manufacturing processes can be confusing to students.

The next question concerning the differences between AM and SM processes asked students which process should be used to quickly one-off a part with complex geometry in order to roughly check the size of the part. As expected, the majority of students in both groups indicated that 3D printing should be used instead of machining. Figure 26 shows the student responses to this question by group. Most of the students taking ME2110 were required to first take ME1770, where they were exposed to 3D printing and employed 3D printers for the specific reason of prototyping parts.

4.2.2.2 Questions Concerning the Fundamentals of Machining

The other group of questions on the PreTest was concerned with fundamental aspects of turning and milling processes. These questions served both to examine students' vocabulary and to determine if they understood the broad differences between milling and turning. While the distinctions between milling and turning have begun to blur somewhat

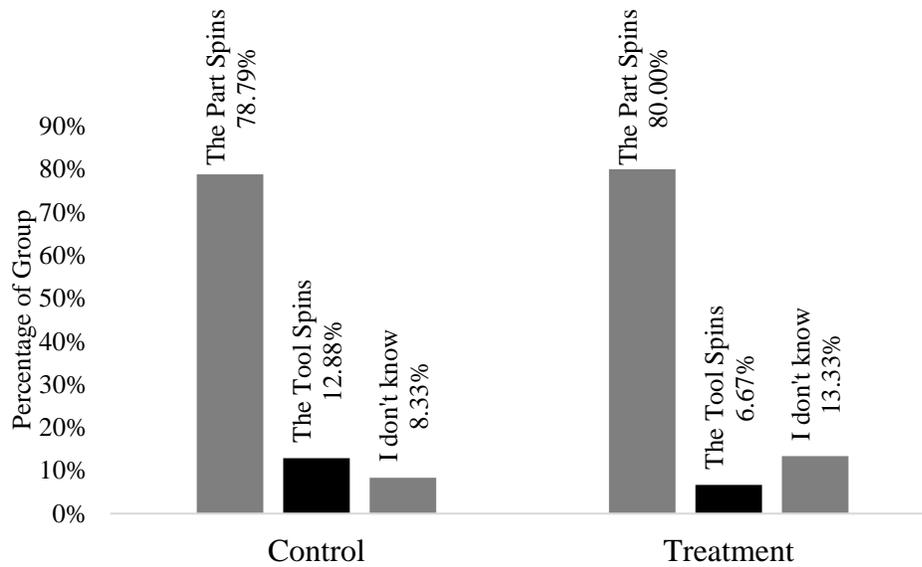


Figure 27. Student Responses to Whether the Part or Tool Spins in a Lathe

with the advent of complex multi-tasking machine tools, for the purposes of this assessment it was assumed that the number of students unfamiliar with such multi-tasking machines was far greater than those who were familiar with them.

4.2.2.2.1 Machine Tool Configuration

The first question in this group asked students if the part or the tool spun in a turning process. Again, the students were already taught the answer to this question during the Intro to Machining lecture. The student responses to this question are presented in Figure 27.

4.2.2.2.2 Workholding

The next machining fundamentals question asked students if a vise would be used in a mill or a lathe. Again, due to the expansion of capabilities of modern multi-tasking machine tools, there are times where a vise would be used on a lathe. For example, if a machinist wanted to clamp a prismatic piece of material into the spindle of a 5-axis lathe and then



Figure 28. Vise Shown to Students in PreTest

perform machining operations on it, that would be possible with a self-centering vise.

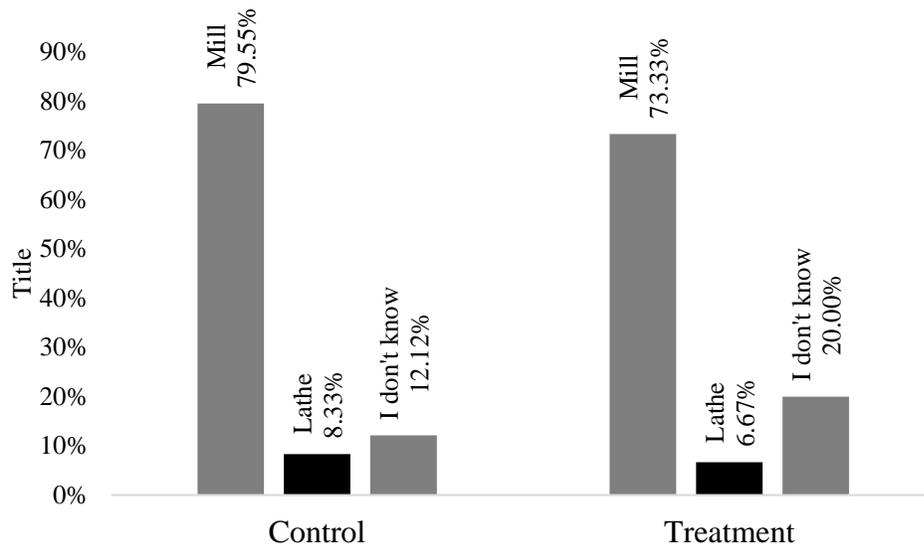


Figure 29. Student Responses to Whether a Vise Should be Used on a Mill or a Lathe

However, for the purposes of this question, it was assumed that the majority of students were unfamiliar with either multi-tasking machine tools or self-centering vises. In fact, the students were even shown a picture of a vise to eliminate any problems with vocabulary. The vise shown to the students is presented in Figure 28 [50]. To further underline the fact that a vise is most often used in a milling machine, the example vise has manual XY axes. Despite this, however, some students either did not know or stated that a vise should be used on a lathe. Figure 29 shows the distribution of responses to this question. Surprisingly, the number of students in the control group answering this question correctly increased to 100% when only the students who selected 3D Printing as the process they were most comfortable with were selected. Additionally, all students who indicated that they were most comfortable with milling answered this question correctly.

4.2.2.2.3 Machine Capability

The questions regarding machine capability were meant to determine if students correctly understood when to use a milling machine and when to use a lathe. Both questions were formulated the same way: the first asked students if a lathe would be used to make an axisymmetric part and the second asked students if a mill would be used to make an axisymmetric part. The questions were designed this way both to probe students' understanding of the term "axisymmetric" and to determine if they were familiar with the

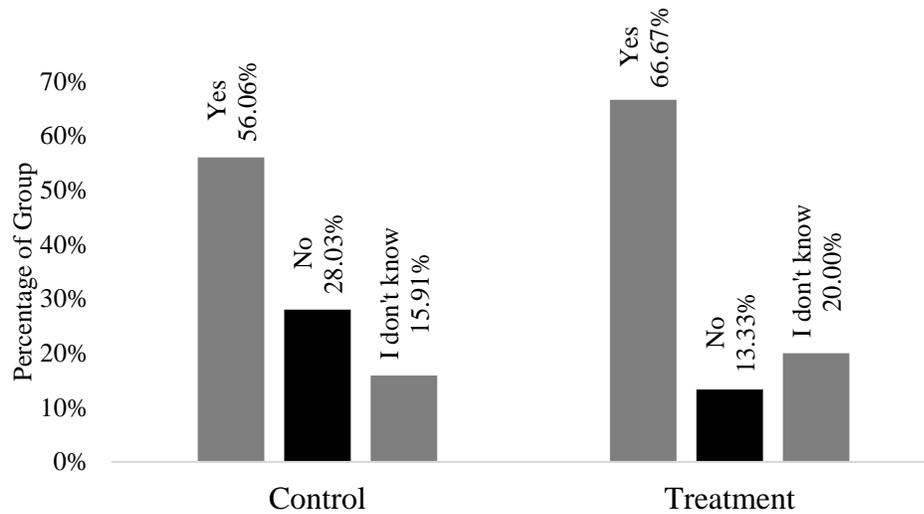


Figure 30. Student Responses to Whether a Lathe Should Be Used to Make an Axisymmetric Part

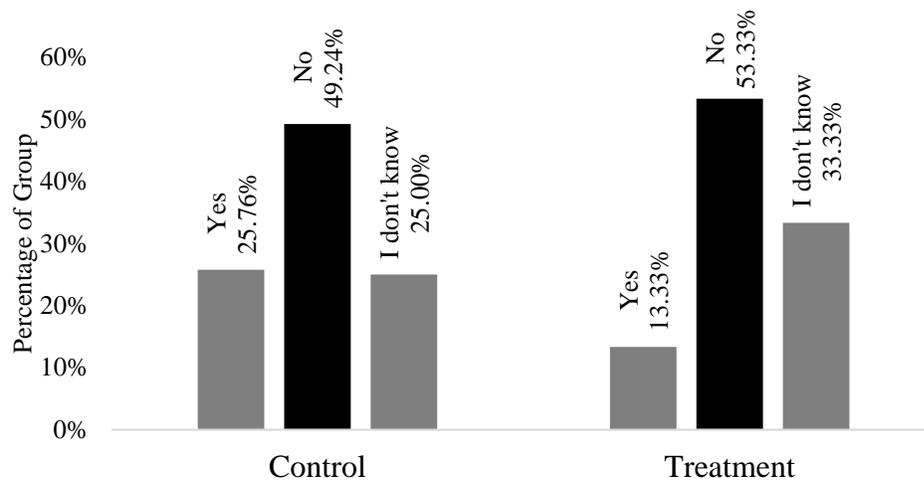


Figure 31. Student Responses to Whether a Mill Should Be Used to Make an Axisymmetric Part

basic concept of a milling machine as opposed to a lathe. The student responses to both of these questions are shown in Figure 30 and Figure 31, respectively.

After each of the machine capability questions, students were asked why they chose the answer they did for each question. In an effort to determine if students understood the

difference between the terms “axisymmetric” and “asymmetric”, a simple word search was performed on the text responses for both the students that responded that a mill should be used to make an axisymmetric part and the students who responded that a lathe should not

Table 13. Results from Text Analysis of Students Who Indicated that a Lathe Should Not Be Used to Make an Axisymmetric Part

	Number of Students Indicating that a Lathe <i>Should Not</i> Be Used to Make an Axisymmetric Part	Response Contains “Asymmetry” or “Asymmetric”	Response Indicates Lack of Understanding of “Axisymmetric”
Control	37	8.11%	83.78%
Treatment	2	0.0%	100.0%
Total	39	7.69%	84.62%

be used to make an axisymmetric part. The word search looked for the words “asymmetry” and “asymmetric” in the student responses. Additionally, a machining expert was asked to manually grade the text responses of the students in these two groups to determine if their response indicated that they understood the meaning of the word “axisymmetric”. Table 13 presents the results of this analysis performed on the group of students who indicated that a lathe should not be used to make an axisymmetric part. The same analysis was performed on the text responses of the students that indicated that a mill should be used to make an axisymmetric part; additionally, the student responses were manually examined to determine if their response indicated that they did not understand the meaning of “axisymmetric”. The results from this analysis are presented in Table 14. It is worth noting that the remaining percentage of responses for which a lack of understanding of the word “axisymmetric” was not established were not necessarily indicative of an *understanding* of the word “axisymmetric”. For many of the responses, the text was somewhat unintelligible and a reliable measure of the students’ understanding could not be determined. It is surely unsettling that many students responded to a question about axisymmetry with a text

response that employed the word “asymmetry”, and indicates that further development of the students’ vocabulary is essential in increasing their understanding of manufacturing

Table 14. Results from Text Analysis of Students Who Indicated that a Mill Should Be Used to Make an Axisymmetric Part

	Number of Students Indicating that a Mill <i>Should</i> Be Used to Make an Axisymmetric Part	Response Contains “Asymmetry” or “Asymmetric”	Response Indicates Lack of Understanding of “Axisymmetric”
<i>Control</i>	34	14.70%	32.35%
<i>Treatment</i>	2	0.0%	50.0%
<i>Total</i>	36	13.89%	33.33%

and manufacturability.

4.2.2.3 Performance on Pre-Training Questions by Group

It was expected that no significant differences would be present between control and treatment groups on the assessment scores before training, as both groups were drawn from the same population. The format of the pre-training questions allowed for simple scoring; Table 15 presents the score results from these questions, by group, out of a total of six

Table 15. Score Statistics on Pre-Training Questions by Group

	μ	σ	$\Delta\mu$	95% CI for $\Delta\mu$	t -Statistic	p -Value	df
<i>Control</i>	4.24	1.51	+0.091	(-0.689, 0.871)	0.24	0.809	18
<i>Treatment</i>	4.33	1.35					

points. A two sample t -test was performed using Equation 5, which yielded a t -statistic of 0.24. This corresponds to a p -value of 0.809, which suggests that there was no significant difference between the two groups in understanding of manufacturing concepts before the training began. The mean difference between the groups is defined by Equation 9,

$$\Delta\mu = \mu_{\text{Treatment}} - \mu_{\text{Control}} \quad (9)$$

where $\mu_{\text{Treatment}}$ and μ_{Control} are the mean scores of the treatment and control groups, respectively.

4.2.3 MANUFACTURING PROCESS CHOICE BEFORE AND AFTER MACHINING TRAINING

Each student was asked to complete the Process Questions (PQ) assessment before machining training and an identical Process Questions Post (PQP) assessment after machining training. This assessment was designed to measure how students thought about choosing a manufacturing process when prompted with a part image. The assessments were scored out of a total of eight points, and the student responses to each question and final score distributions before and after training are analyzed in this section. Students were also provided with a text box to explain their answers to each question, which allowed for text analysis of relevant observations for each of the different questions. The eight questions on the PQ and PQP can be broadly classified into the following categories: process choice for milled parts, process choice for turned parts, process choice for additively-manufactured parts, process choice for millturned parts and machine tool selection for a complex milled part. The broad overview of these questions was presented in Figure 8 of Section 3.3.2.8, and each question is described in detail below. where the correct answers are given in Figure 8.

4.2.3.1 Student Process Choice for Milled Parts

There were three questions on the PQ and PQP assessments that referenced pictures of



a. Part for PQ 2



b. Part for PQ 3

Figure 32. Strictly Milled Parts Given in PQ and PQP

parts that had been milled. One of these questions asked the students about CNC machine selection rather than about manufacturing process selection, and will be discussed in a later section. The two remaining questions, which were questions 2 and 3, referenced the parts shown in Figure 32a and Figure 32b. Both of these parts were clearly processed on a milling

machine at some point during their manufacture, as indicated by the parts' geometry, toolmarks and presence of drilled and tapped holes. As a result, it was expected that the majority of students would select milling when asked which process would be used to make

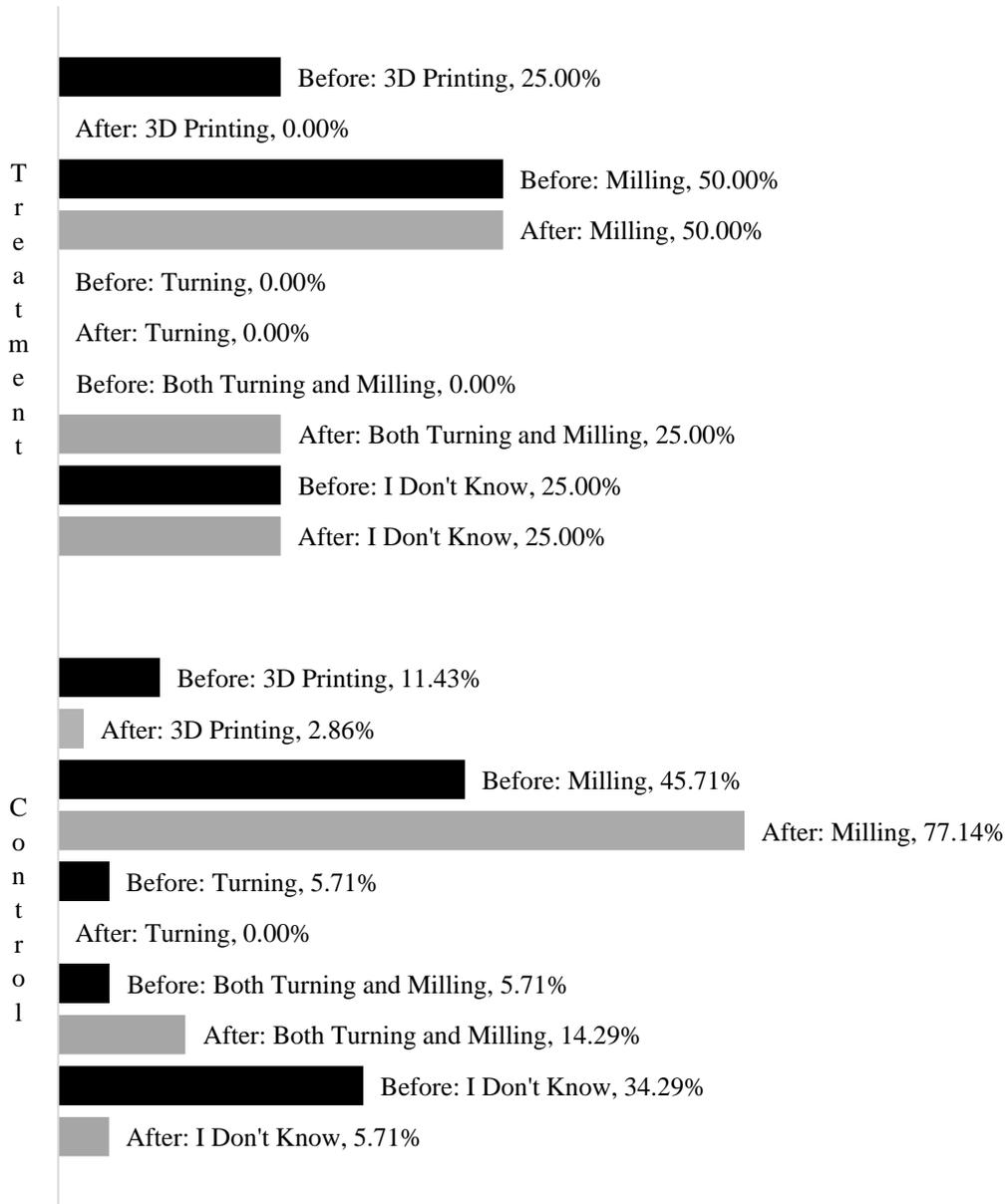


Figure 33. Student Responses to Which Process Should Be Used to Make the First Milled Part Shown in the PQ and PQP

these parts. The provided answer choices were “3D Printing”, “Milling”, “Turning”, “Both Turning and Milling” and “I Don’t Know”. The student responses the second question on the PQ and PQP, for which the prompt image is given in Figure 32a, are shown in Figure

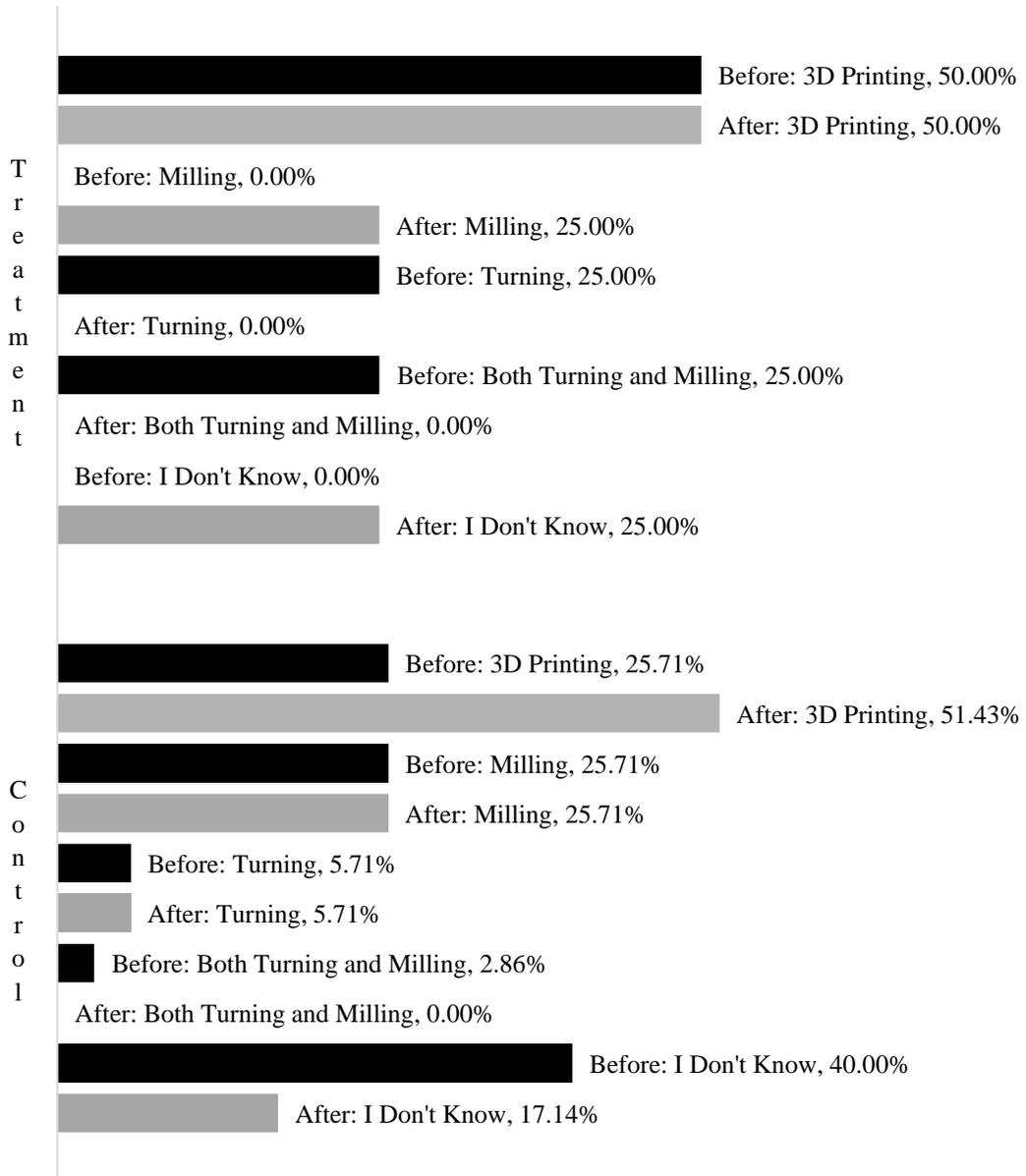


Figure 34. Student Responses to Which Process Should Be Used to Make the Second Milled Part Shown in the PQ and PQP

33. Note that responses labeled “Before” are the percentage of students per group that chose a particular process to answer this question before machining training; likewise, responses labeled “After” indicate the percentage of students per group that chose a given process after machining training. The student responses to the second milled part, which is shown in Figure 32b, are presented in Figure 34. Perhaps the most useful observation from these data is the fact that student responses of “I Don’t Know” decreased for both groups in both questions after training. Additionally, it is interesting to note that the percentage of students selecting “Both Turning and Milling” increased in some cases after training. As was the case in prior assessments, students were asked to textually explain their choice of manufacturing process after each question in the PQ and PQP. A manual text analysis was performed on the responses of students who selected “Both Turning and Milling” after machining training for the first mill part question on the PQ and PQP. This analysis revealed that many of the students selected to both turn and mill because there were some

Table 16. Test Analysis for Students Responding with “Both Turning and Milling” for the First Milled Part Question on the PQ and PQP After Machining Training

	Number of Students Who Selected Both Turning and Milling for the First Milled Part Question After Training	Percentage of Students Who Indicated that both Turning and Milling were needed for Axisymmetric and Asymmetric Features
<i>Control</i>	12	58.33%
<i>Treatment</i>	4	75.0%
<i>Total</i>	16	68.75%

axisymmetric features on each part. The results of this analysis are presented in Table 16.

4.2.3.2 Student Process Choice for Turned Parts

Parts that had clearly been turned were also included in the PQ and PQP assessments. Students were asked to choose the best process for the two distinct parts that are shown in Figure 35. The first part, a pawn from a chess set, was shown as machined by the author to



a. Turned Part for PQ 1



b. Turned Part for PQ 6

Figure 35. Turned Parts Used for PQ and PQP

determine if the fact that the part was made of plastic would have an effect on the students' choice of process to manufacture it. Not coincidentally, this is the exact same part that was made by the students in the pilot implementation of this study in Spring 2016. These two parts were placed as questions 2 and 6, as indicated in Figure 35a and Figure 35b, respectively. As expected, student responses indicating that the parts should be turned increased after machining training. Figure 36 shows the response choices by group for the first turned part, the pawn. Again, students were allowed to pick one response from the

following list: “3D Printing”, “Milling”, “Turning”, “Both Turning and Milling” and “I Don’t Know”. The student responses to the second turned part, a metallic pipe reducer, are

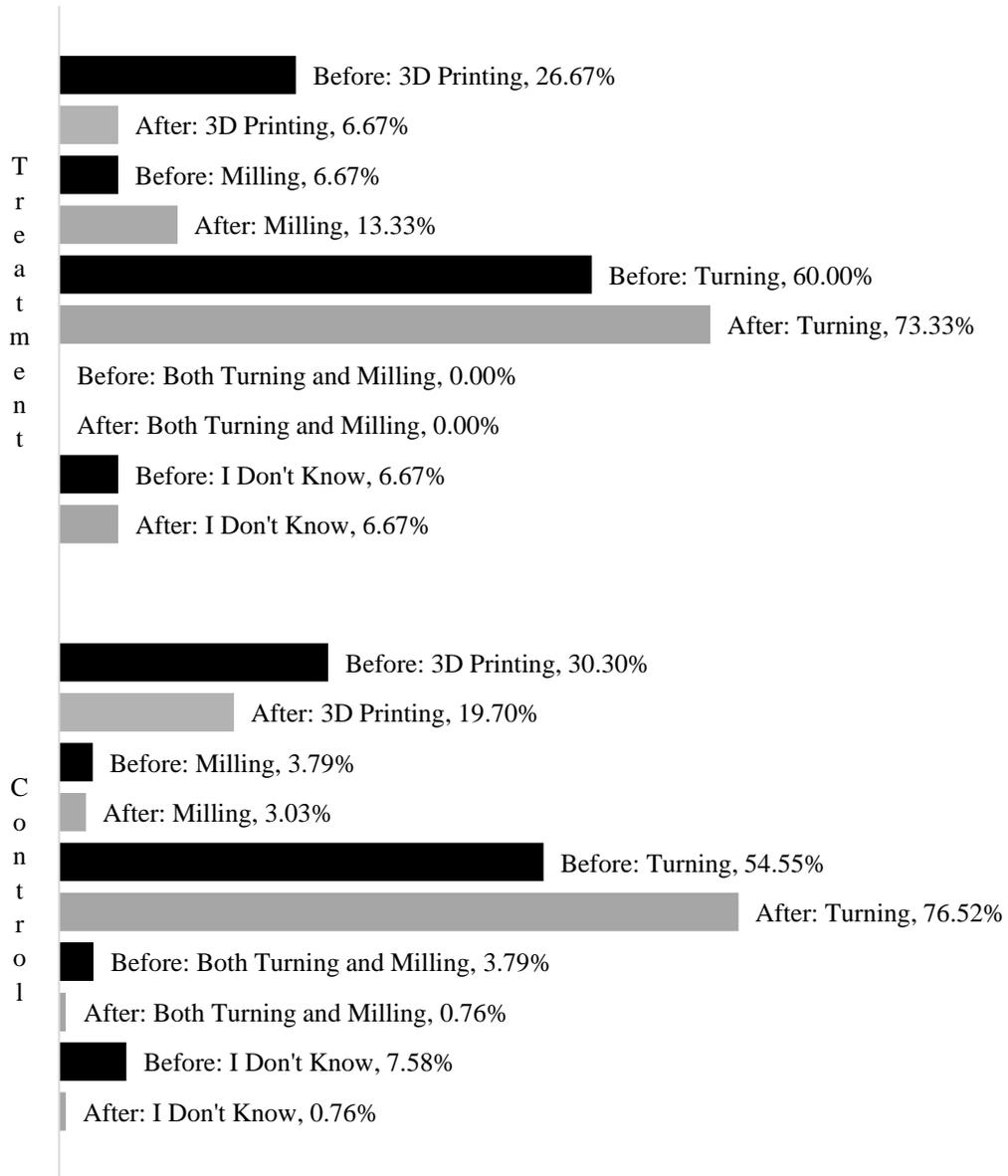


Figure 36. Student Responses to Which Process Should Be Used to Make the First Turned Part Shown in the PQ and PQP

shown in Figure 37. There is some room for interpretation as to how these parts should be

made. For example, using an AM process for the pawn would be perfectly acceptable for the following reasons: first of all, it is plastic; the strength requirements are loose to nonexistent, as it is a child’s toy; and finally, absolute dimensional accuracy is not of

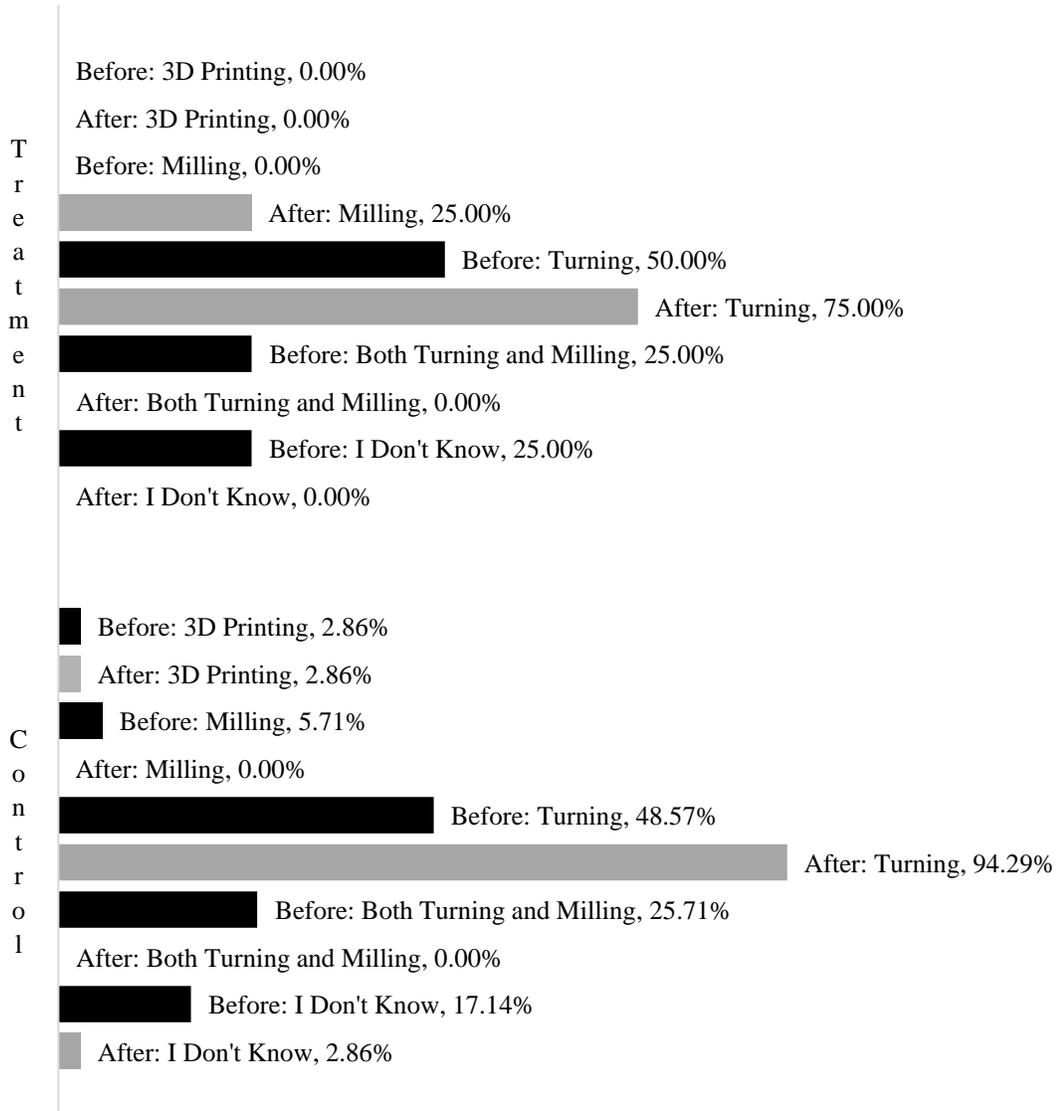


Figure 37. Student Responses to Which Process Should Be Used to Make the Second Turned Part Shown in the PQ and PQP

utmost importance as it, again, is a child’s toy. However, for the purposes of this assessment, the part should be turned as the students were asked to choose the *best* process

to make the part. In this case, a turning process is best because it is the fastest way to make the relatively simple geometry of the axisymmetric part. More observant students may notice the toolmarks on the pawn, which strongly suggest that it was turned. For the second turned part, however, there is slightly less room for interpretation. Judging by the picture alone, it is a safe assumption that the part is metallic. That fact alone rules out the vast majority of AM processes, most of which can only fabricate parts from various polymers. While it is possible to manufacture metal parts with various AM processes, it is much more common to machine metal parts. Additionally, the smooth surface finish on the part is yet another suggestion that it was made using a machining process. Observant students may notice the rough toolmarks in the bore of the part, which are caused by the lack of rigidity of a boring tool. It was therefore expected that a greater percentage of students would respond with “Turning” to the prompt for the second turned part than the percentage that chose turning for the first part. While that was the case for the control group, it was not the case for the treatment group.

4.2.3.2.1 Text Analysis of Student Process Choices for Turned Parts

A closer examination of the text responses for the students who indicated processes other than turning for the turned part questions on the PQ and PQP was conducted to determine the reasons why students chose processes other than turning. To begin with, textual explanations of why 3D printing was chosen for the first question were analyzed by a machining expert to determine if this was caused by the material of the part that was shown to the students. Two distinct trends were noticed during this analysis: first of all, a number of students explained that they selected 3D printing simply because the part was made of plastic. Secondly, many students indicated that they would choose to 3D print the pawn

because of its curvature, and some even said that the spherical head of the pawn could not be turned. The results from this analysis for the before- and after-training responses for the pawn question are shown in Table 17. These results indicate that some students learned

Table 17. Text Analysis on Students Who Selected 3D Printing for the Pawn Before and After Training

		Number of Students Who Selected 3D Printing	Percentage of Students Who Chose 3D Printing Because the Part is Plastic	Percentage of Students Who Chose 3D Printing Because of the Part's Curvature
Before Training	<i>Control</i>	40	12.50%	30.0%
	<i>Treatment</i>	4	25.0%	50.0%
	<i>Total</i>	44	13.64%	31.82%
After Training	<i>Control</i>	26	0.0%	61.54%
	<i>Treatment</i>	1	0.0%	100%
	<i>Total</i>	27	0.0%	62.96%

two distinct things from the machining training: first of all, plastic parts can be machined easily, and just because a part is plastic does not mean it should necessarily be 3D printed; and secondly, training on manual equipment seemed to cement the control group's idea that the cutting tool on a lathe can only move in the axial and radial directions. This indicates that further explanation of the fact that movements of a cutting tool are less restricted in CNC machining operations is required.

4.2.3.3 Student Process Choice for Additively-Manufactured Parts

Parts that were obvious candidates for AM processes were also included in the PQ and PQP assessments to gauge students' understanding of when these processes should be employed. The first of these parts was a very complex plastic ring with integral support

structures, and the second was a thin-walled rectangular shell with a high aspect ratio. These two parts, which were used for questions 5 and 7 on the PQ and PQP, are shown in Figure 38. The first part, used for the fifth question on the PQ and shown in Figure 38a,

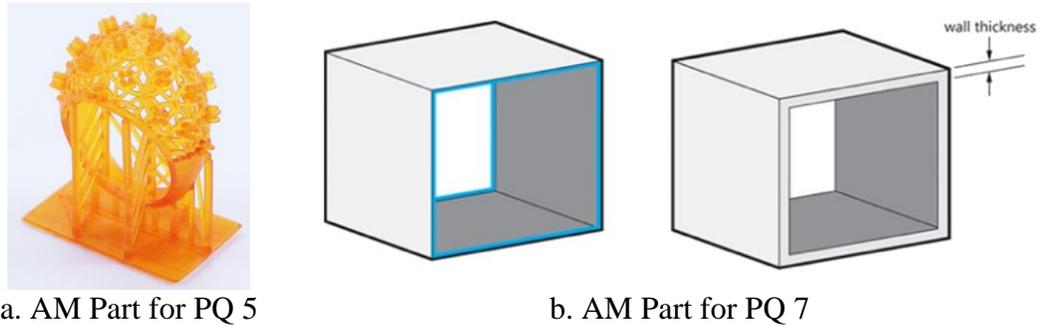


Figure 38. Additively-Manufactured Parts Used for PQ and PQP

contains extremely complex and intricate features; it also has an integrated build platform and support structures, strongly suggesting that it was made using an AM process. While it would technically be possible to mill this part using a 5-axis machining center, the choice of cutting tools would be difficult and the actual planning of the toolpath would be incredibly time intensive. As a result, this part is a perfect candidate for an AM process. As a matter of fact, it was actually manufactured using a stereolithography (SLA) process. The second part, which was used for the seventh question on the PQ and is shown in Figure 38b, leaves much more room for interpretation. The answer choices for this part were slightly different from the ones provided for the previous process questions. For the second question, students were only allowed to pick between 3D printing, milling, either milling or 3D printing and neither milling nor 3D printing to make this part. For this question, it is somewhat challenging for a student inexperienced in manufacturing to determine how the part should be made. However, a number of hints were built-in to the image of the part to suggest that it should be made with an AM process. First of all, the part has a very thin

wall (as indicated by the “wall thickness” dimension shown). This is challenging to manufacture using any process, whether it is additive or subtractive. However, depending on the thickness of the wall, it is arguably more difficult to manufacture this part subtractively because tool chatter would be a big issue during machining. If the part were flipped so that its bore was aligned with the pull of gravity, it would be somewhat simpler to manufacture additively than it is in the orientation shown. The other clues that this part should be made with an AM process are somewhat interrelated: first of all, the part has no internal corner radii. It is impossible to manufacture a part with no internal corner radii using a typical milling process. Arguably, it is also impossible to manufacture a part with no internal corner radii using an additive process, but it is undeniable that internal corners are less of a concern for additive processes as they are for subtractive ones. The part also has a relatively high aspect ratio. The part’s aspect ratio really only presents a problem for milling when the internal corner radii are simultaneously considered. If the radii were larger, it is feasible that a milling cutter could be purchased to pocket out the bore. However, because the radii are either tiny or non-existent, a machinist would need a milling tool with the same radius as the internal corners that is simultaneously at least as long as the part is in the into-the-page dimension. Given the infinitesimal size of the internal radii, it is safe to say that such a milling tool probably does not exist. Note that machining processes that could more easily make this part do exist: specifically, plunge electrical discharge machining (EDM) could easily make a square hole in a workpiece. Additionally, a broaching process could be used because the square hole goes all the way through the part. The part could also be cast, given a suitable core, or it could be extruded. While none of those processes were offered as choices for the students, those students who did not

think that either milling or 3D printing would be suitable for making the part could select the neither process is acceptable. A small number still mentioned alternative processes

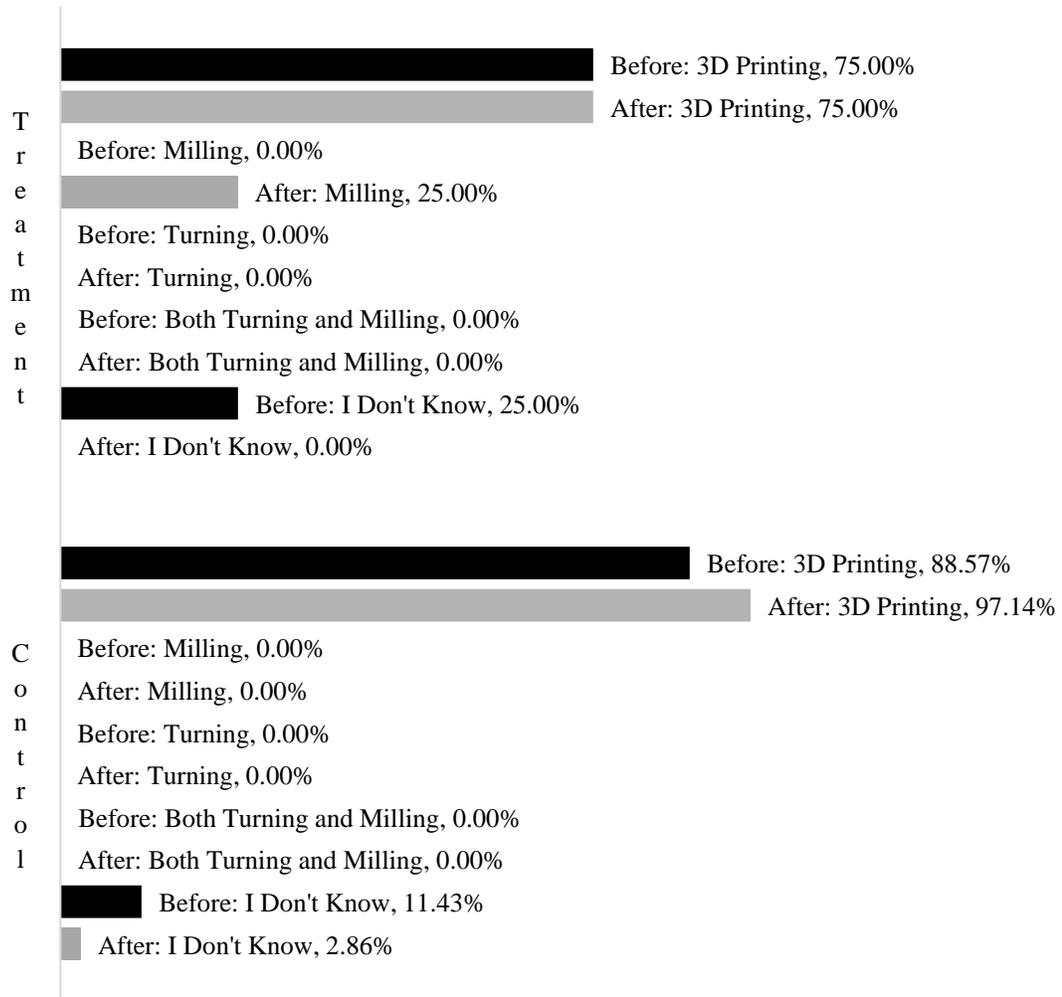


Figure 39. Student Responses to Which Process Should Be Used to Make the First AM Part Shown in the PQ and PQP

(specifically extrusion) in their text explanations for why they chose the processes they did. Extrusion and casting are technically additive processes, as they add material to a workpiece; these processes are arguably the best choices for the manufacture of this object and thus the part in Figure 38b is included in this section. Due to the ambiguity inherent in

this question, both “3D printing” and “neither milling nor 3D printing” were accepted as correct answers. Given the qualitative observations that can be made about both of these parts only by seeing images of them, it was expected that students would pick 3D printing

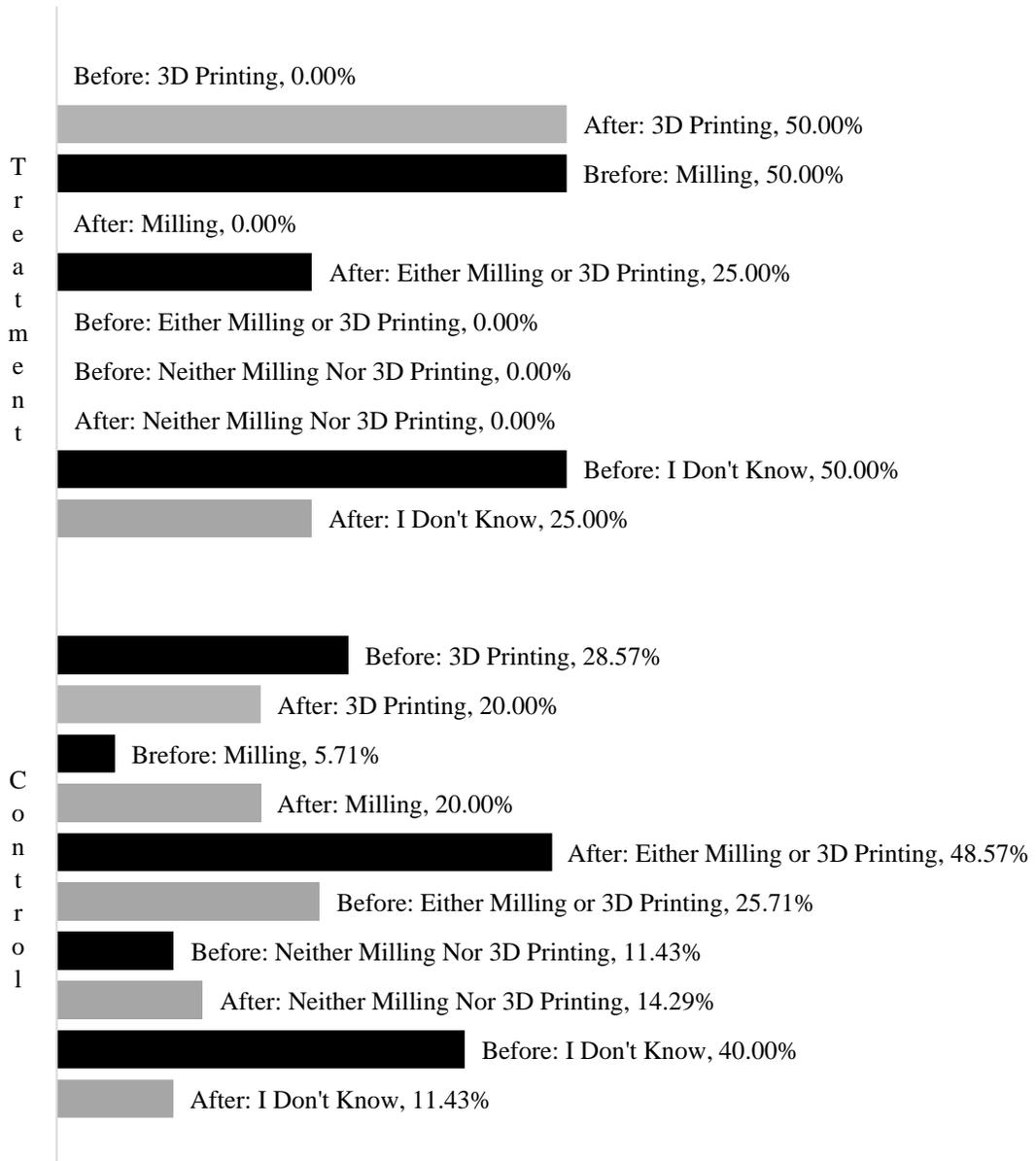


Figure 40. Student Responses to Which Process Should Be Used to Make the Second AM Part Shown in the PQ and PQP

as the process of choice for each of them. Figure 39 shows the distribution of student responses to which process they would select for the first of the two AM parts. The results are stark: almost the entire population chose 3D printing both before and after machining training, suggesting the students are quite capable in recognizing when a given part almost surely cannot be made with any other process. The distribution of responses for the second AM part, the square tube, are shown in Figure 40.

4.2.3.4 *Student Process Choice for Millturned Parts*

One part was included on the PQ and PQP that required both milling and turning. This part



Figure 41. Millturned Part for PQ and PQP

had external axisymmetric geometry with off-axis drilled and tapped holes. It also had a milled slot and a faced surface that was not orthogonal to the symmetry axis; these features indicated that the part could not be made on a typical 2-axis turning center. The millturned part, which was used for question four of the PQ and PQP, is shown in Figure 41. This part is actually a flycutter which is a common cutting tool used on a milling machine. This part was included because it is a familiar sight in both manual and CNC machining operations,

and is thus easily recognizable. Similar to the pawn that was provided in the section of turned parts, this question stimulated students to think about how everyday parts are made. This part could be made relatively simply using both a manual milling machine and a

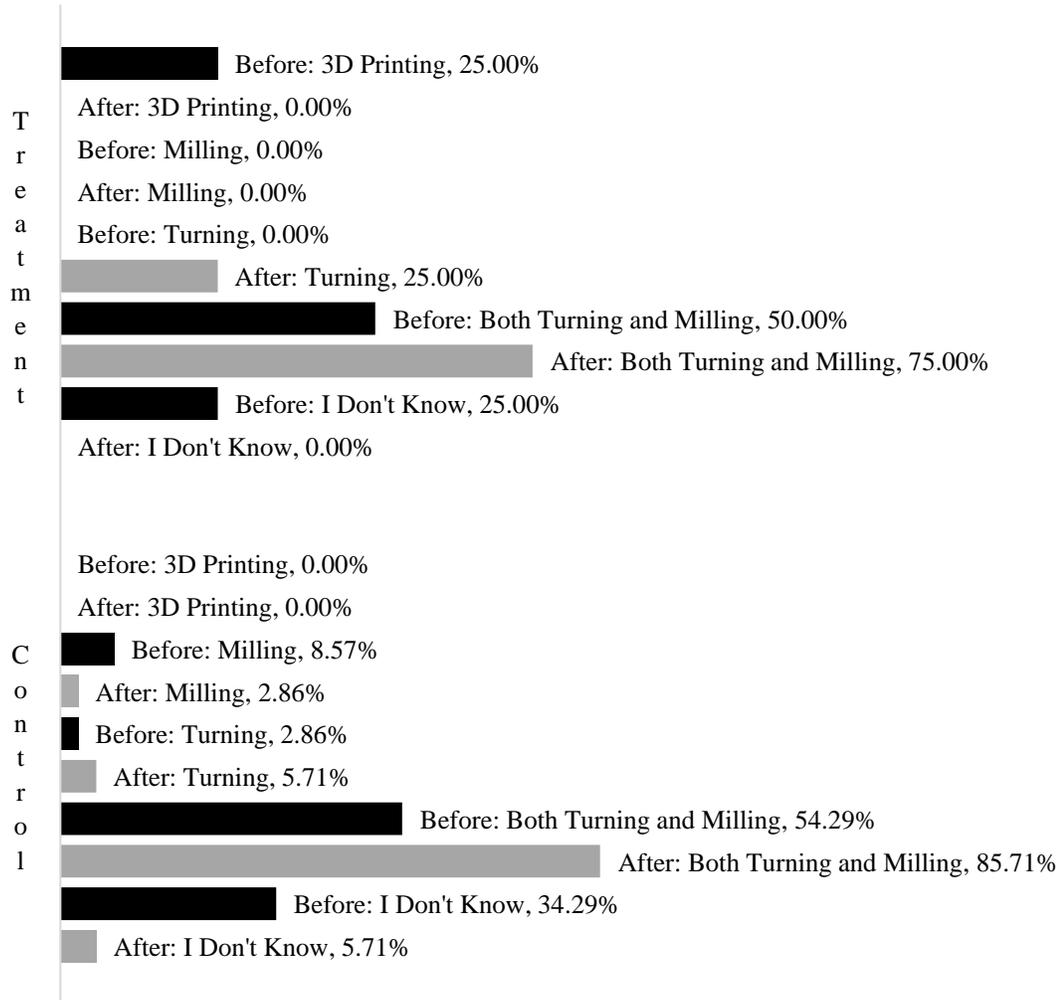


Figure 42. Student Responses to Which Process Should Be Used to Make the Millturned Part Shown in the PQ and PQP

manual lathe: first, the external axisymmetric geometry would be turned on a lathe; then, the part would be transferred to an angle fixture in a manual milling machine to have the slots and faces milled; finally, it would be rotated about its axis to have the homes for the

clamp screws drilled and tapped. In reality, however, it was most likely made on a 4+1-axis CNC millturn machine, where all operations can be performed in a single setup. As was the case in most of the previous questions, students were allowed to pick one of the following as their process of choice to make this part: 3D printing, milling, turning or milling and turning. The student response distribution for this part is shown in Figure 42. As expected, student responses of “I Don’t Know” decreased for both groups after training, and responses for millturning increased after training.

4.2.3.5 Student Selection of Machine Tool Configuration

The eighth and final question on the PQ and PQP asked students to select a suitable

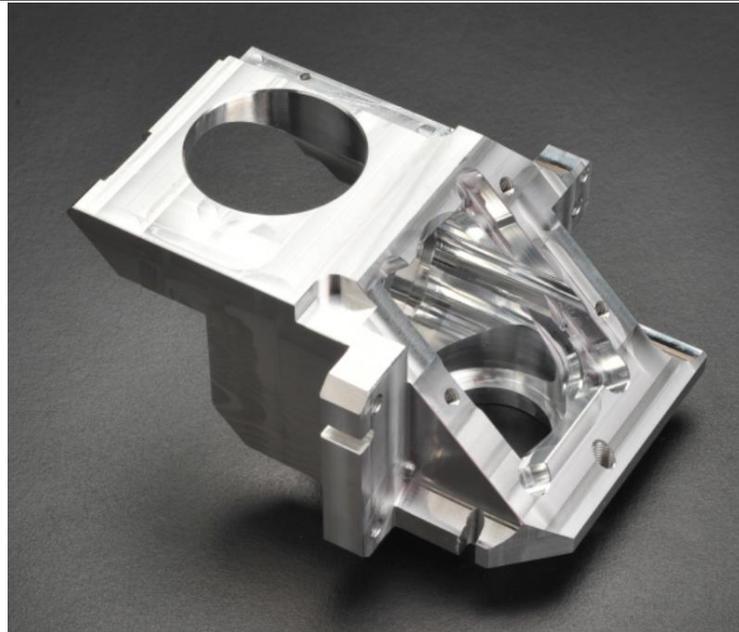


Figure 43. Multi-Setup Milled Part for PQ 8

machine tool configuration for a given part. The part, which is shown in Figure 43, has clearly been machined either with multiple setups, or with an extremely sophisticated fixturing configuration on a 3+2-axis machining center. While it would be possible to

machine this part on a manual milling machine, as the part contains no complex contours or surfaces, it would be most efficiently done on a CNC machining center using careful fixture design. The students were asked which of the following machine tools they would

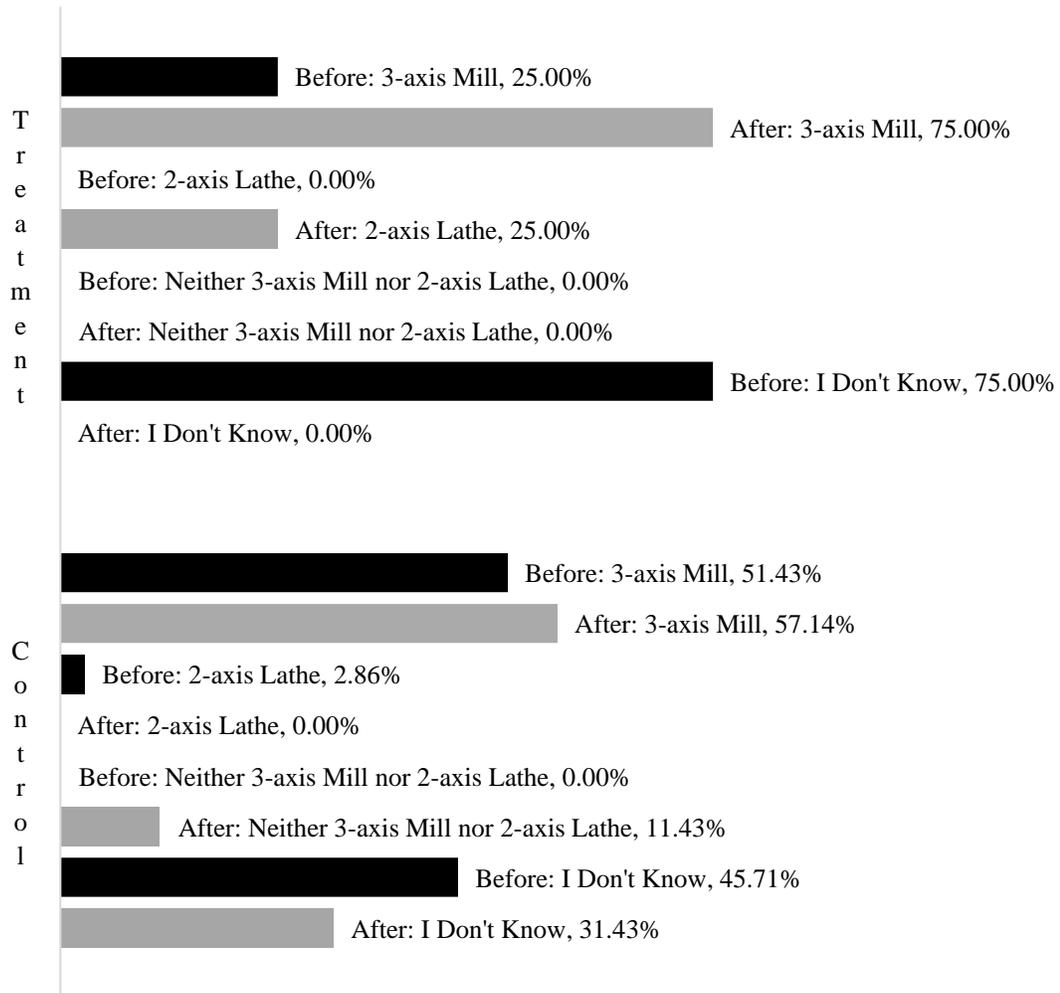


Figure 44. Student Responses to Which Machine Should Be Used to Make the Multi-Setup Milled Part Shown in the PQ and PQP

use to manufacture this part: a 3-axis milling machine, a 2-axis lathe or neither. They were also allowed to respond that they did not know the answer. Given the relative complexity of the part, responses of both “3-axis mill” and “neither 3-axis mill nor 2-axis lathe” were

counted as correct. The response distribution for this question is shown in Figure 44. While it is encouraging that the number of students indicating that they did not know the answer decreased for both groups after training, it is extremely discouraging that the number of students who chose to use the 2-axis lathe from the treatment group actually *increased* after CNC training. Text analysis on the students' text explanations of why they chose the 2-axis lathe was impossible, as the responses consisted of "not neither" and ".".

4.2.3.6 Process Choice Assessment Scores Before and After Machining Training

As all of the graded questions on the PQ and PQP were multiple choice, grading was performed automatically using a computer. The text responses were not graded for accuracy, and were simply used for insight into students' reasons for choosing the processes that they did.

4.2.3.6.1 Score Distributions

The score distributions of both the control and treatment groups, from zero to eight points, in the assessment before and after training are shown in Figure 45. The mean scores of both the control and treatment groups shifted in the positive direction after training. The average score on the assessment before training for the control group was 4.86 ± 2.10 points; for the treatment group, the average score was 4.33 ± 2.15 points. After training, the average score for the control group was 5.97 ± 1.38 points; for the treatment group, the average score was 5.20 ± 2.10 points. These score statistics are shown in Table 18. Rather than simply comparing the mean scores of the two groups, it is perhaps more valuable to compare the difference in means demonstrated by the two groups. It was expected that the treatment group would experience a larger mean difference before and after training than

the control group did; however, that was not the case. The treatment group demonstrated a mean difference of +0.87 points on the assessment after training; the control group, however, demonstrated a +1.11 point mean increase in score after training. While this is

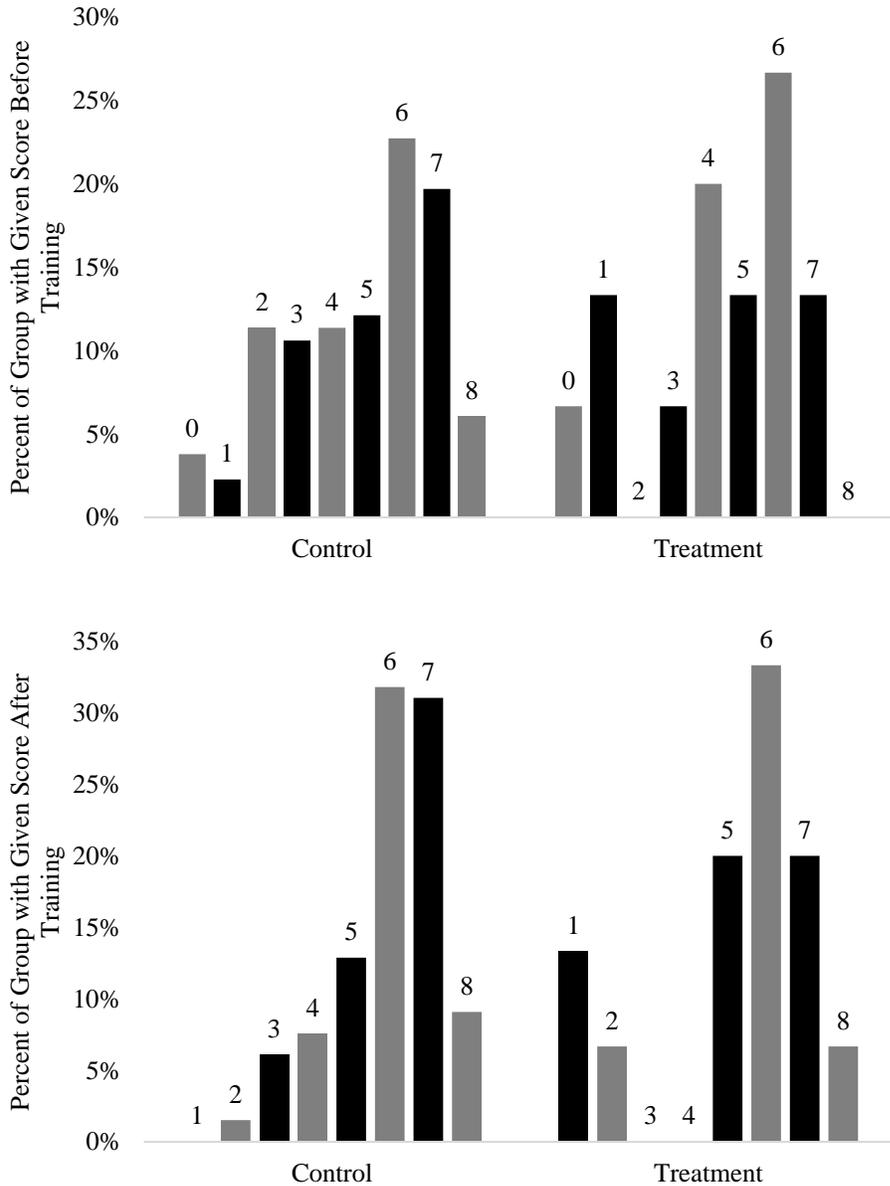


Figure 45. Process Questions Score Distribution for Both Groups Before and After Machining Training

Table 18. Comparison of Process Questions Scores Before and After Machining Training

	Before Training		After Training		$\Delta\mu$
	μ	σ	μ	σ	
<i>Control</i>	4.86	2.10	5.97	1.38	+1.11
<i>Treatment</i>	4.33	2.15	5.20	2.10	+0.87
Total	4.80	2.11	5.89	1.48	+1.09

unfortunate, it is also not entirely surprising. The students in the treatment group were not exposed to manual machining during the training protocol, as the control group was, and thus were not given a chance to build an intuition using hands-on experiences with a manual lathe or milling machine. They did, however, get far more visual demonstrations on the capabilities of the turning process than the control group. These demonstrations allowed the treatment group to excel in other areas where the control group fell short. Additionally, the treatment group was never provided with explanations of why one process should be chosen over another one. Therefore, they were forced to extrapolate from their experiences during the training procedure to pick suitable manufacturing processes for a vast range of parts. Finally, the treatment group had absolutely no exposure to the milling process. Not only did they not use a manual milling machine, but they also did not perform milling simulations in SculptPrint. This left the treatment group at a distinct disadvantage when compared to the control group for any of the questions in the PQ and PQP assessments that asked about milling.

4.2.3.6.2 Statistical Analysis of Scores Before and After Training

Although mean differences do indicate that the treatment group experienced a smaller score increase than the control group did, this must be confirmed statistically in order to make a judgement on the effectiveness of the training approach using voxelized simulations. To begin with, a paired *t*-test was performed on the pre- and post-training scores for both groups separately. This test allows for determination of whether or not the mean scores before and after training differ significantly. The results from this test are shown in Table 19 for both the control and treatment groups. The 95% confidence interval (CI) column states that there is a 95% probability that the respective mean differences for the control or

Table 19. Results from Paired *t*-Test on Scores Before and After Training

	Mean Score Before Training	Mean Score After Training	$\Delta\mu$	95% CI for $\Delta\mu$	<i>t</i>- Statistic	<i>p</i>-Value
<i>Control</i>	4.86	5.97	1.11	(0.82, 1.4)	7.58	5.60E-12
<i>Treatment</i>	4.33	5.2	0.87	(0.03, 1.7)	2.23	0.043

treatment group lies somewhere in the stated range, inclusive. The *p*-Value column indicates the probability that the before and after samples come from populations with the same mean. This test provides the following information: for the control group, there is a probability of 5.6×10^{-12} that the mean score difference between the PQ and PQP is simply coincidental; likewise, for the treatment group, there is a probability of 4.3×10^{-2} that the mean difference is simply coincidental. Whether or not the mean difference is due to the provided intervention will be discussed in later sections.

To determine the significance of the mean differences *between* the groups, two-sample *t*-tests were performed on the raw score data from both groups before and after training. The results from these tests are presented in Table 20. The tests were performed in the following manner: for each assessment, the PQ and the PQP, the score data of the control group was taken as one sample and the score data of the treatment group was taken as the other sample. The PQ and PQP are indicated in the Table as “Before Training” and “After Training”, respectively. In this case, the mean difference indicates the differences in mean scores between the treatment and control groups. Because the control and treatment groups were

Table 20. Results from Two-Sample *t*-Test for PQP Scores Between Groups

	Control Mean Score	Treatment Mean Score	$\Delta\mu$	95% CI for $\Delta\mu$	<i>t</i>- Statistic	<i>p</i>-Value
<i>Before Training</i>	4.86	4.33	-0.52	(-0.76, 1.8)	0.87	0.39
<i>After Training</i>	5.97	5.20	-0.77	(-0.46, 1.99)	1.34	0.20

drawn from the same population of students, the mean difference before training was not expected to be significant; as expected, that result is confirmed by this test. However, because a *p*-value of less than 0.05 was not obtained for the two-sample test that was performed on the post-training scores, it cannot be said with 95% confidence that the mean scores of the treatment and control groups differ. Thus, additional data are needed in order to make a concrete claim on the difference in process choice ability between the control and treatment groups.

4.2.3.6.3 Score Improvement as a Function of Prior Experience

In order to control for students that had prior experience that could significantly affect their scores on the PQ or PQP assessments, a similar analysis to the one above was performed on the responses for the students who indicated that they were not comfortable with any manufacturing process during the Preassessment. The score distribution for these students observed in the assessment before machining training is shown in Figure 46. While a student's indication that they were not comfortable with any manufacturing process did not

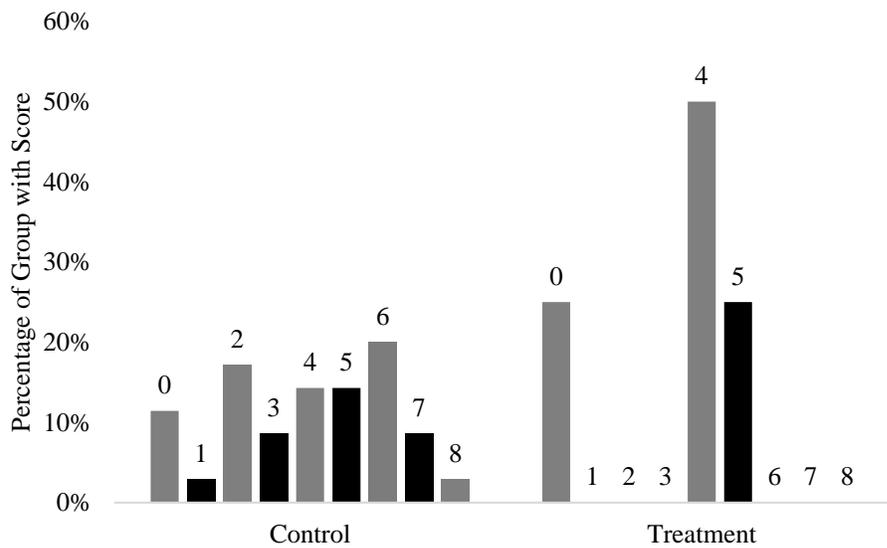


Figure 46. Score Distribution on Process Questions Assessment Before Machining Training for Students Not Comfortable with Manufacturing

necessarily guarantee that any prior experiences would not have an effect on their scores, it served as the most effective control given the data set. After training, the mean scores improved for both groups, as expected. Figure 47 shows the score distribution of both groups after machining for only the students who indicated that they were not comfortable with manufacturing during the Preassessment.

Again, statistical analysis was performed on the scores from the students that were not comfortable with manufacturing to assess the significance of the score differences between

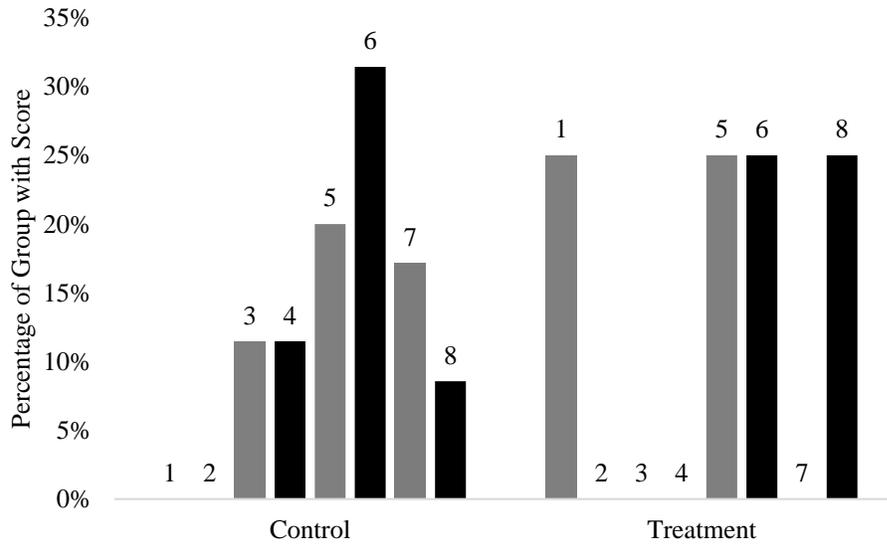


Figure 47. Score Distribution on Process Questions Post Assessment for Students Not Comfortable With Manufacturing After Machining Training

the control and treatment groups. First, a paired *t*-test was performed to assess the significance of the mean differences for each group before and after training. The results

Table 21. Results from Paired *t*-Test on Scores Before and After Training for Students Not Comfortable with Manufacturing

	Mean Score Before Training	Mean Score After Training	$\Delta\mu$	95% CI for $\Delta\mu$	<i>t</i> -Statistic	<i>p</i> -Value
<i>Control</i>	3.94	5.57	1.63	(-0.98, 2.27)	5.17	8.61E-7
<i>Treatment</i>	3.25	5.0	1.75	(-0.97, 4.47)	2.05	0.13

from this test are presented in Table 21. The group of students who were not comfortable with any manufacturing processes was the only subset of students where the treatment group demonstrated a larger increase in mean score than the control group did. However,

the results of this test indicate that, again, additional data are needed to enable a concrete judgement to be made on the mean differences. Table 22 shows the results from a 2-sample

Table 22. Results from 2-Sample *t*-Test for PQP Scores Between Groups with No Experience

	Control Mean Score	Treatment Mean Score	$\Delta\mu$	95% CI for $\Delta\mu$	<i>t</i>-Statistic	<i>p</i>-Value
<i>Before Training</i>	3.94	3.25	-0.69	(-4.43, 3.04)	-0.59	0.596
<i>After Training</i>	5.50	5.00	-0.57	(-5.32, 4.18)	-0.38	0.727

t-test used to determine if the observed difference in score increase is significant at the $\alpha = 0.05$ level; for this case, the results are inconclusive. Although the sample size of students that are both in the treatment group and not comfortable with any manufacturing processes is small, this group of students is the only subset of the treatment group demonstrating a larger mean increase in score than the control group.

4.2.3.7 Observations on Student's Text Answers to Process Choice Questions

After selecting a process for each of the PQ and PQP questions, the students were asked why they chose that particular process. This allowed for additional analysis of the students' responses that could not be performed by simply using the answers to the multiple choice questions alone. A text analysis was performed on these responses yielded the significant result that many students were unaware of the fact that a lathe can create external radii on a part. This is surprising for the treatment group, considering the yoyos they made had external curvature; however, such features were not addressed on the SPE, which could account for their lack of knowledge in this area.

4.2.4 IN-DEPTH MACHINING QUESTIONS AFTER MACHINING TRAINING

Students were presented with in-depth questions related to the turning process after machining training using the Post Test assessment. This assessment contained the most detailed questions of all the assessments, and was meant to highlight the differences between the control the treatment sections in terms of grasp of some of the finer details of the turning process. Students in the treatment group were expected to show a significant advantage over those in the control group for the PT, given their experience with SculptPrint's visualized simulations of the turning process. One of the most stressed topics during the PT was tooling geometry, which was the focus of five of the nine questions on the PT. As the ability of a student to mentally visualize the volumetric subtraction process during machining is essential to understanding subtractive manufacturing, it was given utmost importance in this assessment. Other questions in the assessment focused on process planning and process choice given part requirements. Questions types on the Post Test were either free-response, multiple answer selection or sketching. This section first reports the score distribution on the Post Test assessment by group, and then describes the findings from the individual types of questions.

4.2.4.1 Score Distribution on PT by Group

Much of the PT had to be scored manually, as the questions were more open-ended than

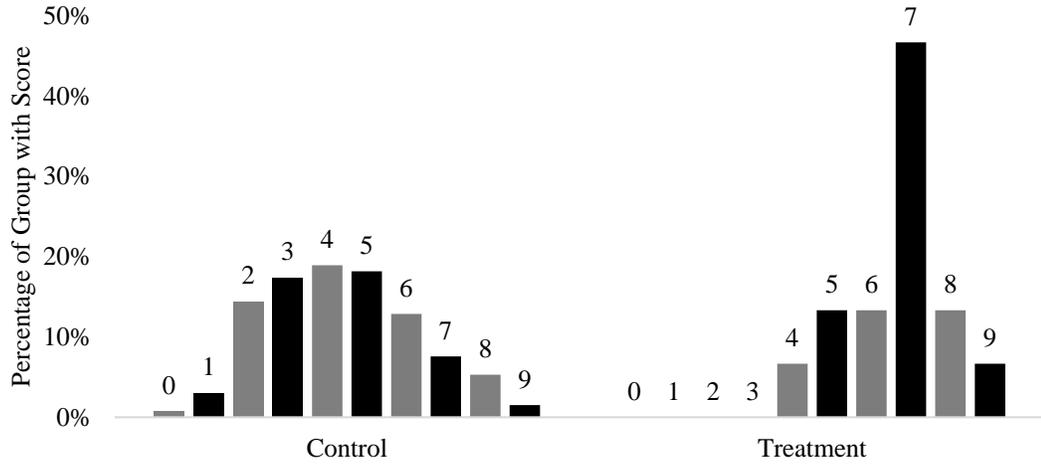


Figure 48. Score Distrubution by Group on Post Test

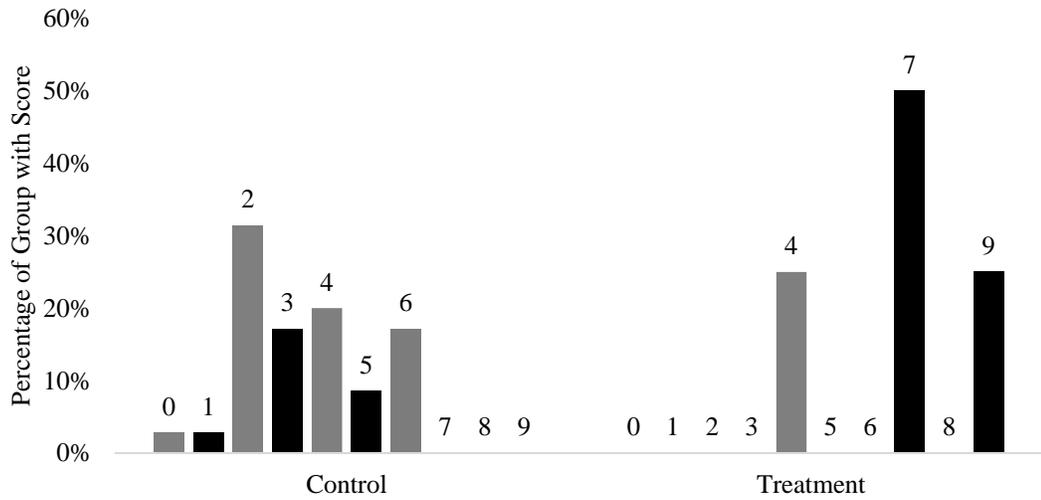


Figure 49. Score Distribution on Post Test for Students Not Comfortable with Manufacturing

those in previous assessments. Students were given binary credit for each question, which was scored blindly out of a total of nine points.

Figure 48 shows the score distribution of both control and treatment groups on the Post Test. Additionally, a score analysis of only those students not comfortable with any manufacturing processes was performed to remove variability that could be caused by students with prior experience. The score distribution for only the students not comfortable with manufacturing is presented in Figure 49.

Table 23 shows the score statistics for the PT, in addition to two-sample *t*-test results between the two groups. The results of the *t*-test indicate that the improvement

Table 23. Score Statistics for Post Test by Group

Entire Population								
	Score Range	μ	σ	$\Delta\mu$	95% CI for $\Delta\mu$	<i>t</i>-Statistic	<i>p</i>-Value	df
<i>Control</i>	(0, 9)	4.37	1.90					
<i>Treatment</i>	(4, 9)	6.67	1.25	+2.30	(+1.52, +3.07)	6.16	1.19E-5	21
Students Not Comfortable with Manufacturing								
<i>Control</i>	(0, 6)	3.43	1.60					
<i>Treatment</i>	(4, 9)	6.75	1.78	+3.32	(-0.07, +6.72)	3.11	0.053	3

demonstrated by the treatment group in comparison to the control group is statistically significant for the results from the entire population. For the students not comfortable with manufacturing, although the mean difference is large between the two groups, the 95% confidence interval size indicates that additional data are needed to determine if the treatment group has a statistically significant difference from the control group.

4.2.4.2 Tooling Geometry

Five of the nine questions in the PT were concerned with tooling geometry to some extent. Charts of student responses to these questions will be presented throughout this section,

and the numerical statistics for all of the tooling geometry questions will be presented in a table at the end of the section.

4.2.4.2.1 Included Angle of a Cutting Tool

The first of the tooling geometry questions asked the students whether or not the included angle of a cutting tool would affect the geometry of a cut it can make. The included angle of a single point cutting tool is defined as the angle between the major and minor cutting

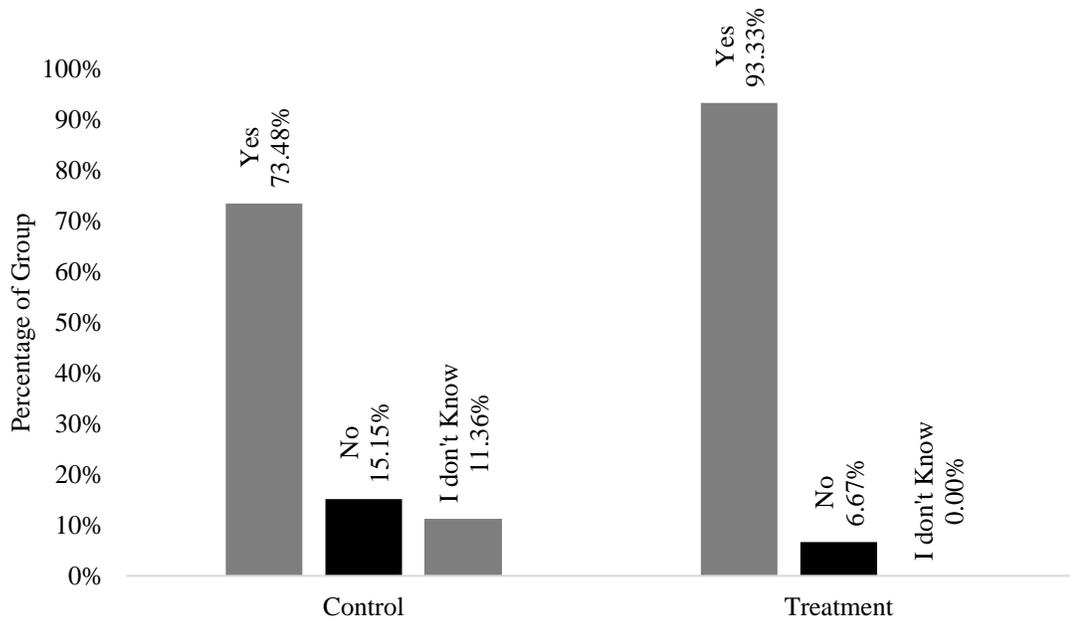


Figure 50. Student Answers to Whether or Not the Included Angle of a Cutting Tool Will Affect the Cut

edges of the tool [51]. The included angle is important, as it dictates the maximum relief angle that the tool can cut. While the lead angle of the insert also plays a role in determining the maximum relief angle a single point tool can cut, it is typically small in comparison to the tool's included angle. The answers to the question about included angle, by group, are shown in Figure 50.

4.2.4.2.2 Right- and Left-Handed Tooling

The students were also asked when a left-handed tool would be used in a turning operation. A left-handed tool is defined as a turning tool where the relief angle of the tool is to the left of the major cutting edge; alternately, it is a tool where the cutting direction is from left to right along the spindle axis (which is typically *away* from the spindle on most turning centers). Left-handed tooling is essential for realizing reliefs on turned parts that face towards the spindle, as the clearance angle of a right-handed tool would not allow cutting of such reliefs. Students must understand the differences between right- and left-handed tooling in order to thoroughly grasp the intricacies of the turning process. For this question, the possible answer choices were: a. the operator is left-handed; b. the tool is left-handed; c. for light machining; d. when machining towards the chuck; and e. for machining a particular profile. The students were allowed to select multiple answers for this question. Clearly, the use of a left-handed tool is completely unrelated to the handedness of the operator, so choice a is incorrect. Left-handed tooling can be just as rigid (and sometimes more so) as right-handed tooling, so answer choice c is incorrect. Answer choices b and d were dummy answers and only used to increase the number of available choices; depending on the students' interpretation, these choices could be either correct or incorrect. For example, a left-handed tool would be used for machining toward the chuck if the chuck were located to the right of the operator when facing the machine (assuming the top of the insert was facing downwards). The answer choice that was most correct was choice e. This question was scored as follows: credit was given if and only if the students selected choice e, that a left-handed tool would be used when machining a particular profile, and they

selected neither a nor c. Figure 51 shows the results from this question by group. From these results, it is apparent that both control and treatment groups understood that left-

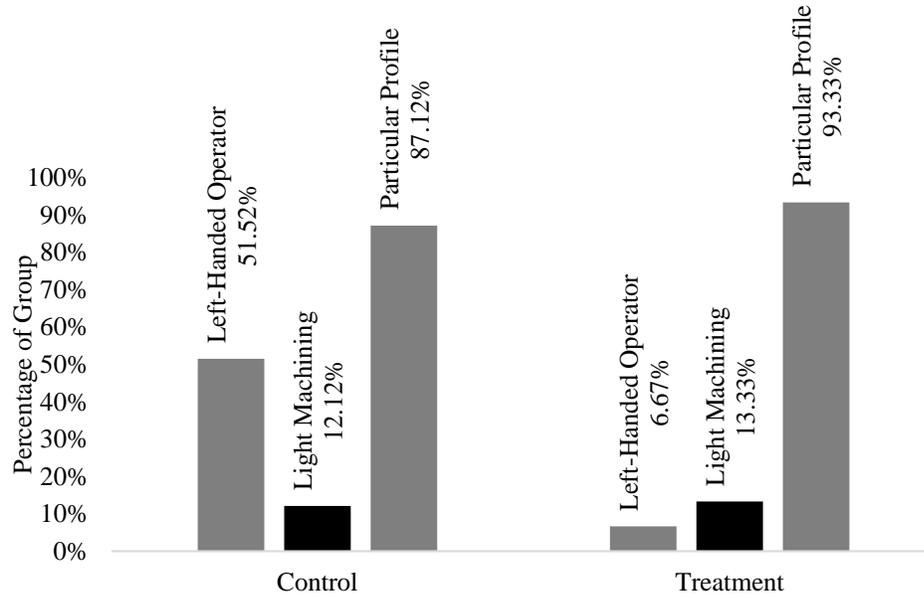


Figure 51. Student Responses to When a Left-Handed Tool Should be Used

handed tooling is needed to cut certain geometry, but the control group was confused about vocabulary: over half of the control group responded that a left-handed tool would be used by a left-handed operator.

4.2.4.2.3 *Sketching of Volumetric Subtraction with Different Single Point Tools*

The next group of tooling questions required students to sketch the result of two different turning operations on a cylindrical blank that was destined to become the example part shown in Figure 21. The first of these questions asked students to sketch the result of rough turning the blank with the provided 75° right-handed tool. Because the only available question type in Qualtrics that allowed students to sketch was a signature box, some leeway had to be given to the students in terms of grading. There was no feasible way for them to

put dimensions on the sketch, and all lines were drawn freehand. Additionally, the question was open to interpretation, and there was not necessarily one absolutely correct answer. Correctness was judged blindly by a machining expert, who considered the geometry of

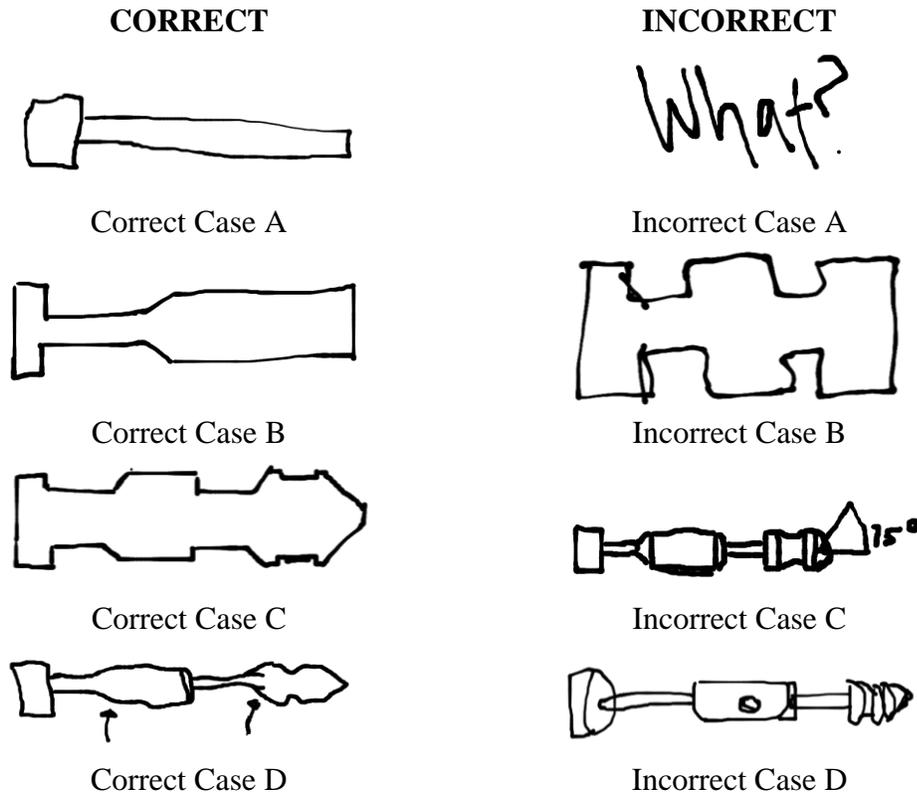


Figure 52. Types of Correct and Incorrect Responses to First Sketching Question

the sketch and the feasibility of cutting that geometry with the given tool. Examples of correct and incorrect responses to this question are shown in Figure 52. The recorded correct answers can be broadly classified in the following ways: either the students responded with a sketch of a cylinder where the major diameter of the part had been cut away (correct case A); or, they responded with a sketch where only the minor diameter on the left hand side of the part had been cut (correct case B); or, they responded with a sketch where both minor diameters had been cut, but the relief angles were not complete (correct cases C and D). The recorded incorrect answers can be broadly classified as follows: either

the students responded with a sketch of something unintelligible (incorrect case A); or, they responded with a sketch with incorrect relief angles (incorrect case B); or, they responded with a sketch with an angular dimension that made it apparent they did not understand the effect that insert included angle has on the turning process (incorrect case C); or, they responded with a sketch that included features not possible to make with a turning process, such as transverse holes (incorrect case D). All of the submitted signature images were downloaded from Qualtrics and anonymously coded by number before being graded. Again, the students were assigned binary credit for their responses to this question; i.e. if their answers could be classified in the correct categories, they were given a point for the question.

The second sketching question that the students were asked was similar to the first, but

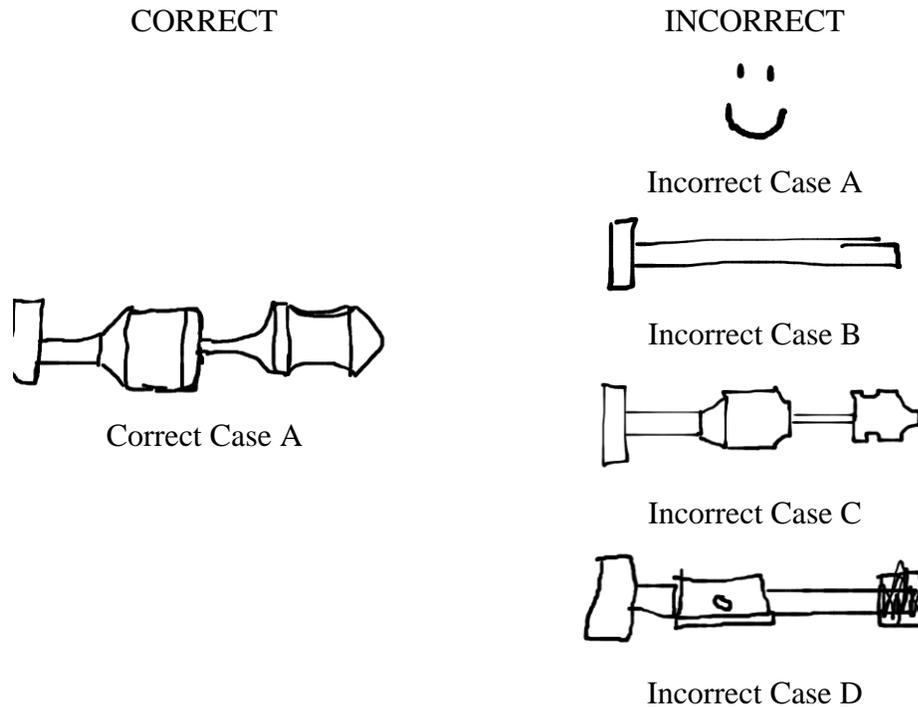


Figure 53. Classification of Responses for Second Sketching Question

used the 35° right-handed tool. They were asked to sketch the resulting part after all material that the tool could reach had been removed. Less leeway was provided when grading this question, as the students were explicitly told to sketch the part after *all* material that the tool could reach had been removed. Because all lines had to be drawn freehand, room for error was allowed for relief angles that were less-than-straight. Figure 53 shows the observed cases of responses and their classifications as either correct or incorrect. For this question, responses were recorded as correct if they conformed to the following criteria: the response demonstrated some non-vertical relief angle between the major and minor diameters of the part; the response showed the concave 7mm radius on the outer diameter of the part; the response showed the 3mm fillet on the major diameter of the part; and the response did not show any features that could not be cut with the given tool, such

as drilled holes (either axial or transverse). Many of the students did not recognize that the 3mm external fillet could be turned with a standard tool, and instead sketched the fillet as a right angle (such as in incorrect case D).

4.2.4.2.4 Tool Selection

The two sketching questions were accompanied by a third question, which asked the students to pick a set of tools from the provided catalog to most completely manufacture all of the turned features on the part. Some room for interpretation was allowed, as the students were not provided with axial dimensions of the part and were thus made to make qualitative judgements on whether certain tools were suitable or not. As a result, there were multiple correct answers for this question. Correctness was again judged blindly by the same machining expert. As long as the students selected a group of tools that was capable of cutting all the reliefs on the part, they were given a point for the problem; for example, if they selected both the right- and left-handed 35° tools, their response was marked as correct. No students recognized that the 0.5mm internal corners between the major and minor diameters were actually not manufacturable with any of the provided tools, so they did not lose points for not mentioning the corner radii.

4.2.4.2.5 Tool Sketching and Selection Question Performance by Group

The two sketching questions and the tool selection question constitute the three most focused questions in regard to tooling on the entire battery of assessments, and the treatment group was expected to perform significantly better than the control group on these questions. While the treatment group was at a distinct advantage due to their prior experience with SculptPrint, students in the control group were capable of figuring out the answers to these questions with the provided information. Figure 54 presents the

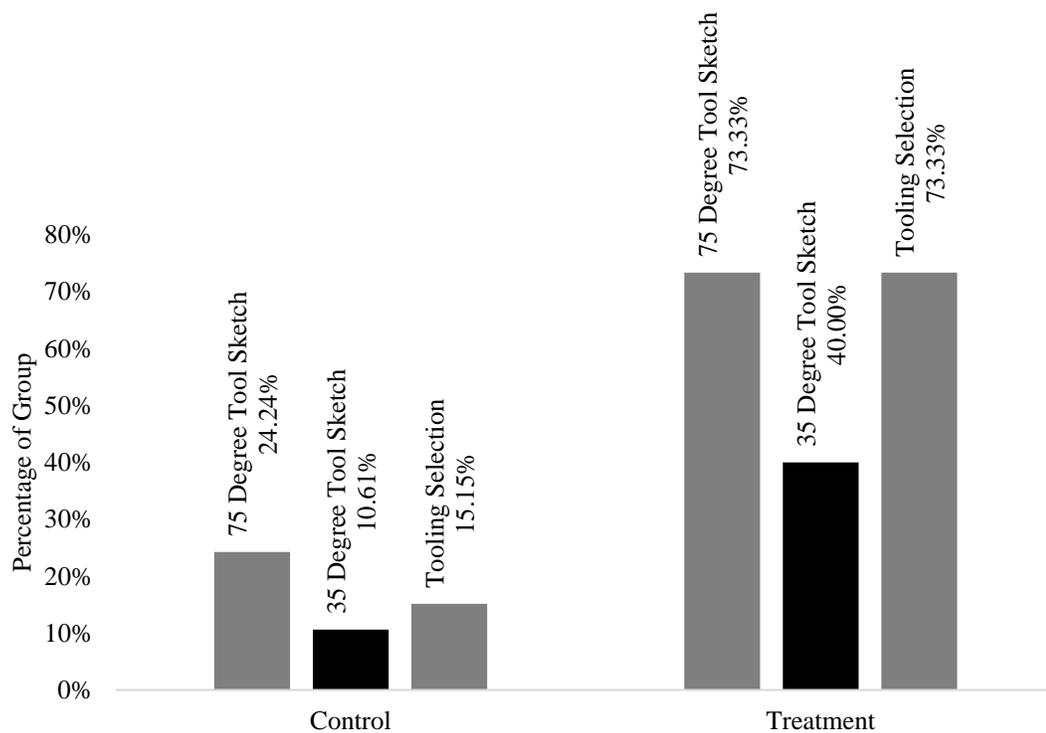


Figure 54. Student Performance on Tooling Questions by Group

percentage of students per group that correctly answered each of the three tooling questions. In order to control for students that had prior experience in manufacturing, the scores on the tooling questions were also analyzed only for the students reporting that they

were not comfortable with any manufacturing processes at the beginning of the course. This analysis more clearly demonstrates the effectiveness of training students in subtractive

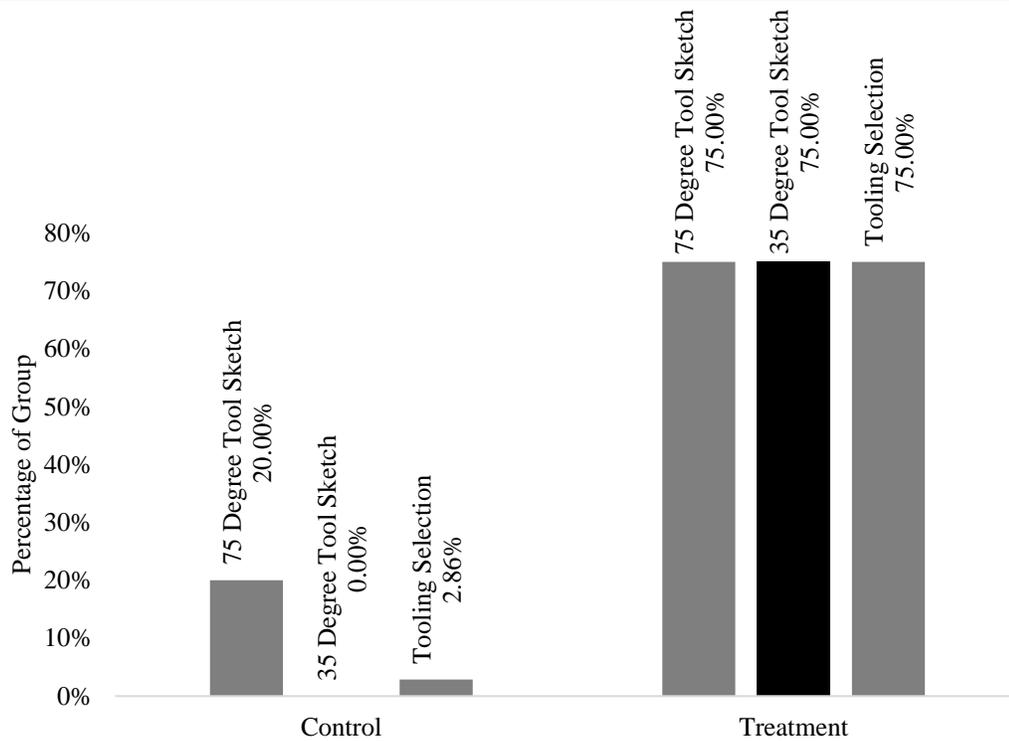


Figure 55. Student Performance on Tooling Questions for Those Not Comfortable with Any Manufacturing Process

manufacturing using visual simulations. Again, as expected, the treatment group performed significantly better than the control group did; however, in this case, the difference is even more pronounced than it was when results for the entire population are included. Figure 55 presents the student performance on the tooling questions for only the students not comfortable with any manufacturing processes. Although the sample size of students not comfortable with manufacturing is smaller than the entire population, the observed score difference is notable.

4.2.4.2.6 Tooling Geometry Question Performance by Group

The numerical score results for the tooling questions are presented in Table 24. These statistics are presented both for the entire population and for only students not comfortable

Table 24. Student Performance by Group on Tooling Geometry Questions

		Entire Population		Students Not Comfortable with Manufacturing	
		μ	Gain	μ	Gain
<i>Control</i>	Included Angle	73.48%		60.0%	
	Left-Hand Tool	43.2%		25.7%	
	75° Tool Sketch	24.24%		20.0%	
	35° Tool Sketch	10.61%		0.0%	
	Tool Selection	15.15%		2.86%	
<i>Treatment</i>	Included Angle	93.33%	19.85%	100.0%	40.0%
	Left-Hand Tool	86.67%	43.47%	75.0%	49.3%
	75° Tool Sketch	73.33%	49.09%	75.0%	55.0%
	35° Tool Sketch	40.0%	29.39%	75.0%	75.0%
	Tool Selection	73.33%	58.18%	75.0%	72.14%

with manufacturing. Additionally, it is apparent that the greatest gains were made by the treatment group when compared to the control group on the sketching and tool selection questions for both students comfortable and not comfortable with manufacturing before the study. The gain reported in Table 24 was calculated according to Equation 10,

$$\text{Gain} = (\mu_{\text{Treatment}} - \mu_{\text{Control}}) \% \quad (10)$$

where μ_{Control} and $\mu_{\text{Treatment}}$ are the percentages of students responding correctly to a given question in the control and treatment groups, respectively.

4.2.4.2.7 Machine Selection and Process Design Questions

The remainder of the questions on the PT were focused on other aspects of machining besides tooling geometry; namely, students were asked about machine selection, manufacturing process choice given design constraints, workholding and the order of operations in a machining process. The first of these questions, which concerned machine selection, asked students if a lathe or a milling machine should be used to make an

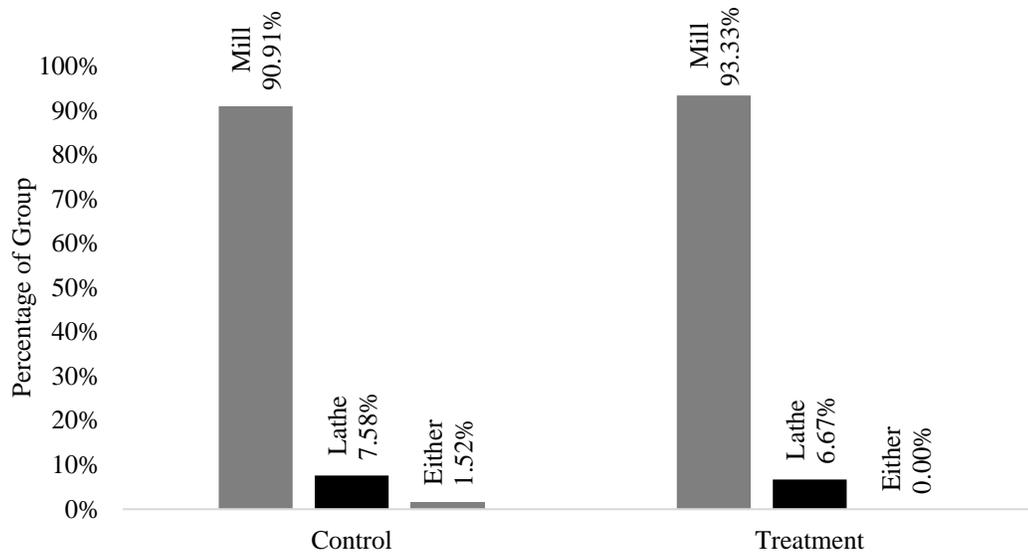


Figure 56. Student Indication of Whether a Mill to Lathe Should be Used to Make an Asymmetric Part

asymmetric part. While this question is clearly open to interpretation for those with experience in multi-axis CNC machining, the general concept is that lathes are most frequently used to make axisymmetric, not asymmetric, parts. In conjunction with the other observations on confusion with vocabulary presented in previous sections, this question provides further insight into students' understanding of terminology after machining training. Figure 56 presents the percentages of students in each group that responded with

“mill”, “lathe” or “either” to this question. Interestingly, the students were not explicitly asked if either machine was acceptable, and this was a free response question; however, some students still provided “either” as their answer. One student in the control group, who clearly had prior CNC experience, even responded with “Either. Use CNC”.

The manufacturing process choice question was somewhat of an extension of the questions that had been asked during the PQ and PQP assessments, but this time it was delivered using text instead of a part image. The question asked students to pick between 3D printing and machining for the manufacture of a gear for their ME2110 machine. The students were told that the gear would have to withstand a substantial amount of force. Although they were not provided with an image of the part to be made, they had to consider both the

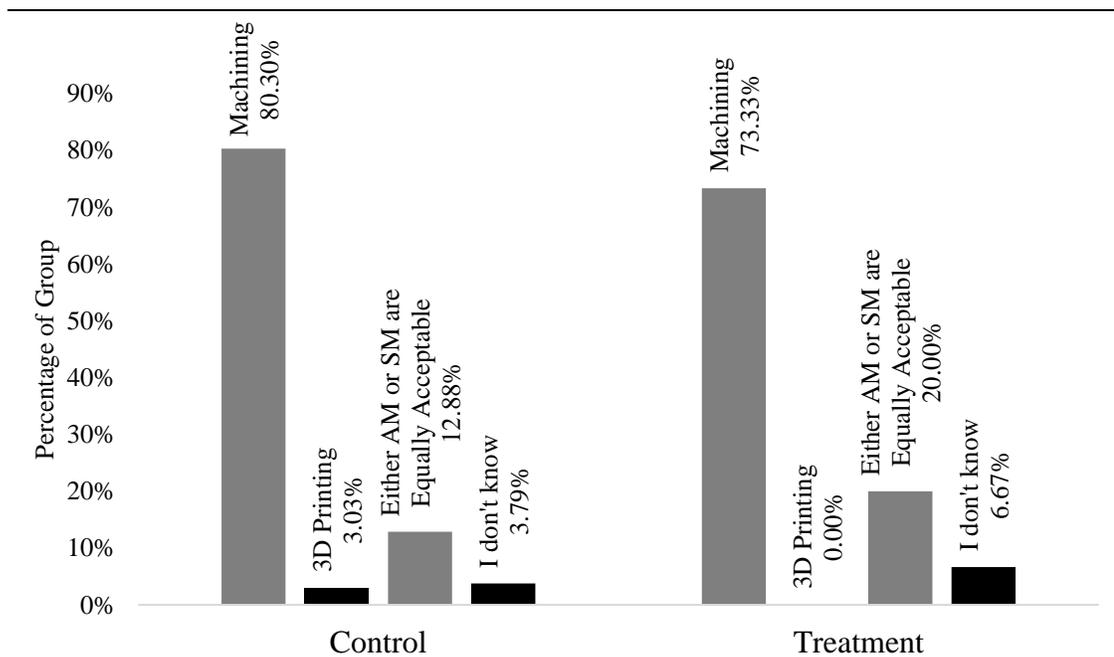


Figure 57. Student Responses to Whether Machining or 3D Printing Should Be Used to Manufacture a Gear

geometry and functional requirements of the part in order to answer the question. The

students' answers to this question, by group, are presented in Figure 57. Although quantitative specifications for the part were not provided, the correct answer to this question was "machining". From the results, it is apparent that some students do not understand when to properly apply additive and subtractive processes, even after subjected to both CNC and manual machining training. The results also suggest that further treatment of the part characteristics from AM and SM processes is needed.

4.2.4.3 Qualitative Observations

As was the case in previous assessments, many of the students, even those that were in the treatment group, did not seem to understand that a CNC machining process can produce curved external part features. This came as a distinct surprise, considering they were shown multiple times that radii and even spline curves can be created on an axisymmetric part using a CNC lathe.

5 DISCUSSION AND CONCLUSIONS

While the pilot study was successful when comparing the mean scores between control and treatment groups, additional data were needed to definitively determine if a voxelized approach to DFM education was indeed more effective than the typical approach with manual machining training. Consequentially, the population size for the second implementation was dramatically increased, enabling the more thorough analysis that was presented in Section 4. However, the loss of a substantial amount of data due to lack of student participation or completion hampered the statistical relevance of some findings. This chapter is organized as follows: first, the differences between the control and treatment groups before training is discussed; next, observations on CNC machine training are presented; next, a discussion on the differences between groups after training is presented; sources of error are identified and possible solutions are presented; and finally, conclusions and recommendations for a future implementation are described.

5.1 DIFFERENCES BETWEEN GROUPS BEFORE TRAINING

As both the control and treatment groups were drawn from the same population, the differences between them with respect to prior experience was expected to be negligible. While this was generally true, there were a number of exceptions. Perhaps the most relevant exception was the difference in machining experience: more than 30% of the control group reported prior experience in milling, turning or both; for the treatment group, less than 10% of the students reports such experience. However, a number of other major trends were observed simultaneously for both groups. Specifically, the highest percentage of students in each group reported prior experience with 3D printing; additionally, when asked which

process the students were most comfortable with, the two most popular answers for both groups were “3D Printing” and “None of the above”. This is in agreement with the population’s current academic status: the vast majority of them were sophomore ME students that had not taken any manufacturing or design/build courses previously. Additionally, it is likely that an appreciable percentage of the students surveyed has used the Invention Studio previously, which would most likely provide them with experience using AM processes. It is worth noting that a large percentage of students in the treatment group, 53.33%, reported that they were most comfortable with 3D printing; this is in contrast to 40.15% for the control group.

These differences in machining experience manifested as significant differences in ability during the PreT assessment. The treatment group had a larger percentage of “I don’t know” answers for every question on the PreT with the exception of the last question; perhaps not coincidentally, the last question was the only question on the PreT concerning 3D printing. While these differences are notable, they did not sufficiently impact the score distribution of the treatment group on the PreT. Upon scoring assessment, it was observed that no significant difference existed between the control and treatment groups. This result was expected, as both groups were drawn from the same population. The differences in prior experience could also have caused the lower mean score that the treatment group exhibited on the first PQ assessment.

5.2 OBSERVATIONS ON CNC TRAINING

The students in the treatment group were pleased with the fact that they were taught to operate CNC machine tools, and some were so excited that they used Snapchat to share the

entire experience with their friends. The use of standardized G-Code and the removal of the requirement that students set the work offset for each part, which was done in response to observations made during the pilot study, greatly reduced stress on the instructor. It would be absolutely catastrophic for a student in the study to wreck a machine tool, most importantly because it would be very unsafe for the study participants. It would also seriously delegitimize the study as the study designers and executioners would be seen as completely incompetent. Allowing students to run their own programs after setting their own work offsets in the pilot study, although it did not result in any collisions, did require the instructor to control the speed of the machine during some of the student programs. Not only does this approach not allow students to learn how to control the machine, but it also provides somewhat of a qualitative impediment to the purpose of the training. The goal of DFM training using this CAM software is not to teach the students to operate a CNC machine tool; rather, it is to educate them to be better designers. Concerning them with collisions of a machine tool would only create more confusion than was already present. Although some students were disappointed that they were not allowed to run their own G-Code, others were relieved that they would run a program that was already proven to work.

Transfer of the yoyos between machine tools was made easy with the fixturing pieces that were developed for this project, and assembly of the yoyos was similarly smooth. Some difficulties were encountered with the cycle time of the parts, however, in addition to the large number of students that were present during machining training. The size of the group made it slightly unwieldy for the instructor to move each student through the multi-step process individually, and the machining training sessions often ran over the allotted time.

5.3 DIFFERENCES BETWEEN GROUPS AFTER TRAINING

While both groups showed a statistically significant increase in score on the PQP as compared to the PQ, the mean difference for the control group was almost always higher than that of the treatment group. There was one exception to this, however; for students that reported they were not comfortable with any manufacturing processes during the PA, a larger increase in score from the PQ to the PQP was observed as compared to the control group. However, this result was not deemed significant at the $\alpha = 0.05$ level, indicating that additional data are needed to make a claim that the training procedure is most effective for students with the least amount of experience.

The most significant finding of this study was the vastly superior performance that the treatment group exhibited on the tooling geometry questions. As tooling geometry was the focus of the SPE, this result demonstrates that exposing students to visualized simulations of turning is more effective in teaching students about the manufacturability considerations of a turning process than simple training on a manual machine tool. Interestingly, however, many students did not understand that the creation of external curvature on a turned part, such as the fillet in the PostT part, is possible using a CNC machine tool even after they were trained to use such a machine.

While it is disappointing that the treatment group demonstrated inferior performance on the PQP as compared to the control group, it suggests that training changes are in order to address process choice in future studies. No treatment of either milling or AM processes was provided during the actual training procedure, which could have resulted in the treatment group's lower performance.

5.4 SOURCES OF ERROR

Although the assessment instruments deployed in this study were designed to measure students' understanding of manufacturing and DFM concepts, some error is unavoidable. The most significant source of error comes from the lack of control that is inherent in online surveys. Nothing prevented students from seeking outside assistance with the surveys, such as from classmates or online sources; they were merely asked not to do so. The only way to control for this error would be to force students to complete the surveys while under supervision, but that was deemed unrealistic given the size of the population and the amount of time it would take. Consequently, some error must be accepted, and students should not be given additional credit on a survey for correct answers.

There is also error inherent in multiple choice questions. While a student may indeed know the answer to a question and select the correct choice, it is also possible that the correct answer was selected at random. This can be mitigated to a point by providing additional reasonable answer choices, but it can only be completely eliminated by using free response questions. Those questions, however, have their own challenges; namely, grading of free response questions requires either human input or a sophisticated automated analysis system.

Error was also present in the design of the questions themselves. For instance, some students responded to questions on the PQ based on the apparent material of a part shown. Although the designers envisioned that the students would answer based on the geometry of the part, that occasionally turned out to not be the case. As a result, some of the results were tainted with responses that did not address the desired measurement. However, this phenomenon did provide valuable insight into the improvements that can be made to the assessment instruments.

5.5 STUDY LIMITATIONS

While the approach was deemed successful in better equipping students to geometrically analyze the turning process, there are limitations to the conclusions that can be drawn from the gathered data. Perhaps most importantly, the part that was given to the students during the PostTest assessment was similar to the one provided for the visualization exercises. As the treatment group's vastly superior performance on the PostTest is one of the major findings of the study, this limitation is important to consider. For the students that performed the visualization exercises, they could simply recall the end result of the various turning operations that they were asked about. In order to offset this tendency, a number of features were included in the PostTest part that were not present in the one provided for the visualization exercises; namely, the external corners and drilled holes. Some students recognized this, while others did not. In either case, the use of a part in the assessment instrument that was quite similar to the training part gives the treatment group an unfair advantage.

Another limitation of this study is the fact that the study designer also served as the instructor for the DFM training. This could have skewed the results in favor of the treatment group, as the instructor would have an incentive to focus on teaching the students what they needed to know in order to achieve higher scores on the assessment instruments. While this was not the intention of the study, it does present a nonideality that must be considered when interpreting the data.

The assessment instruments themselves also had a number of limitations; specifically, they were geared towards subtractive manufacturing processes and they did not necessarily

target specific areas of understanding. For example, in the Process Questions assessment, the students were not instructed which criteria they were to use to evaluate how to choose the “best” manufacturing process. Given that part geometry was the main focus of this study, it would have been preferable to instruct students that they were to choose a process for a given part by considering its geometry only. Some of the parts were metallic, which could skew student responses toward subtractive manufacturing processes. Thus, interpretation of score improvement data from the PQ to the PQP must be done while considering that a student’s choice of the best process may not necessarily be well-informed.

5.6 SUGGESTED IMPROVEMENTS

From observations on the second implementation of the study, a number of changes are recommended to increase both the effectiveness and the efficiency of future studies. These proposed changes will be enumerated according to the chronology of the deployment of the interrelated elements of the implementation.

1. A significant portion of the collected data from the second implementation had to be destroyed, primarily because students did not complete all of the assessments. To combat this issue, it is recommended that additional weight be assigned to the Qualtrics surveys so that student response rate may be increased.
2. Participants in this study frequently struggled with some terminology that was employed in the assessments, most notably the words “asymmetric” and “axisymmetric.” It is recommended that, if these words must be used in the assessments, they should be explicitly defined. Perhaps a better approach would be

to phrase questions in such a way so that those words are not required; additionally, interesting results could be obtained by asking the students to define those words themselves.

3. The part materials that are used for process choice assessments should be considered more thoroughly. A number of students answered that a particular part, specifically the pawn in Figure 35a, should be 3D printed because the provided image showed a part made of plastic. This result suggests two distinct changes: first of all, if the target of a particular question is simply the geometry of the part, it should be shown as a 3D model; secondly, an additional question should be added using a similar part image made of plastic to probe students' choice of process based on perceived material. In the current form of the PQ, it is difficult to determine whether students chose 3D printing because the part was plastic or for another reason.
4. Training of the treatment group students was made possible by the VM setup that was done before the study began. Unfortunately, however, performance of the VMs left much to be desired. The primary issue with the VMs was the speed of rendering visualizations. To address this issue, it is recommended that more powerful graphics hardware be employed. Additionally, if the size of the treatment group is to be increased, the current VM setup will most likely be incapable of handling a significantly increased user load.
5. The actual machining training procedure was cumbersome at times, primarily because it involved a number of complicated operations. Although the manufacture of yoyos was achieved for this small treatment group, a multi-step process would

be significantly more difficult if the entire class of approximately 250 students were required to manufacture the yoyos. It is recommended that CNC training be limited to a single part that can be entirely machined on one CNC machine tool.

6. Part fixturing errors caused a small number of student parts to be defective; as a result, those parts were scrapped and new parts were made for those students. To prevent this phenomenon in future studies, it is recommended that some form of automated material handling and loading equipment be employed to increase repeatability. For a turning center, a bar feeder (or bar puller) could be used to almost completely automate the part production process. Not only would this result in a shorter cycle time, but safety would be increased as the students would not need to interact with the machine tool's hydraulic chuck.
7. A number of students complained that, although they enjoyed making the yoyos, they were left at a disadvantage compared to control group students because they did not have the chance to manufacture the shaft coupler and motor mount that would have been useful in their final machines. Additionally, they were not provided with training on manual machining equipment, which was a hindrance to their fabrication capabilities while building their machines. This suggests two changes to the study: first, the students should make the same parts as the control group during the CNC training phase (or at least be provided with those parts); and second, the treatment group students should receive some form of training on the manual equipment so they can use it during the construction of their machines.
8. Grading of the survey responses was much improved over the pilot study because the surveys were deployed using Qualtrics. However, the data analysis phase of this

work was quite time consuming. It is recommended that all *scored* questions be made multiple choice unless they absolutely must be free response. Tremendous insight was gained from free response questions, however, and they most definitely should not be eliminated. Instead, the free response questions should be used for additional data collection, and the scoring of the assessments should be done using more easily graded question types. If multiple choice questions are employed, it is suggested that a large number of answer choices be provided to decrease error due to random chance. Alternately, an automated system should be developed to grade more complex free response questions.

9. The assessment instruments developed for this study provided somewhat of a proverbial “shotgun blast” of treatment into topics related to manufacturing and DFM. Improvements to these assessments are in order, but it is also recommended that a standardized and academically-recognized assessment instrument be deployed in concert with the study-specific surveys. This will enable comparison against studies performed by other researchers.
10. Some difficulties were encountered in the analysis phase of this work because the amount of data available was too small to enable statistically significant conclusions to be drawn. In conjunction with the proposed changes in point (1) to decrease attrition rate, it is suggested that the size of the treatment group be increased.

5.7 ANSWERS TO RESEARCH QUESTIONS

This work set out to answer three specific research questions as outlined in Section 2.8. Using the data, analysis and observations presented in this thesis, those questions are reiterated and answered below.

1. How does exposure to computer simulations of manufacturing *or* manual machining training affect student' ability to geometrically analyze the turning process?

This question was specifically addressed in the sketching questions that students were asked to complete for the PostTest. Given the statistically significant superior performance of the treatment group on this assignment, it is apparent that the intervention was successful in better equipping students to analyze the turning process geometrically.

2. How is a student's choice of a manufacturing process for a certain part influenced by exposure to computer simulations?

As a whole, the control group demonstrated a larger increase in score on the process choice assessments than the treatment group did. However, statistical analysis of the difference in mean scores between the groups proved inconclusive. Although this result does not necessarily answer research question 2, it is valuable in that it suggests that additional treatment of process choice is needed for future implementations of this work.

3. How does students' prior experience in manufacturing impact the effectiveness of the SBL approach?

A student's prior experience in AM or SM could significantly affect the outcome of the training protocol presented in this work. Given that the objective of this work is to rapidly

educate students about manufacturing and DFM, the cleanest results from the study come from students with no appreciable understanding of AM and SM concepts before training. Students in the treatment group who reported that they were not comfortable with any manufacturing processes on the PA performed better than the whole of the treatment group on both the PQP and the PostTest. In fact, this was the only subdivision of students from the treatment group that exhibited a larger mean increase in score on the process choice questions after machining training than the control group. However, statistical analysis of those results also proved to be inconclusive because only four students in the treatment group reported they were not comfortable with manufacturing. The result is promising, but additional data are required to determine if the use of visualized simulations of SM are indeed more effective in training students about manufacturing and DFM than the traditional approach of training using manual machine tools. This result suggests that prior training on manual machine tools, or training on manual machine tools as a part of the study, confuses students into thinking that movements of the cutting tool on a lathe are limited to independent motion in the axial and radial directions.

5.8 CONCLUSIONS

This thesis presented the design, implementation and analysis of a computer-assisted simulation-based learning approach to education in additive and subtractive manufacturing and design-for-manufacturability. A virtualized system was developed to allow a treatment group of students to use a voxel-based computer-aided manufacturing software package to visualize the process of turning for a variety of parts. The treatment group was also trained on the operation of both a 2-axis CNC turning center and a 4-axis CNC millturn machine and allowed to manufacture a two-piece yoyo. The treatment group students were assessed

throughout the study using instruments that were specifically developed for this work. The data from these assessments were analyzed and compared to results on the same assessments for a control group, which received training only on manual machine tools. Results from data analysis indicate that the visualizations were more effective in training students about geometric considerations in turning than was training on manual equipment. Additionally, the visualization and training protocol showed a higher efficacy among students with negligible experience in manufacturing before the study. Results of the study suggest that the typical training on manual machining equipment confuses students into thinking that subtractive processes have more geometric limitations than they actually do. Sources of error were discussed, limitations of the study were given, and ideas for improvement of future implementations based on the outcomes of this study were presented.

APPENDIX A. ASSESSMENT INSTRUMENT FOR PILOT

STUDY

TURNING

*Relevant prints are attached, as is a sheet of blank paper for answers.

Machine Capability:

1. Consider the part shown in the attached print. Which, if any, of the features shown are impossible to create on a standard 2-axis lathe? Assume that tool sizes do not pose a constraint and consider only the capability of the machine.
2. If this part is not manufacturable on a 2-axis machine, how many axes are needed to create all the features?

Fixturing:

3. Assume you have access to a 2-axis NC lathe. Where would you fixture this part to reach all the features?

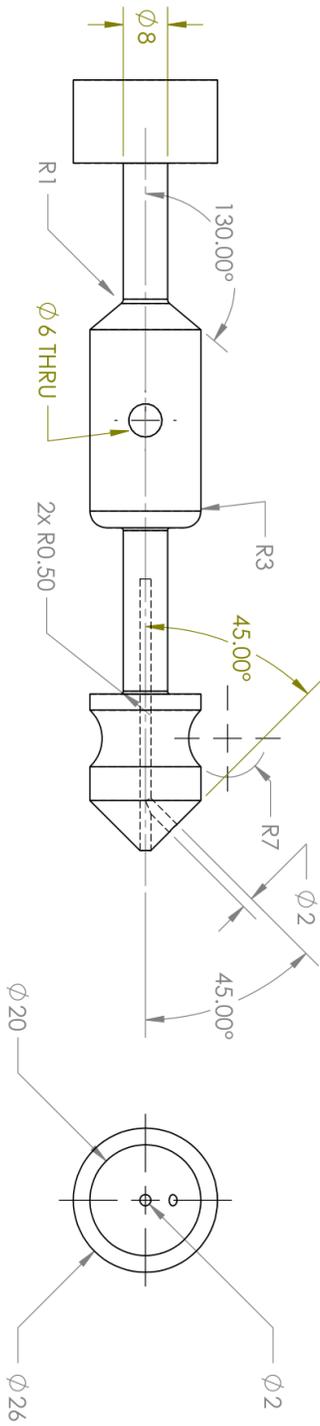
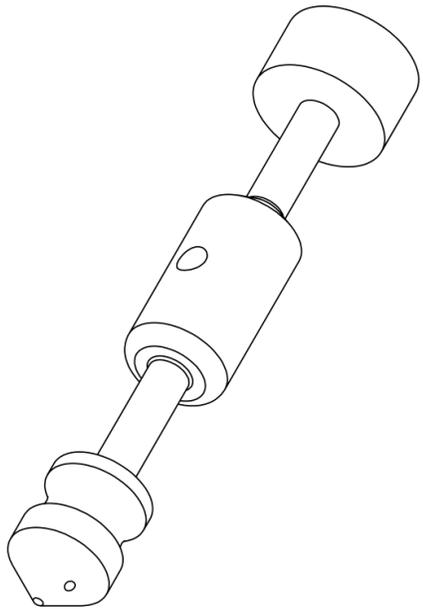
*For questions 4: end, reference the tool profiles on the attached print. Also, neglect any features that cannot be reached on a 2-axis machine that you described in (1).

Tool Choice:

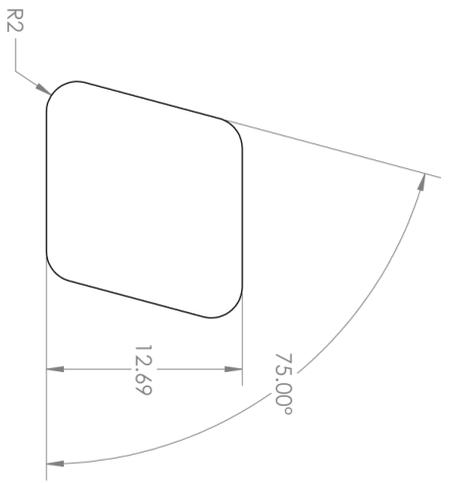
4. Assume the part is fixture in the configuration you selected in (3). Sketch the part after it has been roughed out with the 75° insert.
5. The machine indexes the turret to the 35° right-handed tool. Sketch the part again after all material that this tool can reach has been removed.
6. What is the smallest number of available tools needed to make this part? Which tool(s) is/are needed?

Path Planning

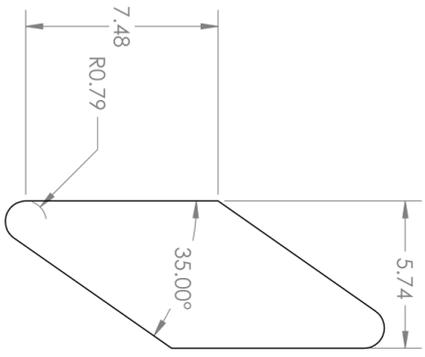
7. If part deflection is a concern, in what order should the turned features be machined to minimize bending of the workpiece?
8. Are there any additional features of a lathe that could be useful in minimizing deflection? If so, what are they and how would they support the part?



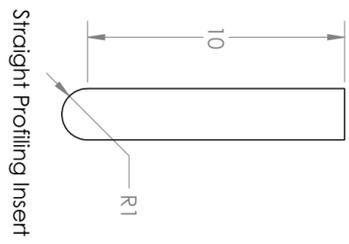
DRAWN	R. LYNN	11/15/15	GEORGIA TECH
DIMENSIONS ARE IN MM			EAGER Turning Example Part



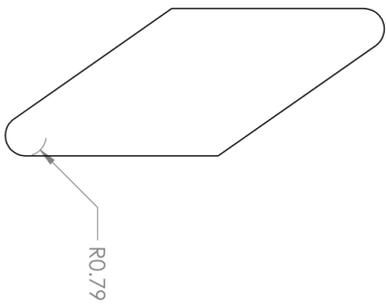
75 Degree RH Insert



35 Degree RH Insert



Straight Profiling Insert

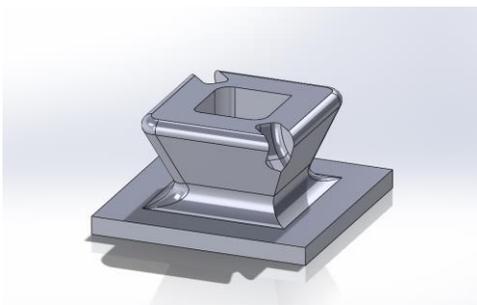


35 Degree LH Insert

DRAWN	R. LYNN	11/15/15	GEORGIA TECH
DIMENSIONS ARE IN MM			EAGER Turning Tool Inserts

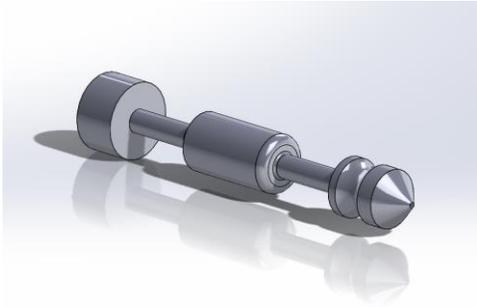
APPENDIX B. PREASSESSMENT

1. What is your name?
2. Which section are you in (A-M)?
3. Indicate all previous fabrication/manufacturing experience (i.e. 3D printing, machining, etc) you have had: 3D printing, Lathe, Mill, CNC, Laser cutter, Welding
 - 3D printing
 - Lathe
 - Mill
 - CNC
 - Laser cutter
 - Welding
4. Which manufacturing processes are you most comfortable with: 3D Printing, Lathe, Mill, CNC, Laser Cutter, Welding, None of the above
 - 3D Printing
 - Lathe
 - Mill
 - CNC
 - Laser Cutter
 - Welding
 - None of the above
- 4a. Why?



5. How would you choose to make the part above? 3D Printing, Lathe, Mill, CNC, Laser Cutter, Welding, I don't know

- 3D Printing
- Lathe
- Mill
- CNC
- Laser Cutter
- Welding
- I don't know



6. How would you choose to make the part above? 3D Printing, Lathe, Mill, CNC, Laser Cutter, Welding, I don't know

- 3D Printing
- Lathe
- Mill
- CNC
- Laser Cutter
- Welding
- I don't know

APPENDIX C. PRETEST

1. Is turning an additive operation or a subtractive operation?

- Additive
- Subtractive
- I don't know

Explain your answer:

2. In a lathe, does the part spin or does the tool spin?

- The PART spins
- The TOOL spins
- I don't know

3. What is at least one advantage that a lathe has over a mill?

4. Should a lathe be used to make an axisymmetric part?

- Yes
- No
- I don't know

5. Why?

6. Would a vise be used on a lathe or mill? (Below is a photo of a vise)

- Lathe
- Mill
- I don't know



7. Should a mill be used to make an axisymmetric part?

- Yes
- No
- I don't know

8. Why?

9. A group of students wants to make a fast prototype of a part to see if the part is of a reasonable size and shape. For such a prototype, should machining be used or should 3D printing be used? (Assume the part's geometry is relatively complex)

- 3D Printing should be used
- Machining should be used
- It doesn't matter
- I don't know

APPENDIX D. PROCESS QUESTIONS

Figure 1



1. For the part in Figure 1 it is better to...

- Turn
- Mill
- Both Turn and Mill
- 3D Print
- I don't know

Why?

Figure 2



2. For the part shown in Figure 2 it is better to...

- Turn
- Mill
- Both Turn and Mill
- 3D Print
- I don't know

Why?

Figure 3



3. For the part shown in Figure 3 it is better to...

- Turn
- Mill
- Both Turn and Mill
- 3D Print
- I don't know

Why?

Figure 4



4. For the part shown in Figure 4 it is better to...

- Turn
- Mill
- Both Turn and Mill
- 3D Print
- I don't know

Why?

Figure 5



5. For the part shown in Figure 5 it is better to...

- Turn
- Mill
- Both Turn and Mill
- 3D Print
- I don't know

Why?

Figure 6

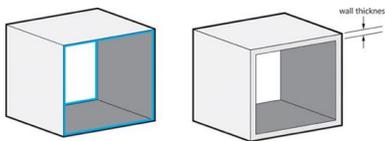


6. For the part shown in Figure 6 it is better to...

- Turn
- Mill
- Both Turn and Mill
- 3D Print
- I don't know

Why?

Figure 7

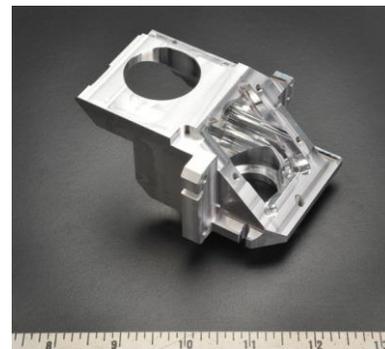


7. For the part shown in Figure 7 it is better to...

- Mill
- 3D Print
- Either Milling or 3D Print
- Neither
- I don't know

Why?

Figure 8



8. Can the part shown in Figure 8 be made on a standard 2-axis lathe? 3-Axis mill?

- 2-axis Lathe
- 3-axis Mill
- Neither
- I don't know

If Neither, please explain.

APPENDIX E. YOYO DESIGN CONSTRAINTS

Instructions: You are to design a yo-yo using CAD, SculptPrint, and the Okuma Genos L250, a 2-axis CNC lathe. The provided CNC tutorials describe the operation of this machine. Additionally, a video has been provided that shows an example of the yo-yo manufacturing process. You will create the yo-yo in two pieces and then fasten them together using a dowel pin. Most of the G-Code necessary for this assignment has been provided for you. You only need to make the G-Code to create the curvature, radii or chamfers that you design on the front and back faces of the part. This G-Code will be made using SculptPrint and the appropriate header you need will be pasted in the top of the program. Once you have made the two G-Code programs, one for the front of the part and one for the back, you should choose the order in which you run the programs to minimize the total number of refixturing operations required. The provided G-Code programs are described below.

Design Constraints:

*Reference the attached print for a visual explanation of these constraints.

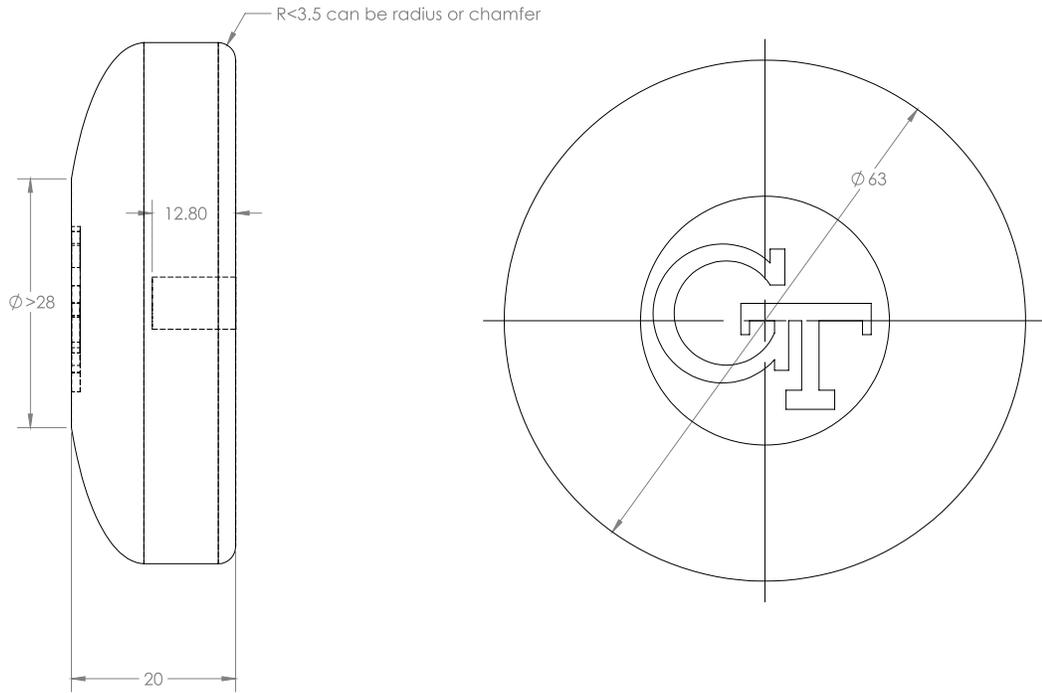
1. The yo-yo must be 2.5 inches in diameter and 20 millimeters in length
2. The yo-yo must have a cylindrical portion whose diameter is equal to 2.5 inches. The distance between the end of the OD and the back face shall be no greater than 3.5 mm; the front radius must be no greater than 40 mm. These constraints are imposed on the part by the design of the fixtures used in this assignment.
3. There must be a drilled and countersunk blind hole in the center of the back of each piece.
4. The front face of the yo-yo must have a flat face that is at least 1.1 inches in diameter.
5. Make sure the no cut plane is set past the MIDDLE of the part (12mm) for both the front and back of the yo-yo.

Provided Yo-Yo G-Code Programs:

1. YOYODRILL.MIN: This will drill a hole in the back of the yoyo for a pin to be put into it
2. YOYOCOUNTERSINK.MIN: This will countersink the hole for the pin making it easier for the pin to go in
3. YOYOSTOCKRESIZE.MIN: This will face and size both sides of the piece you cut on the horizontal saw
4. YOYOENGRAVE.MIN: This will engrave the GT logo into the front face of the yoyo. We will not be making yo-yos with UGA logos this semester.

Programs to Be Created in This Assignment:

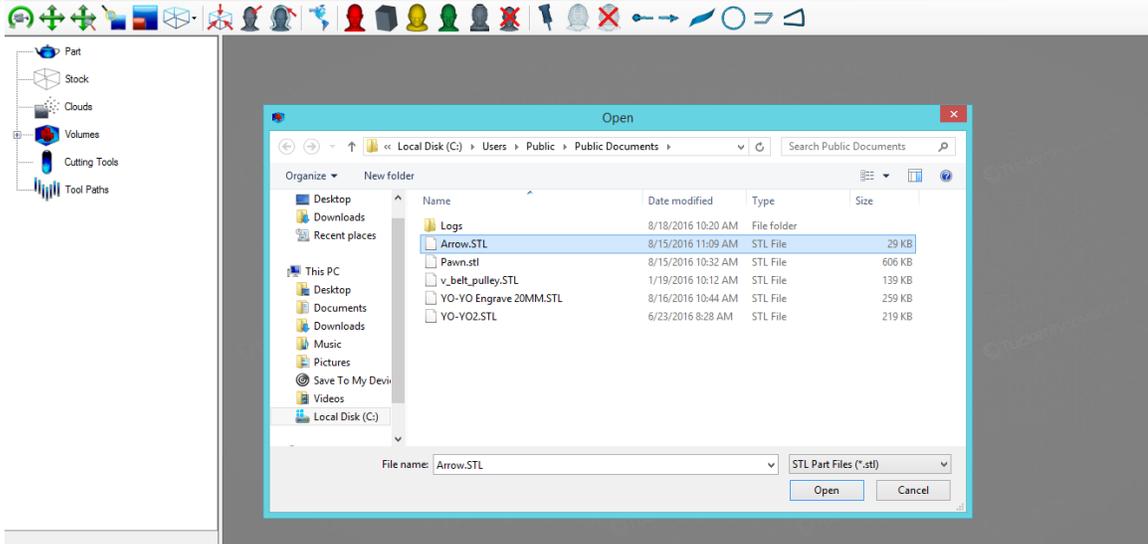
1. YOYOBACK[NAME]: This will turn the features you design onto the back of the yo-yo. Replace [NAME] with your first name and the first letter of your last name (for example, "YOYOBACKGEORGE").
2. YOYOFRONT[NAME]: This will turn the features you design onto the back of the yo-yo.



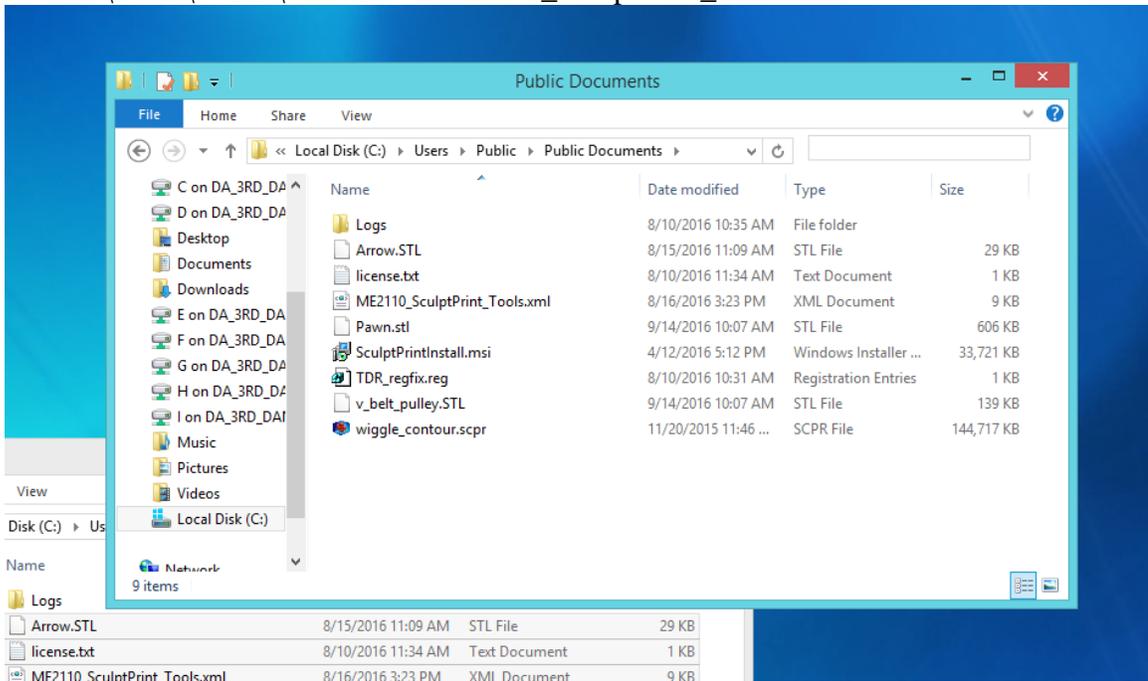
DRAWN	E. Barnett	7/21/16	GEORGIA TECH
DIMENSIONS ARE IN MM			Yo-Yo Parameters

APPENDIX F. SCULPTPRINT EXERCISES

1. Open SculptPrint and go to File > Import Mesh, import the arrow.stl file from directory C:\Users\Public\Public Documents\arrow.STL

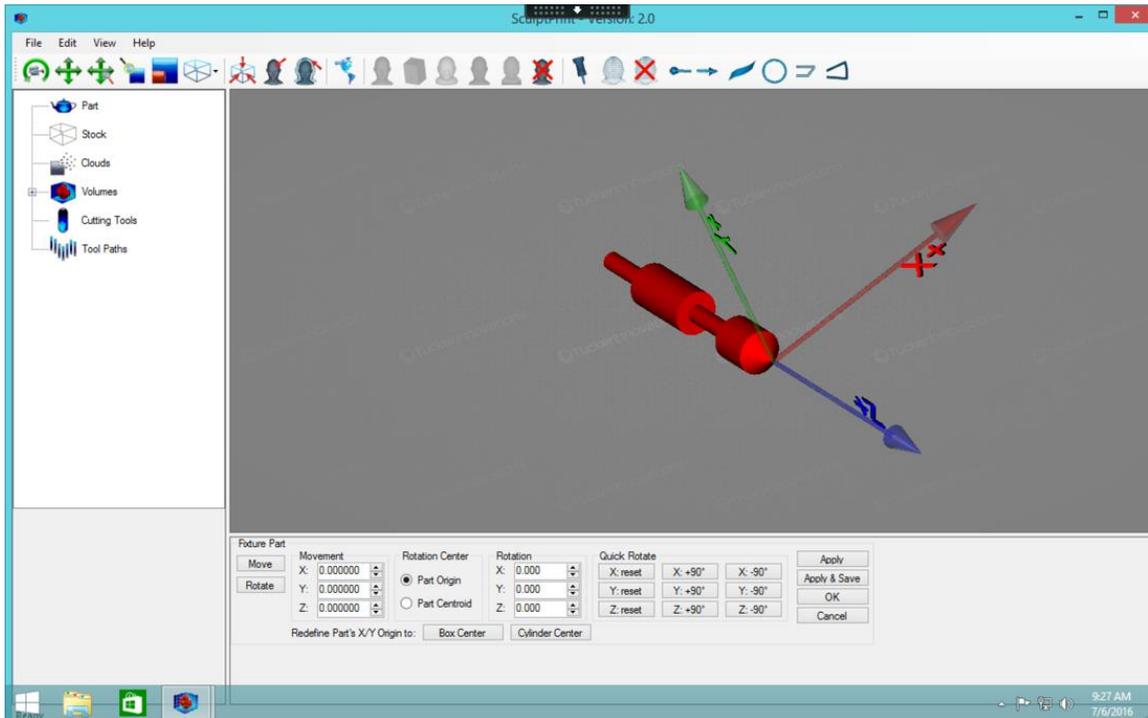


2. Next, import the tool catalog. Click File and Import Tool Catalog from C:\Users\Public\DocumentsME2110_SculptPrint_Tools.xml

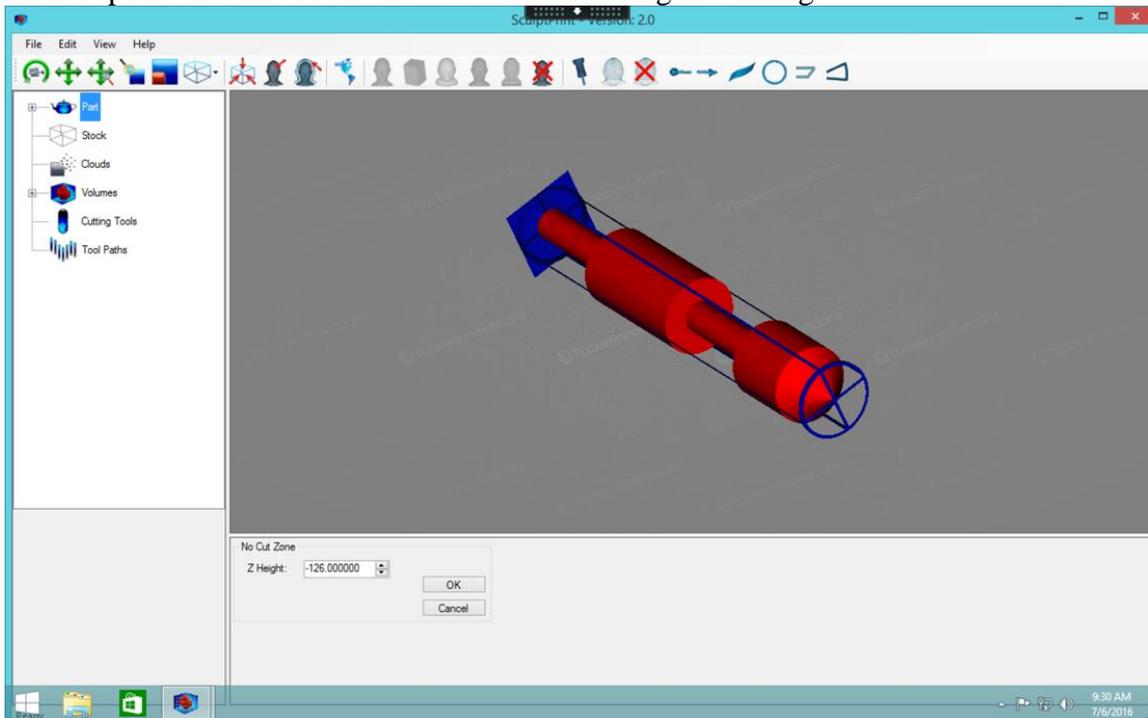


3. Now fixture the part by right clicking on the Part Menu then Fixture Part. Make sure the positive z-axis is sticking out from the tip of the arrow (as shown in the example below). Use the Cylinder Center buttons to make sure the part is centered. (Click multiple

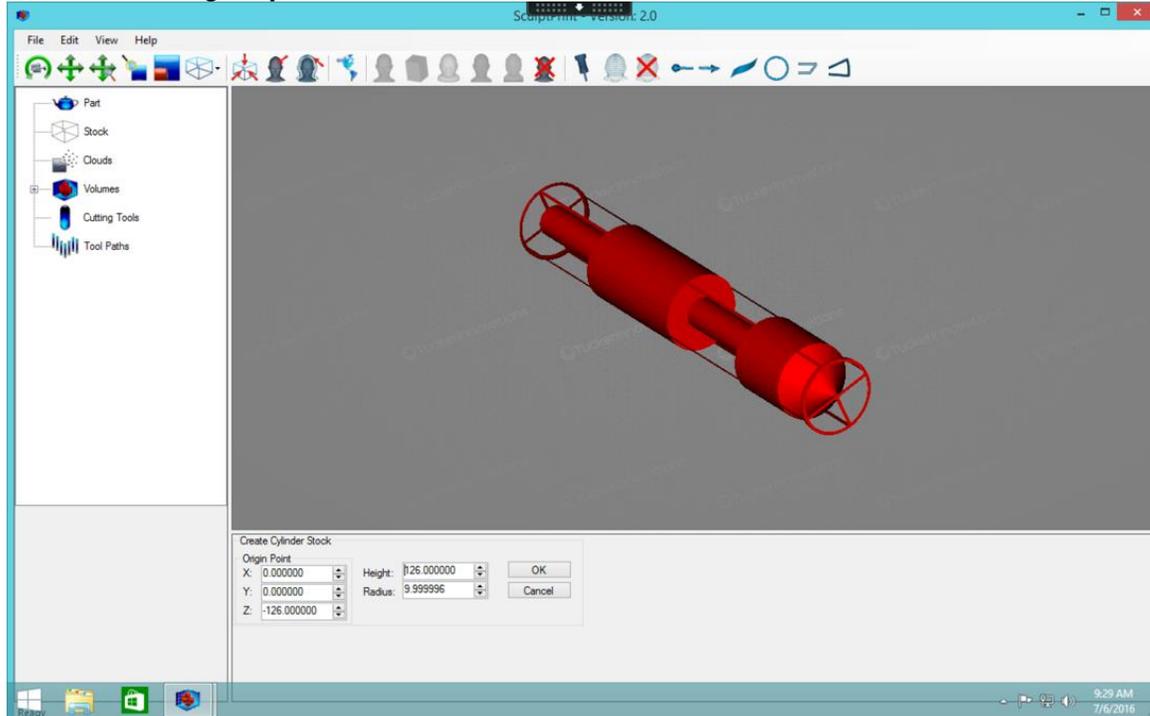
times if needed). This step defines the coordinate system of part orientation. If the axes look like those in the picture below without changing the part orientation, you can simply select "OK".



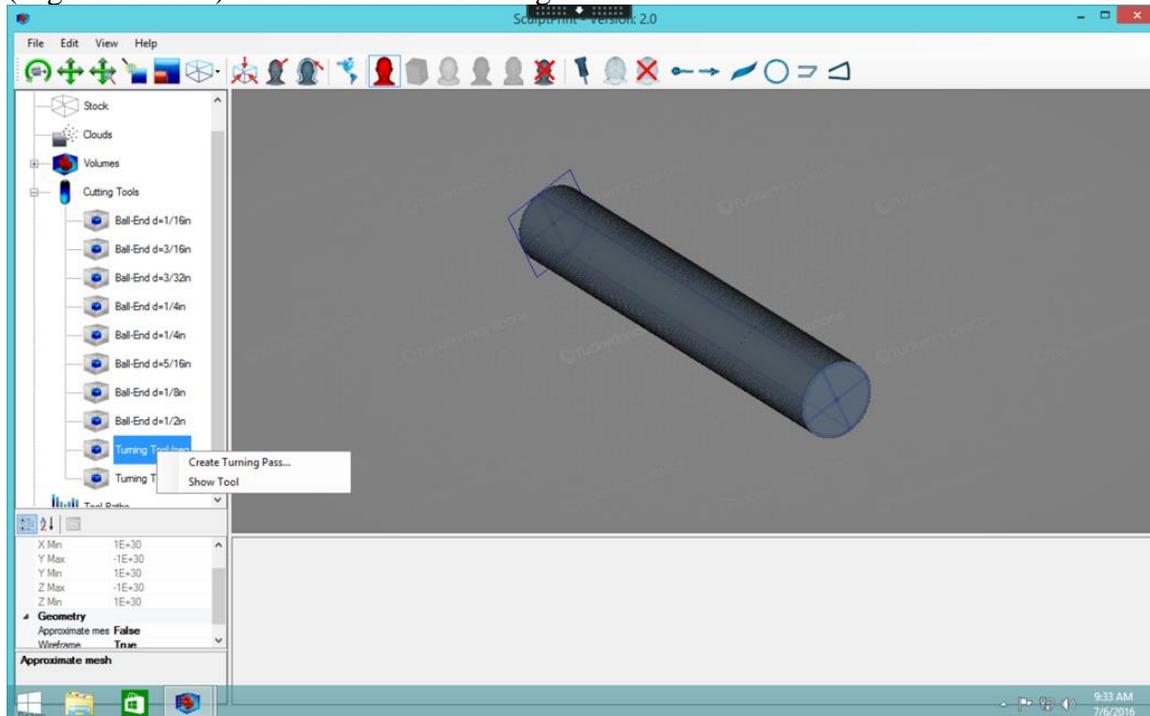
4. Next, define the No Cut Zone at the bottom of the arrow. This plane decides the farthest point that the tool is allowed to reach during machining.



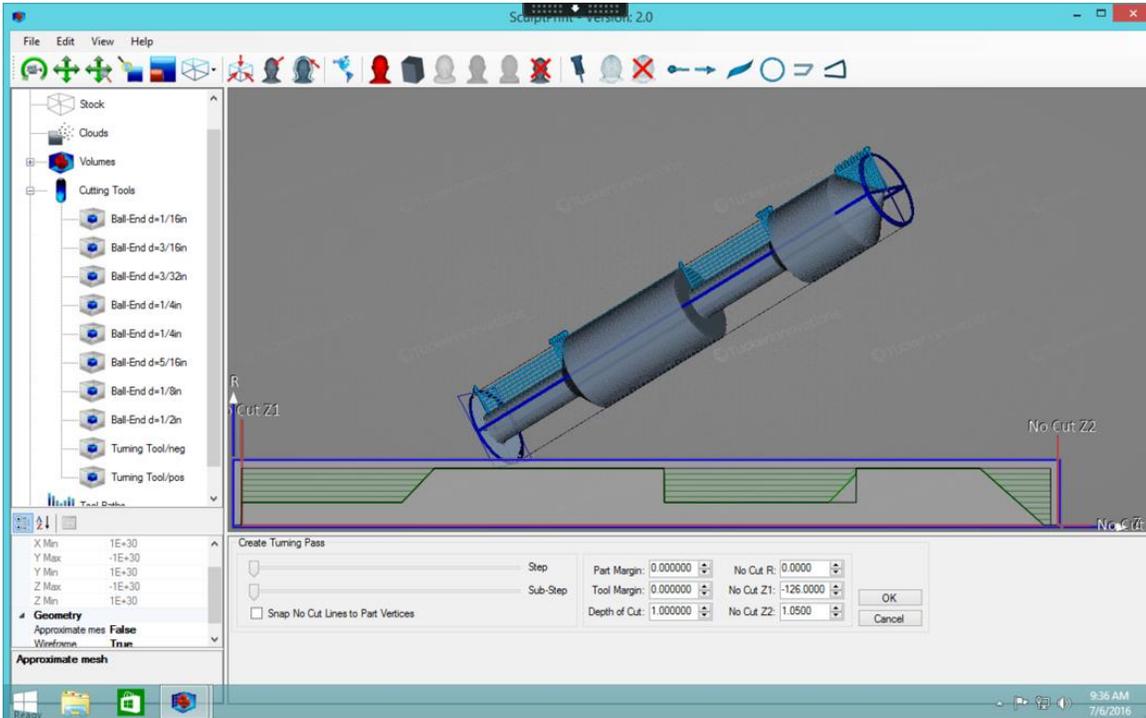
5. Create the Cylinder Stock by right clicking Part Node > Create Cylinder Stock. Then, increase the height by 1



6. Now create the volumes by right clicking on Part > Create Volumes. Once the previous step finishes, expand the Tools Menu and right click on Turning Tool 35 degree Negative (Right hand tool) and click Create Turning Pass.



7. Make sure the No Cut R is set to zero and then click Create



Upload a screenshot similar to the image labeled "EndwithPass" when finished.

Question 1. Describe the difference between the resulting end volume after the tool pass and the original part volume (shown in red such as in the image labeled "PartVolume").

Now expand the Tool Pass menu and right click on Tool Pass 1. Then click Playback Path and click Go To End. After seeing the end volume, delete Tool Pass 1 and repeat the steps of creating a turning pass with a No Cut R of zero with the 35 degree positive turning tool. (Note that the 35 degree positive turning tool is a left-hand tool).

Upload a screenshot of the end volume of the positive turning tool when finished.

Question 2. Describe how the end volume differs from the end volume made by the 35 degree negative (right-hand) turning tool.

Now expand the Tool Pass menu and right click on Tool Pass 1. Then click Playback Path and click Go To End. After seeing the end volume, delete Tool Pass 1 and repeat the steps of creating a turning pass with a No Cut R of zero with the profiling turning tool.

Upload a screenshot of the end volume of the profiling turning tool when finished.

Question 3. Describe how the end volume differs from the original end volume made by the negative (right-hand) turning tool.

Now expand the Tool Pass menu and right click on Tool Pass 1. Then click Playback Path and click Go To End. After seeing the end volume, delete Tool Pass 1 and repeat the steps of creating a turning pass with a No Cut R of zero with the 75 degree negative turning tool. (Note that the 75 degree negative turning tool is a right-hand tool)

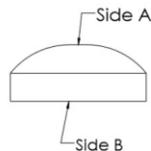
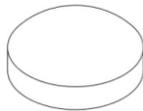
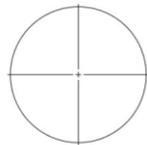
Upload a screenshot of the end volume of the 75 degree negative turning tool when finished.

Question 4. Describe how this end volume differs from the original end volume made by the 35 degree negative (right-hand) turning tool.

APPENDIX G. POST TEST

1. Will the included angle of a cutting tool affect the cut? If so, how?
2. A group of students needs to make an asymmetrical part, should they use a lathe or a mill to cut their piece?
3. Identify which of the parameters feed rate is dependent on.

	[Depends on]	[Doesn't depend on]
Number of Teeth (1)	<input type="radio"/>	<input type="radio"/>
Spindle Speed/RPM (2)	<input type="radio"/>	<input type="radio"/>
Left/Right Handed Tooling (3)	<input type="radio"/>	<input type="radio"/>
Chip Load (4)	<input type="radio"/>	<input type="radio"/>
Coolant Level (5)	<input type="radio"/>	<input type="radio"/>



4. A group of students are instructed to use a lathe to manufacture a dome with a cylindrical base (as shown in the drawing titled EAGER Dome Example). Side A of the stock is the side that will be turned for the dome and Side B is the base. The group must do a few operations to reach the desired piece. They must face both sides of the stock and turn Side A to make the dome. The group must also flip the piece at some point. To be efficient, the group must flip the piece as little as possible. Which of the following is the most efficient and correct order of operations?

- a. Face Side B, Turn Side A, Face Side A
- b. Face Side B, Face Side A, Turn Side A
- c. Face Side A, Face Side B, Turn Side A
- d. Face Side A, Turn Side B, Face Side B
- e. I don't know

4a. Explain your answer to question #4

Figure 1

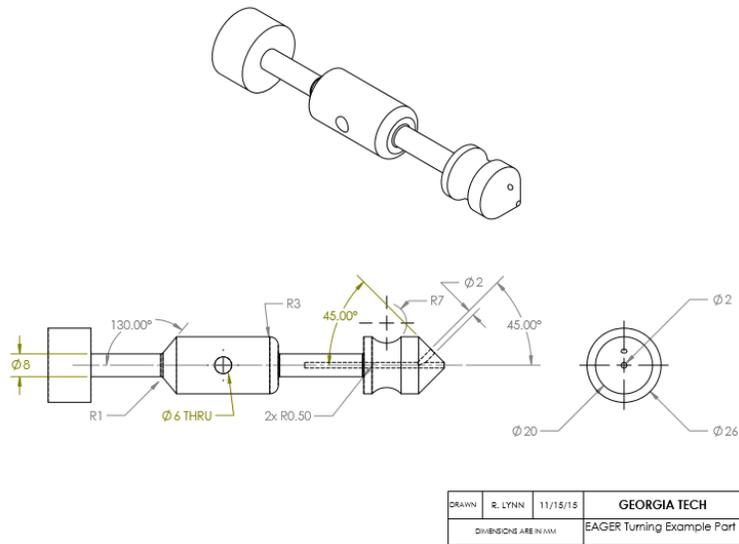
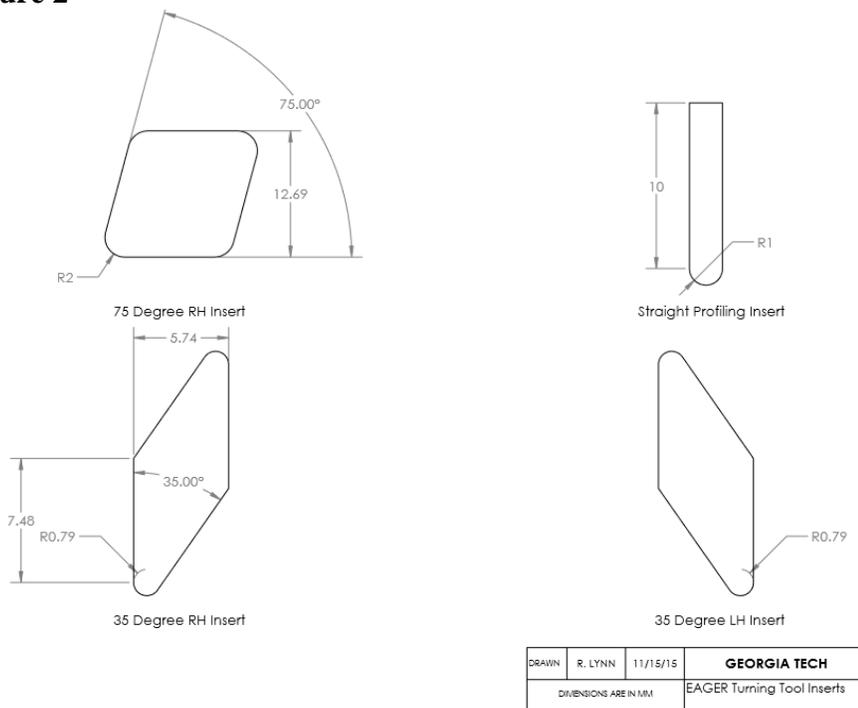


Figure 2



5. Assume the part shown in FIGURE 1 is fixed by the cylindrical base of the piece in the chuck. Sketch the part after it has been roughed out with the 75° insert (as shown in FIGURE 2).

6. Next, the machine indexes the turret to the 35° right-handed tool (shown in FIGURE 2). Sketch the part again after all material that this tool can reach has been removed.

7. What is the smallest number of available tools needed to make the part shown in FIGURE 1? List which tool(s) is/are needed below.

- 1
- 2
- 3
- 4
- 5
- I don't know

7a. List those tools.

8. Why would someone use a collet as opposed to a chuck to hold a work piece?

	Yes (1)	No (2)
When using high spindle speed	<input type="radio"/>	<input type="radio"/>
For plastics as opposed to metals	<input type="radio"/>	<input type="radio"/>
When using a 4 axis lathe	<input type="radio"/>	<input type="radio"/>
For high precision clamping / concentricity	<input type="radio"/>	<input type="radio"/>
For very long workpieces	<input type="radio"/>	<input type="radio"/>

9. Why is a left hand tool sometimes required instead of a right hand tool?

	Yes (1)	No (2)
The operator is left handed	<input type="radio"/>	<input type="radio"/>
The tool is left handed	<input type="radio"/>	<input type="radio"/>
For light machining	<input type="radio"/>	<input type="radio"/>
When machining toward the chuck	<input type="radio"/>	<input type="radio"/>
For machining a particular profile	<input type="radio"/>	<input type="radio"/>

10. A group of students wants to make a gear for their project for 2110. The gear will need to withstand a substantial amount of force. Taking this into account, does it matter if they 3D print or machine it? If so, which method should be used?

- No, both are equally acceptable
- Yes, it matters -- Machining
- Yes, it matters -- 3D Printing
- I don't know

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