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# The Impact of Manufacturing Process Awareness on Computer-Aided Design

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# The Impact of Manufacturing Process Awareness on Computer-Aided Design

Daniil Nikitin, Alexander R. Murphy, Ph.D., Matthew Mueller, Ph.D.

## ABSTRACT

A cornerstone of most modern engineering curricula includes Computer-Aided Design (CAD), often taught alongside introductory engineering design principles. However, these courses often omit topics such as manufacturing, machining, and production, or instruction on how the parts students model are actually manufactured. In response to an observed gap in education on the connections between manufacturing processes and CAD, this paper intends to explore the impact of manufacturing education on student design methodology. Second-year undergraduate engineering students had the opportunity to observe an engineered part manufactured in a university machine shop or 3D print lab. Specifically, students observed the operation of a CNC (computer numerical control) milling machine, lathe machine, or Fused Deposition Method (FDM) 3D printer. Data collection primarily occurred through the Multi-User Computer-Aided Design program (MUCAD) Onshape, which allowed direct access to students' modeling data and summative statistics natively. Following the manufacturing demonstrations, students were tasked with modeling the part observed during the manufacturing demonstration in Onshape. A control condition without exposure to a manufacturing process was compared to the conditions that witnessed the part being manufactured on a CNC machine, a lathe, or an FDM 3D printer. Results indicate a significant difference in students' approach to creating their CAD models. Students who observed the part being printed on an FDM 3D printer modeled with less efficiency (more overall CAD features to achieve the same final model) compared to the Control Condition. In addition, correlations exist between prior manufacturing experience and their modeling behaviors overall, regardless of condition. This work demonstrates how exposure to manufacturing processes early in an undergraduate engineering program can impact students' CAD behaviors and design efficiency.

## 1. INTRODUCTION

Computer-Aided Design (CAD), as well as Computer-Aided Manufacturing (CAM), are essential skills for the modern engineer. Within an undergraduate degree program, these principles and applied knowledge are skills every graduating engineer should possess. As such, CAD and CAM courses are built into the core curriculum of modern engineering undergraduate programs [1]. As industry progresses, so does engineering curricula. As new and improved manufacturing processes are being introduced, there becomes a growing need for a solid foundation in CAD among undergraduate students [2]. Recent advancements, such as the implementation of artificial intelligence in CAD for automated decision-making [3], could reinforce the need for a stronger foundation in basic CAD skills before leveraging these new technologies. For example, these new tools have been adapted to support efforts on generative modeling tools [4] during the engineering design process.

There are a wide variety of manufacturing processes available to an engineer, each with their own inherent limitations and strengths. Recently, additive manufacturing has been at the forefront of innovative manufacturing [5]. One such process is Fused Deposition Modeling

(FDM), which uses thermoplastic filaments to create 3D objects. FDM has become increasingly common, especially in undergraduate curricula. The main advantage of FDM printers is the lack of rigid constraints for production, allowing the process to manufacture components too complex for other machines. In comparison to other manufacturing processes, the material and the 3D printers are generally low-cost. As interest increases and widescale availability improves for FDM manufacturing, engineering education is generally lagging behind current technology [6]. The new additive manufacturing trend has forced universities and engineering programs to respond with new and adapted curricula to fill gaps of knowledge [7] before they enter careers in engineering.

As university programs attempt to address these gaps, studies have examined the effects of introducing the FDM process on students' design methodologies. For example, Prabhu et al. looked at the direct influence from the introduction of Design for Additive Manufacturing (DfAM) in lectures, demonstrating that students placed no greater emphasis on DfAM best-practices when designing [8]. Further work by Prabhu et al. demonstrated that exposure to DfAM (and particularly restrictive DfAM techniques where concerns such as support structure accommodations and warping due to thermal stress are introduced) resulted in "designs with greater AM technical goodness" [9]. In this case, technical goodness refers to designs that are more robust and account for the variety of issues that additive manufacturing encounters. While there is a large body of work on the effects of additive manufacturing on CAD behavior, there is an appreciable gap in the literature on how these behaviors are impacted by exposure to other additive or subtractive manufacturing processes. It is critical that undergraduate engineering students are exposed to manufacturing processes other than FDM printing to be competitive in the engineering job market.

This paper explores how the integration of manufacturing education can affect CAD behavior. Studies have noted that CAD behaviors develop rather quickly within CAD-centric courses [10]. This might be explained by CAD behaviors being easily affected by different forms of bias. Specifically, unconscious bias and design bias may play a significant role in the rapid uptake of CAD skills by undergraduate engineering students. Unconscious bias can be defined as an involuntary tendency towards certain behaviors or actions [11]. Design bias refers to a repeated proclivity towards CAD behaviors, such as generally starting all models from a large cube or having a preferred plane to model from [12]. In fact, it has been shown that the way CAD is taught to students directly affects how they conceptualize problems and approach design [13]. Due to the existence of bias, students can be nudged towards certain modeling behaviors that improve their general CAD abilities and increase their modeling efficiency. Manufacturing awareness may also be a major contributor. This work aims to address the following research questions:

RQ1. To what extent does exposure to different manufacturing processes impact students' approach to computer-aided design in an engineering context?

RQ2. What evidence exists, if any, for relationships between additive manufacturing processes, subtractive manufacturing processes, and computer-aided design feature usage?

To address these research questions, the authors formulated the following hypotheses:

H1. Participants exposed to a manufacturing demonstration will use fewer features when modeling their part than those not exposed to a manufacturing demonstration.

H2. Participants will use more additive features to a model when exposed to additive manufacturing processes, such as FDM, and will use more subtractive features when exposed to subtractive manufacturing methods such as CNC.

## 2. BACKGROUND

Within the context of this study, design efficiency is measured by recording the time participants spend modeling and the number of features they use to construct their CAD model [14]. Features in this case are actions that directly edit the geometry within a CAD model. A more efficient design is one that takes less time and uses overall fewer features compared to a baseline. The general push towards greater efficiency amongst engineering design and methodology is due to the observed lack of adequate industry-ready CAD knowledge as students graduate [15]. There is a variety of previous research done on design methodology and efficiency as researchers try and understand the issue. For example, some research has focused on activities within CAD education itself and their effect on design efficiency and enthusiasm of participants [16], [17]. Research by Shih and Sher analyzed how preliminary sketches affect architecture students' CAD behaviors, claiming that dissatisfaction with the sketch phase led to uncertainty, resulting in a loss of efficiency within the CAD phase [18].

Given the availability of additive manufacturing machines on consumer markets, studies began looking at how additive manufacturing could affect CAD behavior. A study by Prabhu et al. investigated how educational interventions on DfAM topics could impact the design efficiency of participants [19]. Overall, results showed that after a lecture on these topics, all participants demonstrated a decrease in design robustness when accounting for manufacturing processes; however, participants who were presented with restrictive DfAM inputs demonstrated the greatest increase in design efficiency. A following study by Prabhu et al. that investigated how the timing of educational interventions affected modeling behavior demonstrated that restrictive DfAM education had no difference between differently timed interventions [20].

Overall, it's difficult to claim that the manner of CAD education has a strong effect on how students perceive and approach a design challenge due to the differing results across studies. The overall goal of these studies, such as work by Hamada et al., is pushing students to design with greater efficacy and intent [21]. Understanding how exposure to manufacturing processes other than FDM 3D printing impacts CAD behavior may inform undergraduate engineering curricula as it attempts to track market and industry trends.

### 2.1 CAD Education

Work by Daud et al. presented an evaluation approach to determine the level of CAD education necessary for undergraduate students to help ensure graduates have the necessary skills for a career in engineering [22]. This is critical, as ensuring students graduate with sufficient CAD experience will help them be more marketable when searching for careers. Menary and Robinson assert that CAD skills are essential for those in engineering fields [24], which may warrant a closer look at how and when we teach CAD. Dori and Tombre claim that there have been no serious attempts at moving CAD education into higher-level coursework [23], as it is typically taught in the first or second year of an undergraduate engineering degree. Further, a panel on the challenges of CAD/CAM education emphasized the need for CAD/CAM education for the workforce and that the relevant curriculum should continuously grow alongside industry, not follow behind it [25]. A 2008 survey observed how the environment surrounding an engineer can influence design fixations among students [26], which may be related to unconscious bias.

### 2.2 Manufacturing Education

A variety of sources identify a lack of manufacturing knowledge amongst recent engineering graduates. For example, Todd et al. claimed a need for more manufacturing education through a series of industry surveys and identified approaches to remedy the issue [27]. This initiative to better prepare students for industry is not a recent effort. A 1996 paper by Bengu and Swart conducted a study on the development of undergraduate engineering education, claiming that pedagogical approaches should be updated and that students should be provided with new tools that promote efficient learning [28]. Manufacturing education is difficult to teach effectively because of the wide variety of possible manufacturing processes and the rapid development of technologies. Chryssolouris et al. state that "collaboration between academia and industry will be of strategic importance" and argue that industry and academia should work closely together to improve manufacturing education [29]. Recent papers support this view, as Rentzos et al. explain the creation of a two-way communication of knowledge between academia and industry, detailing a "teaching factory" with numerous benefits [30]. This work highlights a need for students to engage in hands-on experiences, be exposed to a wider variety of manufacturing methods, and have more opportunities to engage with engineering professionals.

### 2.3 Choosing CAD Tools for the Study

As part of a two-semester design sequence, participants in the second course are expected to already have CAD experience in SolidWorks and have attempted the Certified SolidWorks Associate (CSWA) exam. However, SolidWorks may not be best suited for an experimental study because it does not natively record a user's actions within the software. Capturing data from SolidWorks would require additional resources such as video recording, screen recording, custom software, etc. to fully characterize a user's actions within the software. For these reasons, alternative CAD solutions were explored.

A viable CAD package appropriate for this study required it to be similar in structure to SolidWorks without a significant departure in workflow to ensure educational consistency. In addition, an ideal CAD package needs to offer a simplified process for data collection. A variety of modern software packages were considered against these criteria such as Fusion 360, Onshape, AutoCAD, Inventor, and Mastercam. Of the options explored, Onshape best fulfilled the criteria. Onshape is a Multi-User Computer-Aided Design platform, or MUCAD, that has recently entered the market by comparison to its competitors. The platform is entirely web-based and allows easy collaboration on design projects by multiple users. A 2018 thesis by Ngoc Le, compares Onshape and SolidWorks, claiming that Onshape has a similar interface to SolidWorks, while providing more flexible data structures [31]. Due to the cloud-based nature of the online platform, data can be accessed anywhere through a Representational State Transfer Application Programming Interface (REST API), which eliminates complications associated with data collection.

A variety of studies have already leveraged and demonstrated the advantages of Onshape for experimental research. For example, Phadnis et al. used the MUCAD features of Onshape to investigate how engineers perform while working in pairs and suggested that “pairs were less efficient than individual designers due to overhead like communication” [32]. However, in a following study by Phadnis et al. it was observed that “parallel works in CAD produced the worst quality outcome.” [33]. Novel research by Zhou et al. linked designer emotions with their CAD behavior in a synchronous CAD environment, finding that pairs of designers showed more emotion compared to solitary designers [34]. The novel usage of cloud-based software like Onshape in recent work exemplifies its strengths and features, while its similarity to the framework of SolidWorks doesn’t pose learning curve issues for participants making it a confident choice for the study.

## 3. METHODS

The following section describes the study context, experimental conditions, participants, and overall design of the study. Commonly used terminologies through the paper are defined.

### 3.1 Study Context

Considering that this research focuses on the abilities and behaviors of undergraduate STEM students, the study took place during the second course of a two-semester, second-year undergraduate engineering design sequence. The first course introduces students to the basics of CAD and Geometric Dimensioning and Tolerancing (GD&T) using SolidWorks. The second course focuses on engineering, design, and manufacturing principles while building on their CAD experience from the previous semester. The study took place over two class periods during the second course in the sequence, with each session lasting 75 minutes for a total of 150 minutes. Data was collected at a STEM-focused public university in the southeastern United States. The study received approval from the university’s institutional review board.

### 3.2 Study Design

The first-class period was used to obtain participant consent and familiarize participants with the Onshape platform. In the first 15 minutes of the lecture, participants received a consent form. The consent form requested that potential participants allow their coursework to be used for this research study since the lectures, assignments, and manufacturing demonstrations already existed in the course curriculum. Students who did not provide informed consent still participated in the activities, but data was not collected and is not reported on in this paper. Students were taught how to navigate the menus, environments, and tools in Onshape in a brief demonstration. Spending time orienting students with the Onshape platform was critical for the study to ensure that any observed experimental effects could be attributed to the interventions themselves and not to a lack of proficiency with Onshape. Some participants may have had prior experience using Onshape in high school, university clubs, or for personal projects. As part of the study, students' prior experience with the platform was collected through a survey to verify a baseline and to identify any potential outliers. The training included two engineering drawings, which the students were tasked with modeling in Onshape. During their in-class work, a faculty member and undergraduate research assistant provided individual feedback to students as they progressed through these examples. The chosen training models were carefully selected to require any features that might be necessary for the creation of the model used in the study.

The second day of lecture occurred after students had familiarized themselves with the Onshape platform. The study was spread across four separate sections of the same course, yielding a total of 106 participants that voluntarily consented to participate in this study. Accordingly, the study was split into four separate conditions. The four conditions were the Control, FDM, CNC, and Lathe Conditions. Apart from the Control Condition, each condition observed a different manufacturing process that is commonly used for production. Each condition is explained in the following sections.

### 3.2.1 Control Condition

Participants in the Control Condition did not view a manufacturing demonstration before completing their modeling task in Onshape. At the beginning of the class period students were provided with an engineering drawing of a part that they needed to model and were allotted 45 minutes to complete the assignment. After this 45 minutes, these students were taken to a demonstration of an FDM manufacturing process. Students in the control condition still had an opportunity to observe a manufacturing demonstration as it was part of the course content but was adjusted to occur after the modeling activity to ensure educational equivalence. In the last 15 minutes of the lecture period, students were brought back to their classroom and asked to fill out a survey on their prior manufacturing experience as well as a short reflection assignment on the manufacturing demonstration and CAD process. Those who did not consent to the study did not have to complete the survey, but did complete the reflection assignment as a course assignment.

### 3.2.2 FDM Condition

In the FDM Condition, students were shown a demonstration of an FDM manufacturing process at the beginning of the second day. After a 15-minute demonstration, students were brought back to their lecture room. Upon returning, students were provided with an engineering drawing of the exact same part that was used as a manufacturing demonstration and asked to model it. In the last 15 minutes, participating students were asked to fill out a survey form that asked them questions about prior manufacturing experience and all students completed the short reflection on the manufacturing demonstration.

### 3.2.3 CNC Condition

Participants in the CNC Condition were shown a demonstration of a CNC milling process. At the start of the lecture period students were brought to the on-campus machine shop and given an operational presentation of a CNC mill in action. Following the 15-minute presentation, students were brought back to their classroom and were provided with an engineering drawing of the same part they observed being milled and tasked with modeling it. The last 15 minutes of the class period were used by the participating students to fill out a survey form on their prior manufacturing experience followed by a short reflection on the demonstration and how it relates to their model, which was completed by all students.

### 3.2.4 Lathe Condition

In the Lathe Condition, students took the first 15 minutes of the lecture to watch a demonstration of a lathe manufacturing process in operation in the on-campus machine shop. Following the demonstration, students returned to their classroom and were provided an engineering drawing detailing the exact same part in the demonstration. Students were asked to model this part. In the last 15 minutes of the lecture period, participating students were provided with the same survey as the other conditions. All students completed the same short reflection assignment on the manufacturing demonstration and their CAD model.

## 3.3 Model Design

To examine how manufacturing demonstrations affect modeling approaches, an iterative process was employed to design a model that would capture differences in modeling approach. For consistency and educational relevance, the part being manufactured in the demonstrations and the part students were tasked with modeling needed to be the same. The model was designed so a variety of basic CAD features could be leveraged to produce it. It was also critical that this part could be manufactured by any of the machines being shown in the manufacturing demonstrations. This process resulted in the part shown in the bottom right of Figure 1.

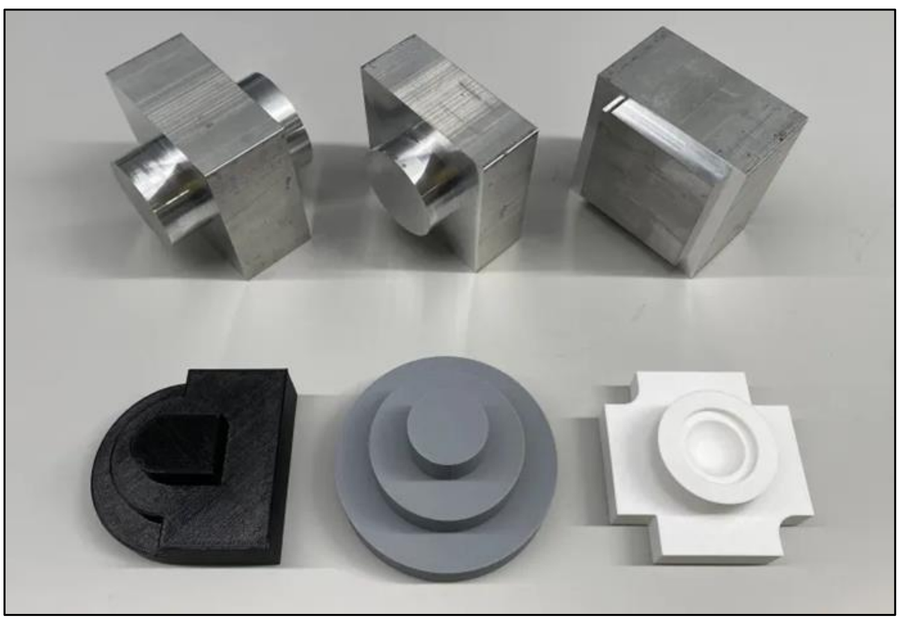

***Figure 1:*** *The machined aluminum blocks used in the manufacturing demonstrations (row above) and iterations of the 3D printed model used for the modeling task (row below).*

The part requires a minimum of four different features to model it with the possibility for more features to be used depending on approach. This design attempts to avoid “layer-caking” the model, which is a common practice amongst novice CAD students. In other words, certain aspects of the part could not be modeled with layer-by-layer bottom to top approach, primarily using extrude features. The divot in the center of the model served as a primary aspect of the part that could not be modeled with this “layer cake” approach. Overall, the design choices of the model are intended to deter prior design bias and determine whether unconscious bias was introduced following the manufacturing demonstrations.

A selection of iterated 3D models is shown in the bottom half of Figure 1, depicting the evolution of the model. In total there were 9 different iterations (not all shown) with the final iteration being the rightmost 3D-printed component. For the CNC and Lathe condition demonstrations, aluminum blocks were machined at the on-campus machine shop, with the post-demonstration resulting parts shown in the upper half of Figure 1. The leftmost component was used in the Lathe demonstration, which needed an additional rounded end so it could be secured to a chuck in the Lathe. The middle component was part of the CNC demonstration, requiring a flat base. Finally, the rightmost component was the result of a test-run of the CNC mill before the study.

## 4. RESULTS

All presented results are a combination of gathered data from both the surveys and the CAD work of participants. The collected results explored the relationship between a participants’ performance within the CAD software, with reference to their condition and manufacturing experience. Using Onshape allowed for an investigation into participant behavior and their models through their sketches, time of completion, and feature usage within their models.

### 4.1 Average Time Spent

Modeling time was averaged for each of the four conditions. Figure 2 below presents these averages with ± 1 standard error.

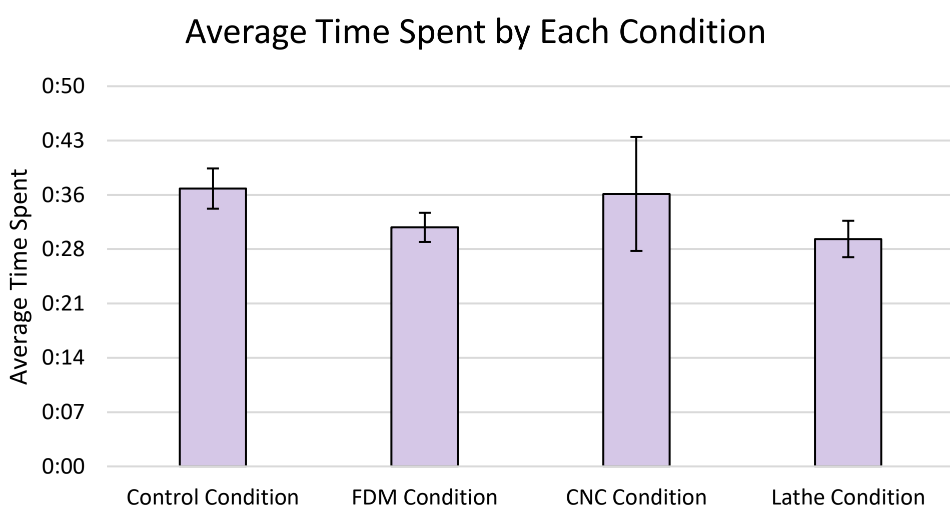


***Figure 2:*** *A comparison of average time spent per condition across all conditions, with ± one standard error.*

In Figure 2, the Control Condition had an average time of 36:50, the FDM Condition an average time of 31:41, the CNC Condition had an average time of 36:07, and the Lathe Condition had an average time of 30:09. The average time spent between all participants and conditions is 33:42. The data sets did not pass Shapiro-Wilk tests for normality, prompting the use of Kruskal-Wallis tests to assess whether differences in time of completion were statistically significant. Differences in average time spent considering all conditions simultaneously and across all possible pairs of conditions were calculated as shown in Table 1.

***Table 1:*** *Kruskal Wallis Evaluation of Average Time Spent Per Condition*

**Kruskal- Wallis Time Spent Evaluation**

| **Comparison** | | **H(3)** | **p-value** |
|---|---|---|---|
| All Conditions | | 0.323 | .956 |
| **Condition 1** | **Condition 2** | **H(1)** | **p-value** |
| Control | FDM | 0.034 | .853 |
| Control | CNC | 0.038 | .847 |
| Control | Lathe | 0.111 | .735 |
| FDM | CNC | 0.002 | .967 |
| FDM | Lathe | 0.276 | .599 |
| CNC | Lathe | 0.216 | .642 |

Table 1 shows no significant differences in completion time across all conditions or between any individual pair of conditions in the study ($\alpha = 0.05$). The results indicate that participants assigned to the different conditions modeled similarly at a surface level as none of the conditions spent a significantly different amount of time designing their part. This gave confidence moving forward that any observed effects could be attributed to the differing manufacturing demonstrations when comparing different feature usage rates by each condition. This also helped ensure that the participants in each condition were roughly at similar levels of CAD modeling proficiency.

### 4.2 Manufacturing Experience Across Conditions

In the surveys, participants had to evaluate their manufacturing experience on a 1-5 scale. The survey asked about 18 different manufacturing processes, with an even split of 9 additive processes and 9 subtractive processes. These processes capture a wide variety of possible manufacturing experiences. The split between additive and subtractive processes was chosen to fully capture any relationships between participants' prior experience and the demonstrations (either additive or subtractive) that they would observe depending on their condition assignment. These processes can be seen in Figure 3. All conditions received the same survey, and the average score was compared across conditions. This data also served as a measure of consistency between the conditions since students were assigned to conditions based on the course section they enrolled in for the semester, which could have introduced unknown variables into the data (e.g., time of day, preferred instructor, etc.).

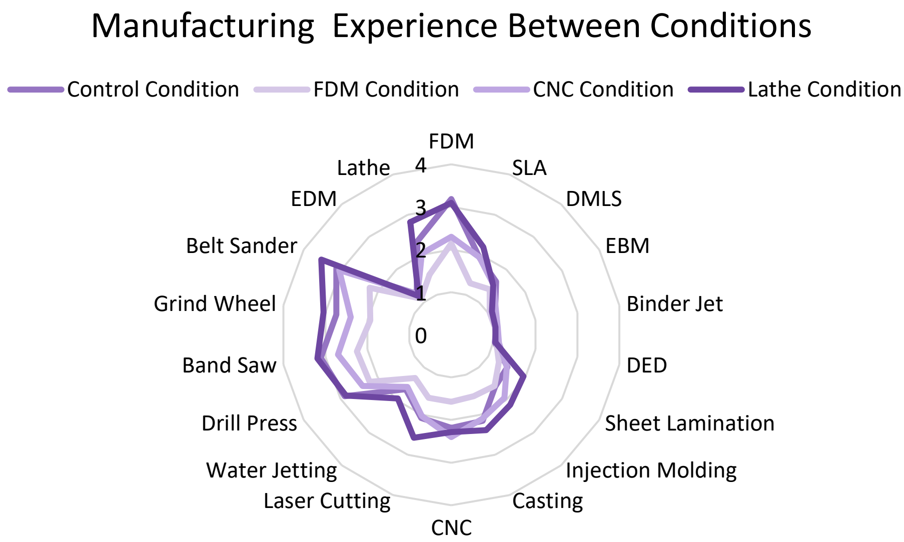


***Figure 3:*** *Averaged self-reported manufacturing experience by each condition and compared.*

As shown in Figure 3, while generally following similar patterns, the FDM Condition and the Lathe Condition had the largest difference in prior manufacturing experience, averaging a one-point difference in their prior knowledge of the respective manufacturing processes. A Spearman's correlation test gave a correlation coefficient of $r(16) = .916$, $p < .001$ when comparing all 18 different manufacturing processes. The Spearman correlation value increases in magnitude as X and Y become closer to being perfectly unchanging functions of each other. When X and Y are perfectly related, the Spearman correlation coefficient becomes 1. While it visually appears that there may be a difference in prior manufacturing experience between the conditions, these differences are relatively small and were shown to be insignificant. Coupled with results from the analysis for time of completion, there are no appreciable differences between any of the conditions.

### 4.3 Comparison of Participant Feature Usage

Using Onshape, the chronological feature usage (or "feature tree") from each participant's CAD model was extracted. This data was extracted by leveraging Onshape's Representational State Transfer Application Programming Interface (REST API). A script was written to extract specific attributes from the final state of the model submitted by the student participants. This analysis focuses primarily on four of Onshape's modeling features: sketch, extrude, revolve, and fillet. Feature usage was averaged and compared between the four conditions.

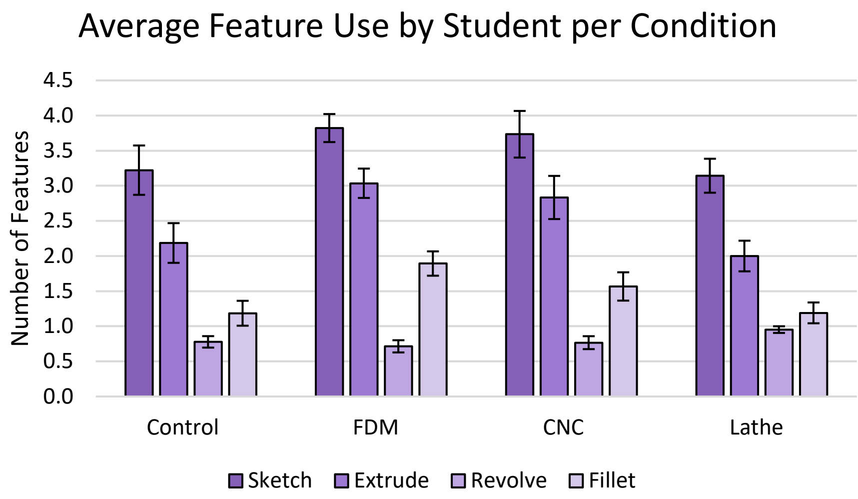


***Figure 4:*** *A comparison between all conditions of the average feature usage with +/- one standard error.*

All subsets of data did not pass a Shapiro-Wilk normality test; therefore, Kruskal-Wallis was used to search for significant differences across all four conditions. Furthermore, all possible pairs of conditions were compared, labeled as Condition 1 and Condition 2 in the table below.

***Table 2:*** *Kruskal-Wallis average feature use evaluation across conditions*

**Kruskal-Wallis Average Feature Use per Condition Evaluation**

| | | Sketch | | Extrude | |
|---|---|---|---|---|---|
| Comparison | | H(3) | p-value | H(3) | p-value |
| All Conditions | | 8.284 | .041 | 11.453 | .010 |
| Condition 1 | Condition 2 | H(1) | p-value | H(1) | p-value |
| Control | FDM | 6.209 | .013 | 6.942 | .008 |
| Control | CNC | 2.763 | .097 | 2.684 | .101 |
| Control | Lathe | 0.470 | .493 | 0.021 | .884 |
| FDM | CNC | 0.801 | .371 | 0.706 | .401 |
| FDM | Lathe | 4.849 | .028 | 9.430 | .002 |
| CNC | Lathe | 1.385 | .239 | 3.482 | .062 |
| | | Revolve | | Fillet | |
| Comparison | | H(3) | p-value | H(3) | p-value |
| All Conditions | | 2.175 | .537 | 9.235 | .026 |
| Condition 1 | Condition 2 | H(1) | p-value | H(1) | p-value |
| Control | FDM | 0.163 | .686 | 6.549 | .011 |
| Control | CNC | 0.014 | .905 | 1.096 | .295 |
| Control | Lathe | 1.058 | .304 | 0.001 | .975 |
| FDM | CNC | 0.079 | .779 | 2.470 | .116 |
| FDM | Lathe | 2.000 | .157 | 7.220 | .007 |
| CNC | Lathe | 1.275 | .259 | 1.029 | .310 |

All significantly different comparisons are highlighted in Table 2. Notably, the Control and FDM Conditions showed significant differences when comparing the usage of sketch, extrude, and fillet features. This is most likely because the FDM manufacturing process is the fastest process of all demonstrated manufacturing processes, allowing participants to observe a larger portion of the procedure as opposed to other conditions. Furthermore, differences between the FDM and Lathe Conditions in their use of sketch, extrude, and fillet features were also observed to be significant. One possible explanation for this finding is that the FDM and Lathe are the most distinct processes, as FDM is an additive and planar process, while Lathing is a subtractive rotary process. In Figure 4, the FDM and CNC conditions on average used more features than the Lathe and Control Conditions. From this analysis, it is shown that exposure to different manufacturing processes, even for a 15-minute demonstration, has a measurable effect on how participants approach the modeling process during computer-aided design.

### 4.4 Additive & Subtractive Revolves:

In a comparison of all feature types analyzed, the revolve feature demonstrated the biggest change between the four conditions. In Figure 5, revolve features were broken down further into additive and subtractive actions, which aligns with how the Onshape user-interface handles the revolve feature (note that this is a departure from how SolidWorks handles revolve functions). The number of additive and subtractive actions were averaged and compared between groups.

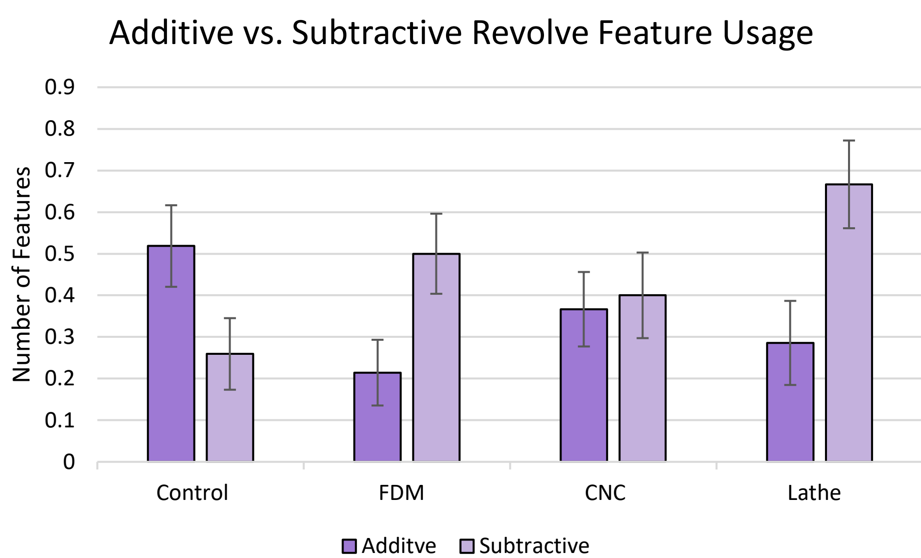


***Figure 5****: Comparison of additive vs. subtractive revolve features across all conditions with +/- one standard error.*

Testing for normality, the entire data set did not pass the Shapiro-Wilk test. To test for significance, Kruskal-Wallis tests were used to search for any significant differences between conditions. Condition 1 and Condition 2 refer to the different comparisons possible between pairs of experimental conditions for evaluation.

***Table 3:*** *Individual Kruskal-Wallis evaluations of additive and subtractive revolve features*

| **Kruskal- Wallis Additive and Subtractive Revolve Feature Evaluation** | | | | | |
|---|---|---|---|---|---|
| | | **Additive** | | **Subtractive** | |
| **Comparison** | | **H(3)** | **p-value** | **H(3)** | **p-value** |
| All Conditions | | 4.094 | .252 | 6.313 | .097 |
| **Condition 1** | **Condition 2** | **H(1)** | **p-value** | **H(1)** | **p-value** |
| Control | FDM | 3.747 | .053 | 2.347 | .126 |
| Control | CNC | 0.966 | .326 | 0.564 | .453 |
| Control | Lathe | 1.881 | .170 | 5.762 | .016 |
| FDM | CNC | 0.992 | .319 | 0.581 | .446 |
| FDM | Lathe | 0.180 | .671 | 0.980 | .322 |
| CNC | Lathe | 0.238 | .626 | 2.805 | .094 |

As shown in Table 3, the only significant difference observed was between the Control Condition and Lathe Condition for subtractive revolve features. This result aligns with the stark difference between these two manufacturing processes, though both are subtractive in nature. Table 4 below compares the differences of additive revolve features vs. subtractive revolve features across all possible pairs of conditions.

***Table 4:*** *Kruskal-Wallis comparison of additive and subtractive revolve features*

| **Kruskal- Wallis Additive vs Subtractive Revolve Features Evaluation** | | | |
|---|---|---|---|
| **Additive Feature** | **Subtractive Feature** | **H(1)** | **p-value** |
| Control | Control | 2.673 | .102 |
| Control | FDM | 0.014 | .906 |
| Control | CNC | 0.759 | .384 |
| Control | Lathe | 0.762 | .383 |
| FDM | Control | 0.082 | .775 |
| FDM | FDM | 3.368 | .067 |
| FDM | CNC | 1.087 | .297 |
| FDM | Lathe | 7.220 | .007 |
| CNC | Control | 0.483 | .487 |
| CNC | FDM | 0.759 | .384 |
| CNC | CNC | 0.007 | .935 |
| CNC | Lathe | 3.271 | .071 |
| Lathe | Control | 0.024 | .876 |
| Lathe | FDM | 1.620 | .203 |
| Lathe | CNC | 0.298 | .585 |
| Lathe | Lathe | 4.465 | .035 |

Based on the comparative analysis shown in Table 4, interesting participant behaviors emerge. First, an increase in subtractive actions in all of the non-control conditions is observed, though only the Lathe Condition shows a significant difference. Further testing through Kruskal-Wallis tests show that while the dataset itself is not significantly different when comparing all actions, there is a significant difference in value in a few conditions. For example, the Lathe Condition had an average of 0.667 subtractive revolve features, while the Control Condition showed a significantly smaller average of 0.259 subtractive revolve features. Further, the Lathe Condition demonstrated a significant increase of subtractive revolve features over additive revolve features, with an average difference of 0.381 features.

## 5. DISCUSSION

The results demonstrate that even a brief exposure to a manufacturing process has an observable effect on the approach used for CAD. Analysis showed that all conditions varied in average feature usage, but the FDM and Lathe Conditions showed significant differences. The FDM Condition used significantly more features than the Lathe Condition and the Control Condition. This difference in feature usage is attributed to the various manufacturing demonstrations observed. One possible explanation for this result stems from the opposing nature of the two manufacturing processes; FDM is an additive planar process, and Lathing is a subtractive rotary process. In other words, those who observed the lathe demonstration may have been more likely to use revolve features in their CAD model. These results do not fully support the first hypothesis, which states “Participants exposed to a manufacturing demonstration will use fewer features when modeling their part than those not exposed to a manufacturing demonstration (H1)”. Interestingly, the FDM and CNC Conditions had the highest average feature usage, despite representing additive and subtractive processes, respectively. In practice, the results demonstrate that the introduction of a manufacturing process, even briefly, can affect CAD behavior.

As stated, the results show that the FDM and CNC Conditions had the greatest number of average features used. This is surprising as the two conditions represent opposite manufacturing processes; FDM is additive while CNC is subtractive. This suggests that observed differences in modeling behavior cannot be directly attributed to the specific manufacturing process demonstrated. Participants in the Lathe Condition may have used fewer features on average after the in-person demonstration because lathing is comparatively a more restrictive manufacturing process than FDM or CNC methods. The inherent constraints of a manufacturing process may influence modeling strategy. This is supported by Robertson and Radcliffe, who describe four phenomena that impact engineering design: 1. enhanced visualization and communication, 2. premature fixation, 3. circumscribed thinking and 4. bounded ideation [26]. A more restrictive manufacturing process may constrain creative thinking during CAD. It is also worth mentioning that CNC and FDM methods are the most common manufacturing processes undergraduate engineering students are exposed to. Their familiarity with these processes, and the relative flexibility of these processes compared to lathe processes may have contributed to increased feature usage.

At first glance, the Lathe Condition shows no difference from the Control Condition. However, further analysis showed that the Control Condition used significantly less subtractive revolve features than the Lathe Condition. This difference likely stems from the subtractive nature of the lathing process, leading to more subtractive revolve features than the Control Condition. Furthermore, when comparing additive and subtractive actions within the Lathe condition, there are significantly fewer additive actions than subtractive actions. This supports the second hypothesis which states that "Participants will use more additive features to a model when exposed to additive manufacturing processes, such as FDM, and will use more subtractive features when exposed to subtractive manufacturing methods such as CNC (H2)". That said, comparing the Control Condition to the FDM Condition, the opposite trend is observed. Notably, this trend was not statistically significant.

Interestingly, the CNC Condition showed no significant differences compared to the other conditions. This might be because CNC, like the lathe, is subtractive, but also shares planar characteristics with FDM. The demonstration of the CNC manufacturing process may have encouraged students to apply methodologies that they could have gained from either the FDM or Lathe Conditions simultaneously when modeling their part. For example, a planar process might encourage modeling from the base upwards, while a subtractive process might encourage removing material from a larger primitive body.

While the study demonstrated interesting findings, it was not without limitations. The participants in this study overall had entry-level CAD skills. This might suggest that the observed effects attributed to the manufacturing demonstrations were exaggerated by a general lack of CAD experience. The findings may change if the participants were from an upper-level engineering course or were industry professionals. More experience may result in more efficient modeling, using fewer features in less time. It may also be that professional engineers settle into a workflow that does not necessarily align with the definition of "efficient" used in this paper, but rather an efficiency that is context- or domain-specific. Secondly, the implementation of a greater variety of manufacturing methods could better demonstrate the effects on CAD and design intent. As a third limitation, there are many other modeling features within the Onshape platform beyond those described in this paper that need to be explored. These additional features may have interactions with each other that this work did not capture. Of note, the participants did not actually participate in physical manufacturing and fabrication. Hands-on experience may influence the results of this study, which is left to future work.

## 6. CONCLUSION

This study demonstrates that students' CAD approaches can be influenced by exposure to different manufacturing methods. For example, participants in the FDM Condition and the CNC Condition used the greatest number of features when compared to the other two conditions. In addition, these effects may be correlated with what kind of manufacturing process is being observed (whether additive or subtractive). Participants in the Lathe Condition used significantly more subtractive revolve features than those in the Control Condition, which is attributed to their observation of the lathe demonstration. Interestingly, the CNC Condition was found to not show any significant differences when compared to any other condition, which could be attributed to its overlapping similarities with all the other manufacturing methods.

The results from this study lay the groundwork for future research on the interactions between exposure to manufacturing methods and students' approach to CAD. For example, a subsequent study is planned to replicate the procedure in its entirety except for using an alternative model for the manufacturing demonstrations and the modeling activity. Using an alternative model may provide clarity about whether the observed effects are model-specific or represent a broader interaction between manufacturing and modeling behavior in CAD. There may also be opportunities for expanding the palette of manufacturing demonstrations that the student participants have an opportunity to observe. In kind, future work could explore how the impact of these different processes on CAD behavior changes if participants are given the opportunity to interact with the manufacturing equipment directly through a more hands-on experience. As a final future direction, it is worth exploring how a creation/revision metric may reveal more insights into CAD behavior, where this metric measures how many steps are taken backwards during the modeling process.

This study has shown that exposure to different manufacturing processes impacts students' CAD behavior. With the rise in popularity of additive manufacturing techniques and the nearly universal access students have to FDM 3D printing, it is critical that we continue to explore how other manufacturing processes impact engineering design skills. It is important to remind students that a diverse range of manufacturing processes exists. The results of this study may motivate educators to explore novel ways to introduce their students to traditional manufacturing methods and how these methods influence the way engineers approach computer-aided modeling and manufacturing. This study provides an example of how exposure to different manufacturing approaches can be built into an engineering curriculum and provides a starting point for discussion about how manufacturing education impacts engineering design.

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