# Exploring the Presence and Cause of Manufacturing Fixation Design in Novice Mechanical Engineers

by

V. Velikonja

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Applied Science in Mechanical Engineering Department of Mechanical and Industrial Engineering University of Toronto

Supervisor: Professor Alison Olechowski

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V. Velikonja

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Department of Mechanical and Industrial Engineering

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**Abstract**

Design fixation is present in all types of engineering. Specifically, for mechanical engineering design problems manufacturing fixation in design (MFD) has been shown to be present. Typically, this has been studied in professional engineers where the bias comes from years of experience in traditional manufacturing processes, like machining and casting. However, in the current generation of young engineers and engineering students, due to the advancements in additive manufacturing like 3D printing, is manufacturing fixation present and does it present differently from current professional engineers? This study focuses on novice engineers and specifically on how previous manufacturing processes can influence their modeling process with computer-aided design (CAD) software.

In this two-part study 10 participants, two professional engineers and eight engineering students, first independently modelled a part in Onshape from 2D drawings and then were interviewed about their CAD style, background in manufacturing, and how their manufacturing experience might influence their CAD style. Overall, three of the 10 participants were found to have a subtractive style of CAD while the remaining had an additive style. Of the eight student participants, six were found to have an additive style with the majority of students stating a preference specifically for 3D printing. This led to the majority of student participants having a

bottom-to-top approach to CAD modeling. Furthermore, a stark difference in how experienced versus novice engineers was apparent in how they believed manufacturing processes affected their CAD style. Experienced engineers stated that they constantly thought about how the part will be manufactured while modeling in CAD while all novice student engineers stated that this is not typically a prevalent thought. Overall novice student engineers' CAD process mirrored the manufacturing process with which they were most familiar. Going forward, future research should focus on how designers with different styles can collaborate, how the difference in popular manufacturing styles of the time can influence MFD and how engineers from multiple generations with similar styles will collaborate due to these advancements in manufacturing.

## Acknowledgements

I would like to take a moment to acknowledge everyone who has supported me and made this thesis possible.

Firstly, Professor Alison Olechowski for taking me on as an undergraduate thesis student and giving me the opportunity to gain experience in engineering research. You have supported and encouraged me this entire year and without you I would not have the skills, experience, or desire to continue with academic research in the Fall.

Next, I would like to thank Kathy Cheng for being the most amazing graduate student. You have helped me in so many ways this year and without you this thesis never would have gotten done. Thank you for answering all my questions, sitting in on my experiments, and just being a massive support to me this entire year.

I would also like to thank J. Chen and their MASc research for being the inspiration for my work this year. Although we have never met, I owe you so much for including three paragraphs in your MASc thesis that inspired this topic and for providing an amazing blueprint on how to conduct CAD experiments. This research has truly been a continuation of all your hard work.

To everyone who participated in my study, thank you. Without you none of this would have been possible

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## 1.0 Introduction

Design fixation is not a novel concept, especially in engineering. Every engineer has previous experiences that can lead to biases in the design process. Design fixation can be defined as adhering to self-imposed constraints based on an overreliance on pre-existing knowledge relevant to the design problem [1], [2]. In engineering it can present in different ways depending on the field of engineering, knowledge, and information given to the designers and the presence of a pre-existing design. Specifically, for mechanical engineering design problems, manufacturing fixation in design (MFD) has been shown to be present [3]. While the presence of MFD in engineering professionals can be linked to their familiarity and bias towards traditional manufacturing processes, such as machining and casting processes, there is a gap in research on novice designers and engineers [4]. Furthermore, it is a possibility that the advancement and accessibility of newer manufacturing processes such as 3D printing, leads to a preference in younger engineers for this type of manufacturing. This would possibly lead to a presence of MFD in novice engineers that would present in a different way to current working professionals. This thesis will explore the presence and cause of MFD in novice engineers by running an experiment to analyze participants' computer-aided design (CAD) modeling style. It seeks to answer the following questions:

1. In novice engineers is manufacturing fixation in design present, and if so to what extent?
2. In the current generation of novice engineering students is there a preference for newer manufacturing processes, such as 3D printing that affects their CAD style?

## 2.0 Background

2.1 Manufacturing Fixating in Design

Manufacturing fixation in design (MFD) is defined as an "*unconscious and often unintentional adherence to a limited set of manufacturing processes and/or constraints and capabilities during the design ideation process*" [3]. Brennan et al. focused on proving the presence and effect of MFD on professional engineers with the majority of their participants having twelve plus years of industry experience. This was done by analyzing their approach to redesigning given parts. After participants completed the first design task, they participated in an educational workshop on additive manufacturing and then completed the second design task. The results showed that for the first design task machining processes were the most popular, while for the second design task additive manufacturing processes became the most popular. Thus, proving that a single workshop could sway a designer's focus from one type of manufacturing to another, it was noted that it was unlikely to cause a long-term effect as design assumptions and decisions are made based on deeply ingrained or subconscious reasoning. In a following study, Brennan et al. interviewed engineering professionals on their perceptions of how MFD has affected their design choices. The result was that, in engineering professionals, MFD presents as a tendency to design for the manufacturing process with which the engineer is most familiar [4]. While this is an understandable bias, to stick with what one knows, it also restricts the engineer's ability to take advantage of newer more advanced technology.

While Brennan et al. studied professional engineers, Abdelall et al. focused on the negative effects of additive manufacturing design fixation in engineering students (ages ranging from 18 to 35), proving that designs heavily influenced by additive manufacturing were more complex and innovative, yet harder to modify than designs influenced by conventional manufacturing techniques [6]. In this study, conventional manufacturing was defined as casting or machining processes. It is important to note that while Abdelall et al.'s experiment was conducted on students, 23 of the 26 participants had extensive previous knowledge of either conventional or additive manufacturing, and the additive manufacturing group was further educated in additive manufacturing before design ideation began through a workshop. This is relevant because while this experiment involved student participants, most had a great amount of experience in manufacturing processes that could affect their performance and it further proves Brennan et al.'s conclusion that manufacturing design fixations can be swayed, even temporarily, through education on the topic right before design ideation [3].

## 2.2 Manufacturing Fixation in CAD Modeling

The previous studies referenced focused on MFD in the overall design process. This study will focus specifically on MFD in the CAD portion of the design process. This interest in MFD in CAD stems from an observation made in Chen's MASc Thesis, Development of a Novel Computer-Aided Design Experiment Protocol for Studying Designer Behaviours. In their thesis, an interesting distinction in participants' CAD modeling was noted. Designers could be described as either having a subtractive or additive modeling style. Additive modeling is characterized by constantly building up or building on a base shape and including details of the design in base sketches. In comparison, subtractive modeling is characterized as building the general shape of the design and then removing material afterwards to add in the details of the design. In Chen's thesis these styles appeared to mirror manufacturing processes with one participant stating that their background and knowledge of machining made subtractive modeling the most intuitive approach for them. Furthermore, it was hypothesized that the younger generation of engineers would not be as constrained by traditional manufacturing processes like current engineering professionals, due to their earlier exposure to the advancements in additive manufacturing [5]. This could mean that

MFD would not present the same as Brennan et al. found in their follow-up study as this younger generation would not have a bias towards traditional engineering processes [4]. This is not to say that the younger generation cannot be influenced by MFD, but rather it could present in a different way.

This study builds upon the work of Brennan et al. and Abdellal et al. in that it investigates the presence of MFD in engineers, but we focus specifically on novice engineers in the current generation of undergraduate engineering students. Following the observation that Chen made in their thesis, this study will focus on whether new additive manufacturing processes have affected the current generation of engineering students and how this may differ their style of CAD from current working professionals.

## 3.0 Methodology

### 3.1 Experiment Overview

The aim of this study is to investigate the presence of manufacturing fixation in an individual's CAD process. As previously mentioned, while this was not the focus of Chen's MASc Thesis, it was apparent that a participant's modeling could be classified as either additive or subtractive and might reflect their preferred manufacturing process. Due to this, Chen's experiment was replicated with slight alterations based on their recommendations and to match the experiment's aim. The ideal participants were novice engineers who had a solid foundation of 3D CAD modeling (either through personal or professional projects), a basic understanding of manufacturing processes, and familiarity and experience with Onshape (a cloud-based synchronous CAD and data management platform). However, two experienced engineers were asked to participate in order to provide a comparison to the novice engineers. For this experiment, novice will be defined the same as in Chen's thesis, as someone who understands the basics of CAD, has made simple parts, and uses CAD for personal and course-related tasks.

The main modifications are:

1. Based on participant preference, the experiment was run either online or in person instead of entirely online.
    - Justification: Allows for participants from outside Toronto to partake and it will allow participants to choose the option they feel most comfortable with thereby not increasing the pressure of the situation.
2. The pre-study interview questions have been modified to include questions on the participant's manufacturing background.

- Justification: Chen's pre-experiment survey did not include any questions specifically about the participant's background experience in manufacturing.

3. Instead of two CAD tasks, where participants were asked to create and then modify their part only one CAD task will be given. The participants were only asked to create the part.
    - Justification: This is due to Chen's recommendation that the modification task did not yield any interesting or important information so future studies should omit this task.
4. A longer post-study interview session was held with participants. During this post-study interview, participants will be shown their modeling and asked to provide clarification to their modeling choices.
    - Justification: In order to gain a better understanding of the participant's thought process while modeling in CAD, they will be shown their process. Afterwards they will be asked questions about their manufacturing experience.

The final experiment outline had three distinctive parts:

- Pre-experiment survey
- CAD Task
- Post-experiment interview

The pre-experiment survey collected information on the participant's background in CAD and manufacturing. It allowed for investigators to get a complete picture of their background. The CAD task was 35 minutes long for each participant and saw them create a part from 2D drawings. Finally, during the interview portion, the participants watched back their CAD task and then answered questions about their manufacturing background and how it might have influenced their CAD style.

### 3.1.1 Experiment Logistics

The experiment was approved by the University of Toronto's Research Ethics Board. All participants filled out a consent form for this study. Participants had the option to partake in the study online through Zoom or in person at the University of Toronto's St. George Campus.

If the study was conducted in person, during the CAD task the participant's screen was recorded onto a Ready Lab desktop computer, then uploaded to a secure OneDrive folder. No audio was recorded for this portion of the study. During the post-experiment interview, only audio was recorded using the investigator's personal phone. After the session, the recording was uploaded to the same OneDrive folder and deleted from the investigator's phone. Then the transcript of the interview was generated through Sembly AI.

If the study was conducted through Zoom, during the CAD task the participant's screen was recorded via Zoom's cloud service. During the interview portion, the investigator shared their screen playing back the participant's CAD task and leading the interview. Using Zoom's cloud services, audio was recorded and if the participant's camera was on their video was recorded as well. Interview transcripts were generated using Otter.ai's automatic transcript integration with Zoom.

All personal information was anonymized, and participants were numbered for analysis. All participants were compensated as a token of appreciation at a rate of $7.50 CAD per every half hour through Amazon gift cards.

### 3.2 Participants

Official recruitment began in the University of Toronto's Winter 2023 term. Potential novice participants were contacted through two channels. Novice participants were targeted through 3rd year and 4th year University of Toronto online group messaging systems (i.e., student run Facebook and Discord groups) with a message outlining the experiment, potential participant eligibility and a link to the online Qualtrics interest form. Experienced participants were directly messaged via the Investigator's LinkedIn contacts with the same message and details as the novices. The message and interest form can be found in Appendix A1 and A2. As seen in Appendix A, care was taken not to explicitly state that the interest in the study was in potential manufacturing biases as not to potentially sway any participant's minds to intentionally think about their own biases before or during the study.

#### 3.2.1 Demographics

Overall, 10 participants agreed to participate in the study. Eight can be grouped as novice or intermediate CAD modelers while two can be grouped as experienced. The eight novice or intermediate CAD modelers were all engineering university students either on Co-op or in their 4th and final year of study with no more than four and a half years of CAD experience. The two experienced engineers were working professional engineers with nine and 25+ years of CAD experience respectively. All participants had some level of experience and familiarity with manufacturing, and all had experience in designing and then manufacturing a part either through personal or professional projects. Demographic information related to employment status and CAD experience is summarized below in Figure 3.1.

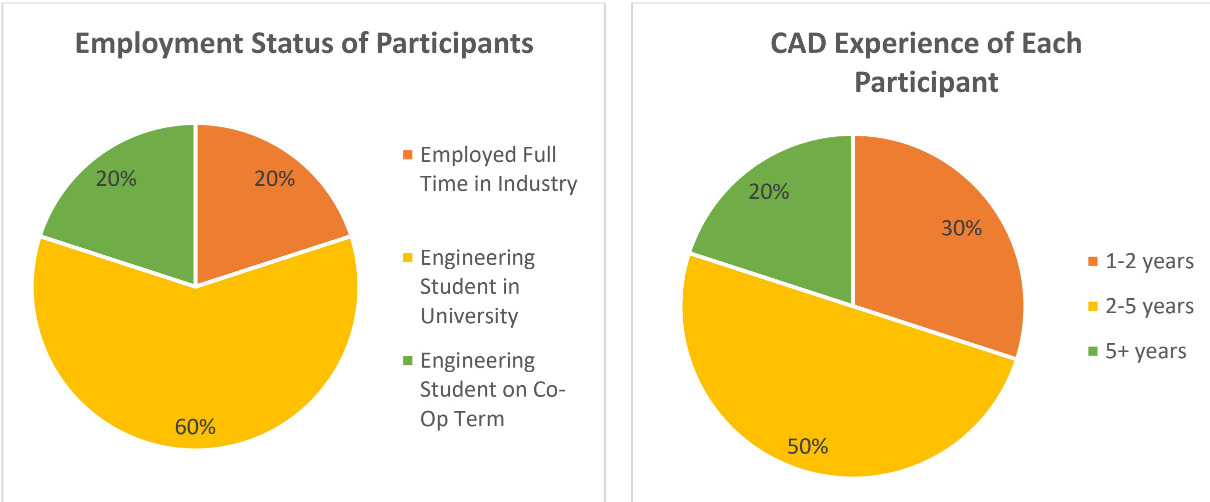


Figure 3.1: Summary of Participant's Employment Status and CAD Experience

### 3.3 Pre-experiment Survey

In order to gauge participant's level of CAD and manufacturing experience, all participants completed a pre-experiment survey. Modifications were made to Chen's MASc Pre-experiment survey with questions added to gain insight into participant's manufacturing experience and preferred manufacturing processes. The added questions to Chen's pre-experiment survey are seen below:

1. What level of manufacturing experience would you consider yourself to have? Please select the level that closest represents your manufacturing experience level.

   **No Experience:** I have never taken a manufacturing course, are not familiar with different processes and haven't taken on any manufacturing project.

   **Novice:** I understand the basics of manufacturing, have made a few simple parts and taken 1-2 courses in basic manufacturing.

**Intermediate:** I am comfortable manufacturing medium to high complexity products that include multiple parts and processes. I am familiar with multiple manufacturing processes and have made meaningful contributions in manufacturing personal and/or team projects.

**Advanced:** I have extensive manufacturing experience in a professional setting or teaching manufacturing to students, with a good mastery of manufacturing principles and processes and regularly lead manufacturing projects of complex products with multiple processes, intricate assemblies and high part counts

2. What manufacturing processes are you familiar with?
3. Which manufacturing processes are you most familiar with? ____________________

<u>3.4 Experiment CAD Task</u>

Following Chen's experiment, participants were asked to CAD the following model in Figure 3.2 in 35 minutes.

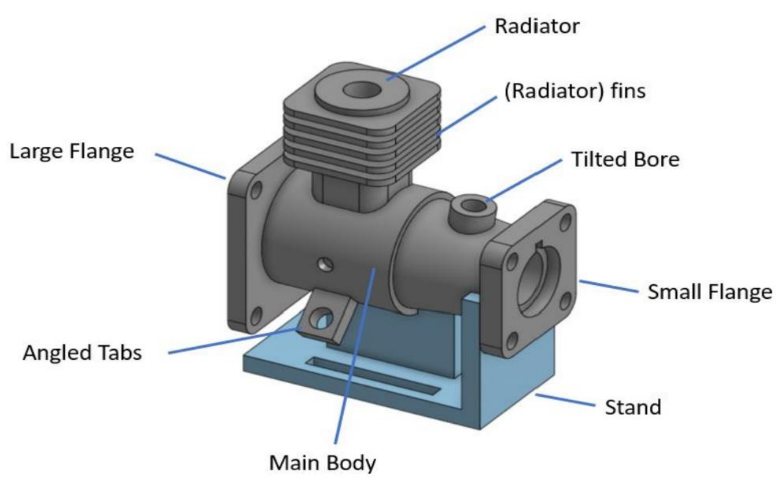


Figure 3.2: Experimental CAD Task Model with Major Features Labelled

It can be broken down into four successive steps, as seen in Figure 3.3, and for each step, the participants were given 2D engineering drawings to aid in their modeling as seen in Appendix B.

All 2D drawings were over-dimensioned so that participants could choose which dimensions would be easiest for them to model.

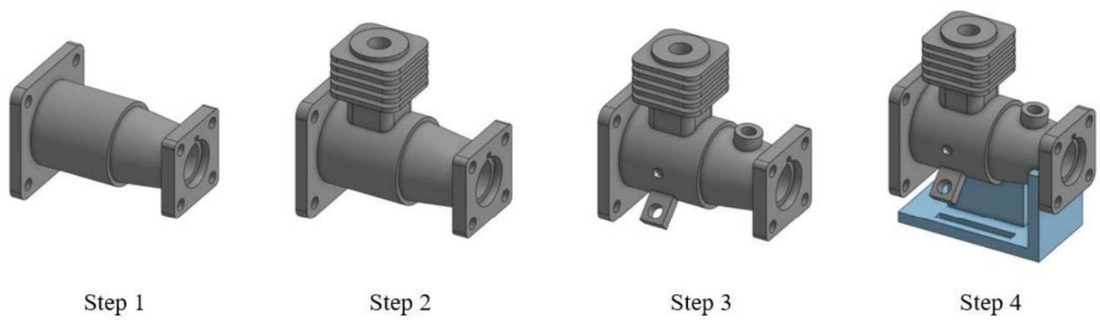


Figure 3.3: Breakdown of Experimental CAD Task

Participants were instructed not to look at the next step's 2D drawing until they felt they had finished the step they were on. This allowed investigators to analyze whether the participant's CAD style changed when new details were introduced to their challenge. Additionally, as the primary target of this experiment were novice engineers, it allowed for these details to be introduced in an easily digestible manner and they would not be intimidated by the complexity of the overall part.

Participants were marked according to the scoring method laid out in Chen's experiment, this can be seen Appendix C. The score was not vital to the experiment's results as the aim was not to classify participants ability, it was merely used to reconfirm novice, intermediate or expert level of CAD modeling as self-identified in the participant's pre-experiment survey.

During the CAD task, participant's screens were recorded with the investigators taking notes of the participant's actions as they happened. Furthermore, as this task was done on Onshape, after the experiment the participant's Audit Trails were downloaded for further analysis. Onshape's Audit Trails track every action the participant makes, for example it tracks when the participant creates a sketch or switches back to the step's 2D drawing. An example of this is seen below in Figure 3.4.

| | Time | Document | Tab | User | Description |
|---|---|---|---|---|---|
| 1 | 2023-04-07 02:40:24 | Experiment Setup ··· | N/A | Victoria Velikonja ··· | Close document ··· |
| 2 | 2023-04-07 02:40:24 | Experiment Setup ··· | Part Studio 1 | Victoria Velikonja ··· | Update Part Metadata ··· |
| 3 | 2023-04-07 02:40:24 | Experiment Setup ··· | Part Studio 1 | Victoria Velikonja ··· | Tab Part Studio 1 of type PARTSTUDIO closed by Victoria Velikonja ··· |
| 4 | 2023-04-07 02:40:19 | Experiment Setup ··· | Part Studio 1 | Victoria Velikonja ··· | Insert feature : Extrude 1 ··· |
| 5 | 2023-04-07 02:40:19 | Experiment Setup ··· | Part Studio 1 | Victoria Velikonja ··· | Commit add or edit of part studio feature ··· |
| 6 | 2023-04-07 02:40:14 | Experiment Setup ··· | Part Studio 1 | Victoria Velikonja ··· | Add part studio feature ··· |
| 7 | 2023-04-07 02:40:10 | Experiment Setup ··· | Part Studio 1 | Victoria Velikonja ··· | Commit add or edit of part studio feature ··· |
| 8 | 2023-04-07 02:40:10 | Experiment Setup ··· | Part Studio 1 | Victoria Velikonja ··· | Add or modify a sketch ··· |

Figure 3.4: Example of Onshape's Audit Trails using the Experiment's Setup Onshape Document

## 3.5 Post-experiment Interview

Immediately following the participants allotted 35-minute CAD task, the post-experiment interview began. Thereby, getting participant's immediate thoughts on their CAD process. Typically, the interviews lasted 45 minutes to 1 hour long. The interview was semi-structured with investigators having prepared some general questions that could be applied to all participants but generally followed this order:

1. Participants and investigators watched the recording of the participant's CAD task. During this time participants were asked for their thinking behind their actions.
    a. Example: When you first saw Step 1 what were your initial thoughts, did you have a plan of action when you first saw it?
2. Once the recording finished, the questions moved towards manufacturing-related questions.

a. Example: Given unlimited time and resources how would you manufacture this part?

This interview format also allowed for participants to organically mention tangential but relevant topics. For example, some brought up manufacturing processes without prompting from the investigators. All interviews were recorded with transcripts being generated later. The interviews were analyzed through inductive coding. Relevant quotes were grouped individually than grouped together into higher themes.

## 4.0 Results

In this section, both the quantitative and qualitative data collected is presented. Based on data collected during participant's experiments, participants were sorted as either an additive or subtractive modeler based on their actions during the CAD task. In order to better visualize their process and confirm their CAD style, event plots were generated for each participant. Finally, participant interviews were analysed to further confirm their CAD style by gaining further insight into their thought process while modeling in CAD. Participant interviews also allowed for insight to be gained into their background in manufacturing and its relationship to their CAD modeling strategies.

### 4.1 Sorting Between Additive and Subtractive Modeling

It was necessary to first define what would be considered additive or subtractive actions in CAD modeling. Any actions that built upon or added on to the part were classified as additive while any actions that removed material from a part were classified as subtractive. General actions were defined by their inability to be classified as subtractive or additive as they were typical actions that any modeler would need to use to CAD. For example, referring back to 2D drawings or creating a sketch. Irrelevant actions were removed from analysis. These actions are ones that were automatically recorded through Onshape's Audit Trails but had no relevance to a participant's CAD. For example, Onshape records an action called "Update Part Metadata" which is an event internally generated by Onshape's system to update their metadata or their data on the data. A full list of CAD actions used by participants were classified. It is important to note that one participant utilized Onshape's Assembly features to build their part. Upon further review of their CAD model and thought process, these assembly actions were classified as additive, as the participant used the assembly features to stack parts together to build up the part.

Classification of CAD Actions used by Participants:

| **General Actions** | **Additive Actions** | **Subtractive Actions** |
|---|---|---|
| Refer to Drawing | Insert Extrude Add | Insert Extrude Remove |
| Create Sketch | Edit Extrude Add | Edit Extrude Remove |
| Edit Sketch | Delete Extrude Add | Insert Loft Remove |
| Delete Sketch | Insert Extrude New | Insert Draft |
| Rename Sketch | Edit Extrude New | Edit Draft |
| Move Sketch | Move Extrude New | Delete Draft |
| Insert Plane | Insert Linear Pattern Add | Create Draft |
| Edit Plane | Edit Linear Pattern Add | Delete Face |
| Delete Plane | Delete Linear Patter New | Insert Hole |
| Delete Face | Insert Loft Add | Edit Hole |
| Create Offset Surface | Create Extrude Add | Create Split Part |
| Create Section | Insert Mirror Add | Insert Revolve Remove |
| | Insert Boolean Union | Delete Revolve Remove |
| | Insert Revolve New | Insert Revolve Cut |
| | Insert Revolve Add | Insert Fillet |
| | Delete Revolve Add | Edit Fillet |
| | (Assembly) Insert Fastened Feature | Move Fillet |
| | (Assembly) Insert Part | |
| | Add assembly instance | |
| | Stop assembly drag | |
| | Start assembly drag | |
| | Add Assembly Feature | |

Using the classified actions above, each participant's overall process could be quantified as mainly additive or mainly subtractive by sorting and then summing their actions. If a participant's actions were more than 50% additive, they were classified as an additive modeler. If a participant's actions were more than 50% subtractive, they were classified as a subtractive modeler. Figure 4.1 below shows the participants ordered from mainly subtractive modeling to mainly additive modeling.

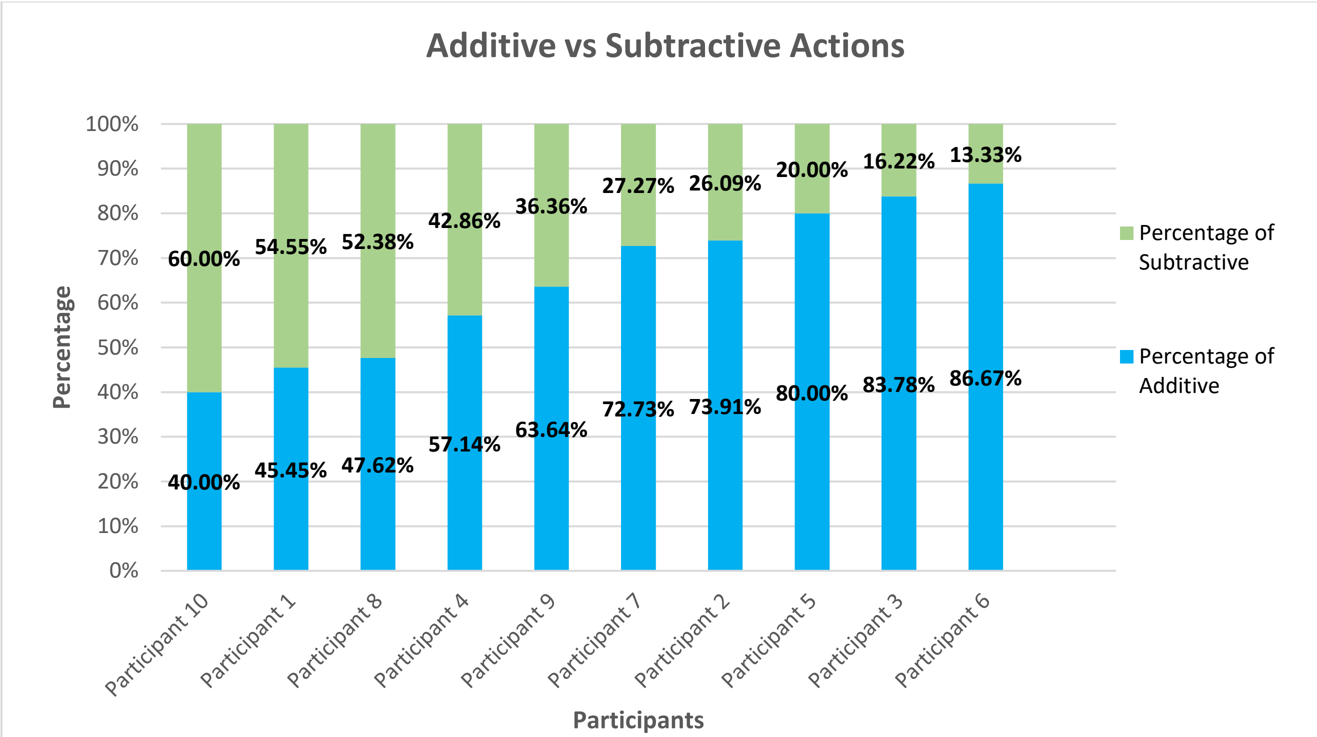


Figure 4.1: Shows the break down between additive and subtractive actions per participant ordered from mainly subtractive to mainly additive; the percentage of subtractive actions is shown in green while the percentage of additive actions is shown in blue.

As seen in Figure 4.1 above, three participants (Participant 10, 1 & 8) used mainly subtractive actions while seven participants used mainly additive actions. The breakdown is summarized below in Figure 4.2.

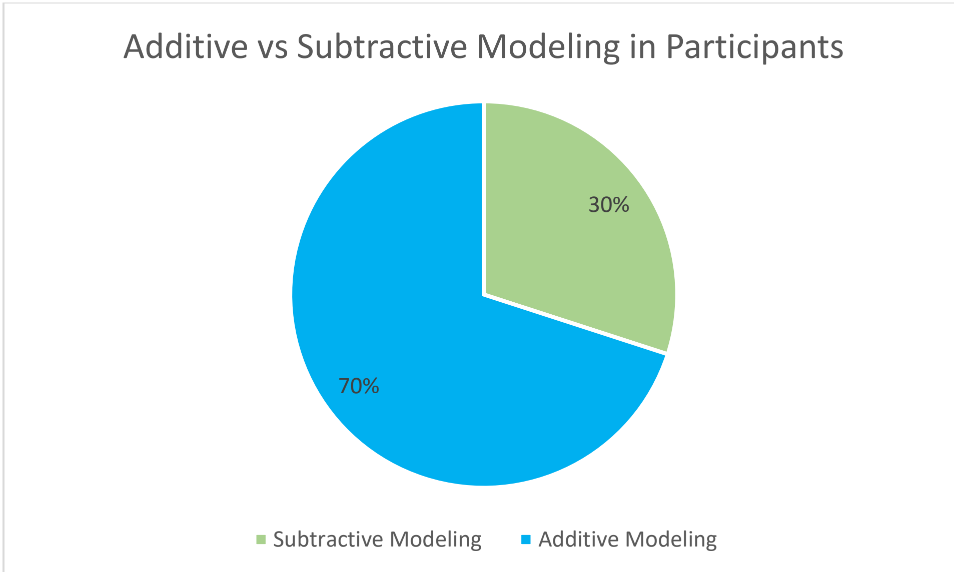


Figure 4.2: Breakdown of additive versus subtractive modeling in participants with the percentage of subtractive modelers in green and additive modelers in blue

## 4.2 Differences Between Additive and Subtractive CAD Processes

In order to further understand not just the difference in the amount of additive and subtractive actions in modelers, but the difference in processes between additive and subtractive modelers, event plots were created. In the event plots, types of actions were grouped together in the following way (starting from the top of the y-axis and moving down):

- Any action that included referring back to the 2D drawings were grouped together in grey.
- Any action involving sketching was grouped together in yellow.
- Any additive actions were grouped together in blue.
- Any subtractive actions were grouped together in green.
- Any action that involved new datum planes were grouped together in purple.

Figure 4.3 below shows the event plot of Participant 6, who was identified as the most additive modeler and Figure 4.4 shows the event plot of Participant 10, the most subtractive modeler.

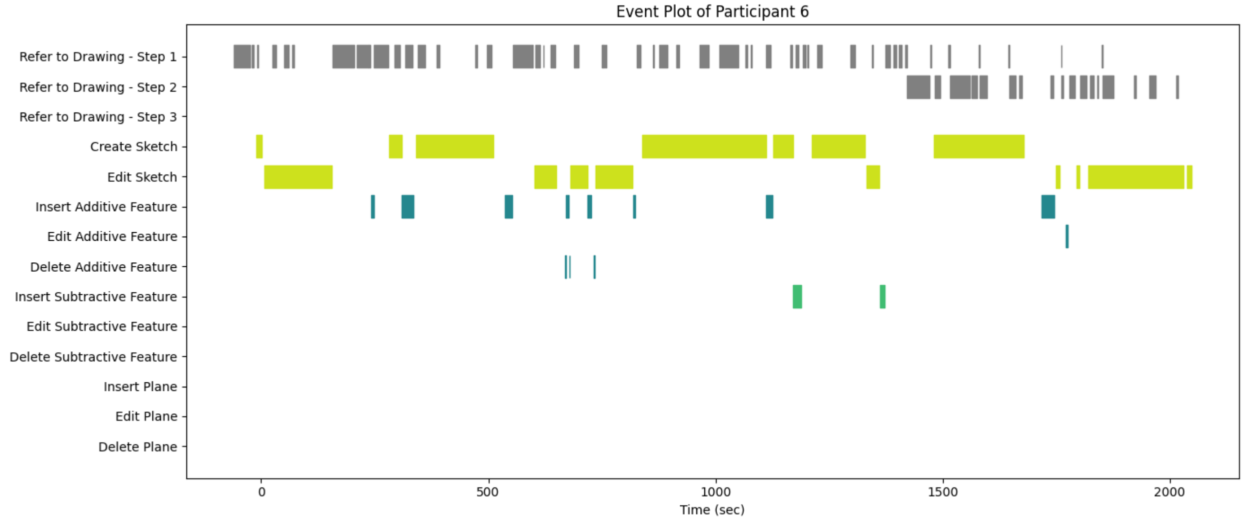


Figure 4.3: Event plot of Participant 6, actions in grey represent referring to 2D drawings, actions in yellow represent any action involving sketching, actions in blue represent additive actions, actions in green represent subtractive actions.

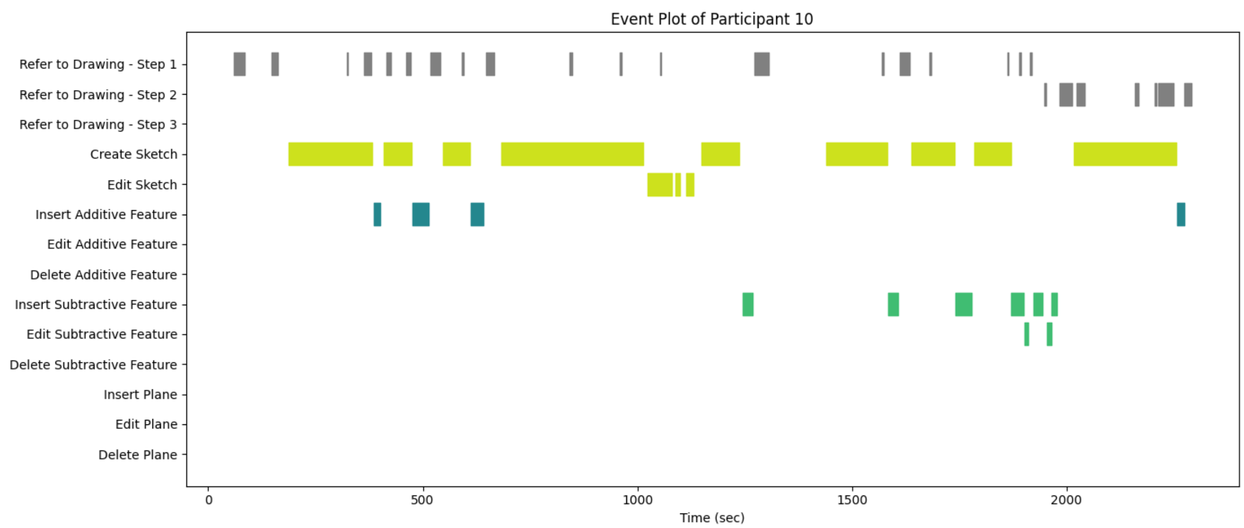


Figure 4.4: Event Plot of Participant 10 , actions in grey represent referring to 2D drawings, actions in yellow represent any action involving sketching, actions in blue represent additive actions, actions in green represent subtractive actions.

When comparing Figure 4.3 and 4.4, the differences are very apparent. Participant 6 rarely used any subtractive actions and focused in both steps 1 and 2 on building the model through additive actions, while Participant 10 used additive actions to create a general shape and then spent the rest of the time adding details through subtractive actions.

4.2.1 Comparison of Novice and Experienced Additive and Subtractive Modelers

While not the focus of the experiment, an interesting comparison can be drawn by looking at the differences between Participant 1 and Participant 10's process. Participant 1 is a novice engineer with one year of CAD experience while Participant 10 is an experienced engineer with 25+ years of CAD experience. As can be seen in Figures 4.4 and 4.5 below, they both tend towards subtractive actions, but in different ways. Participant 10 focused on creating the general shape of the part before adding in details through subtractive actions, while Participant 1 switched between additive and subtractive actions frequently adding in details.

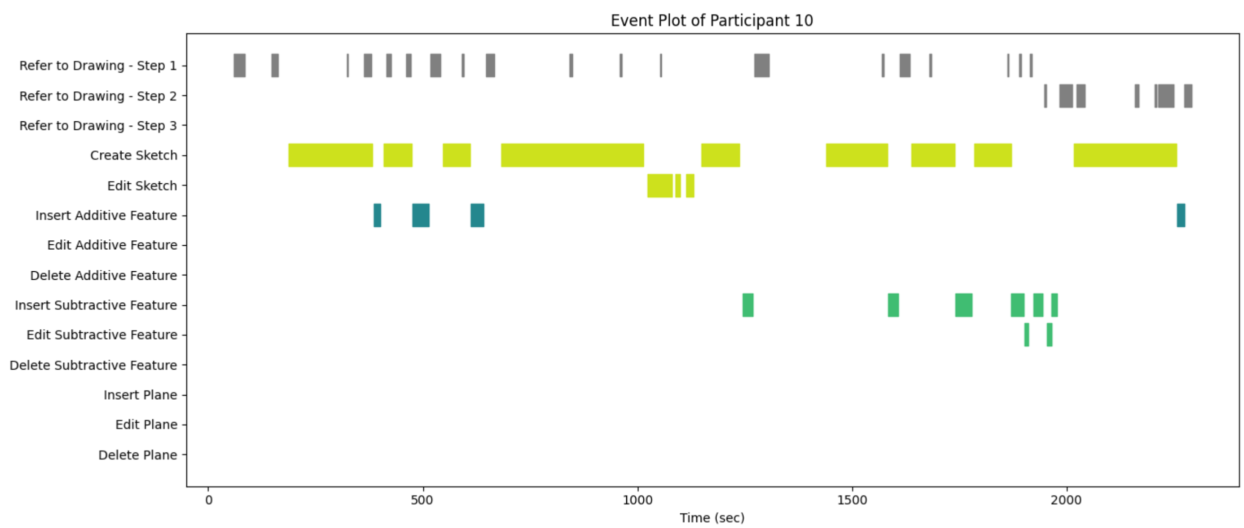


Figure 4.4: Event Plot of Participant 10, actions in grey represent referring to 2D drawings, actions in yellow represent any action involving sketching, actions in blue represent additive actions, actions in green represent subtractive actions.

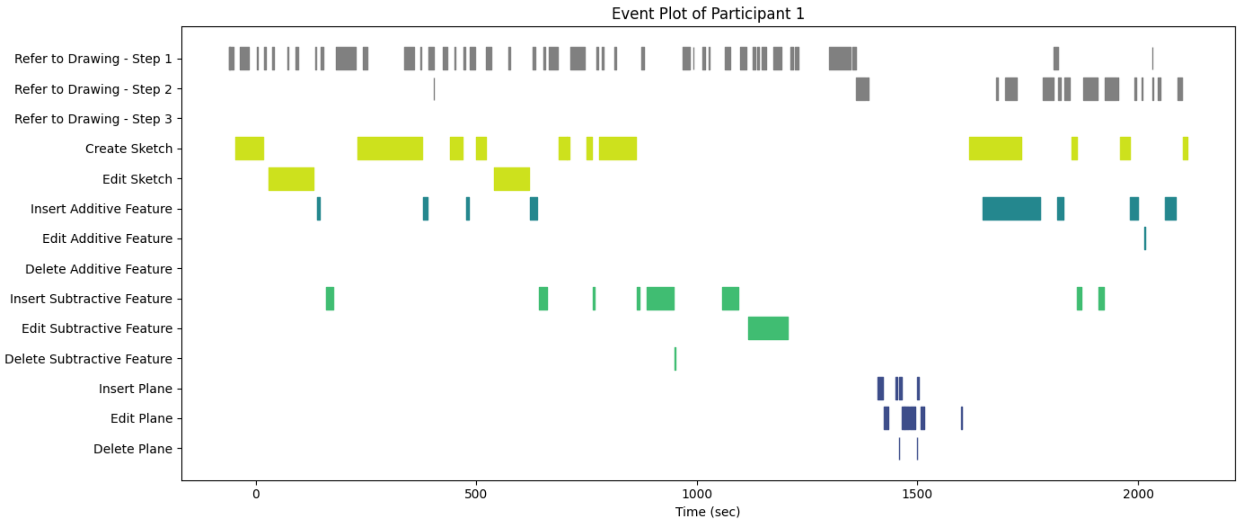


Figure 4.5: Event Plot of Participant 1, actions in grey represent referring to 2D drawings, actions in yellow represent any action involving sketching, actions in blue represent additive actions, actions in green represent subtractive actions, actions in purple represent any action involving new datum planes.

This difference in approach to modeling perhaps can be attributed to their difference in experience. Participant 10's event plot is more clean, focused and orderly. They spent a significant amount of time creating a sketch and very rarely had to edit any features. In comparison, Participant 1 spent less time sketching and more time editing features. They also spent time creating new datum planes to work off while Participant 10 chose to use the original planes given in Onshape.

## 4.3 Qualitative Participant Interview Results

As mentioned previously, after participants had completed their CAD task, they participated in an interview where they watched back their CAD modeling process and provided insight on their thought process and then were asked about their preferences in how to manufacture the part. All following quotes are taken from their interviews.

### 4.3.1 Comparing Novice Additive versus Subtractive Modelers

The first part of the interview had participants watch back their CAD task so that they could explain how they planned to CAD and their process. In this stage of the interview, participants were not asked explicit questions about manufacturing, just to explain their CAD modeling process.

All participants were asked to explain their initial reactions to seeing step one and explain their initial thoughts on how to do it. A commonly occurring topic was how participants described the orientation of the model. For example, Participant 6, the most additive modeler of the group said that their plan was to "start at the base, look at the next part and move at it sequentially", during this part of the interview they continuously stated that they looked at the model "bottom-up", where they first model the base plate including all details in the base sketch, then move up to the cylindrical section before finishing with the top plate. Interestingly, the model is not oriented this way, yet Participant 6's perception of the model was to flip it 90 degrees as seen in Figures 4.6 and 4.7 below.

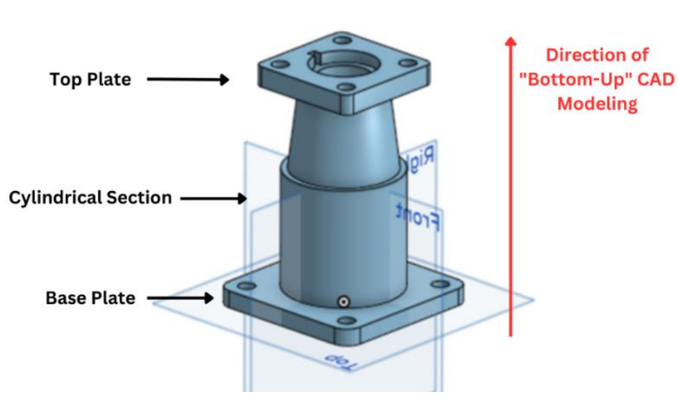


Figure 4.6: Shows Participant 6's Onshape CAD document with the participant's labels of each section and an indication of the direction of their modelling

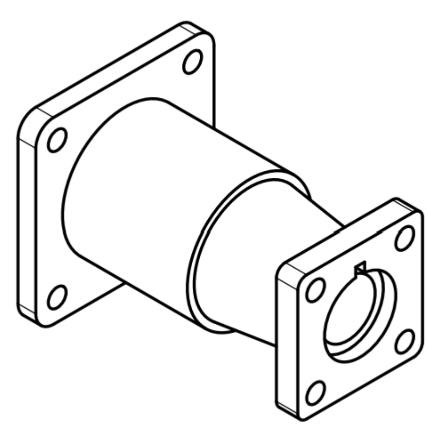

Figure 4.7: Orientation of the model in the given 2D Drawing of Step 1

As seen above, Participant 6's CAD process was to take a bottom-up approach, extremely similar to 3D printing. When asked about the manufacturing process they had the most experience with, they confirmed that they own a 3D printer and most of their personal projects are created using it. Furthermore, through their Co-Op position, they frequently design parts for injection molding. Their primary experience in manufacturing is in additive manufacturing processes, matching their additive style of CAD modeling. Similarly, all participants who are most familiar with 3D printing also oriented their CAD models in a similar way and described their view of the model in a bottom-up manner.

In comparison, for the most subtractive student modeler, Participant 1, most of their manufacturing experience comes from subtractive manufacturing processes. They are most experienced with manufacturing parts through milling. They described their CAD process as building up the part through "basic shapes, like circles and squares" and the adding "intricate little details" like fillets after. Participant 1's CAD process for Step 1 of the CAD Task is seen below in Figure 4.8.

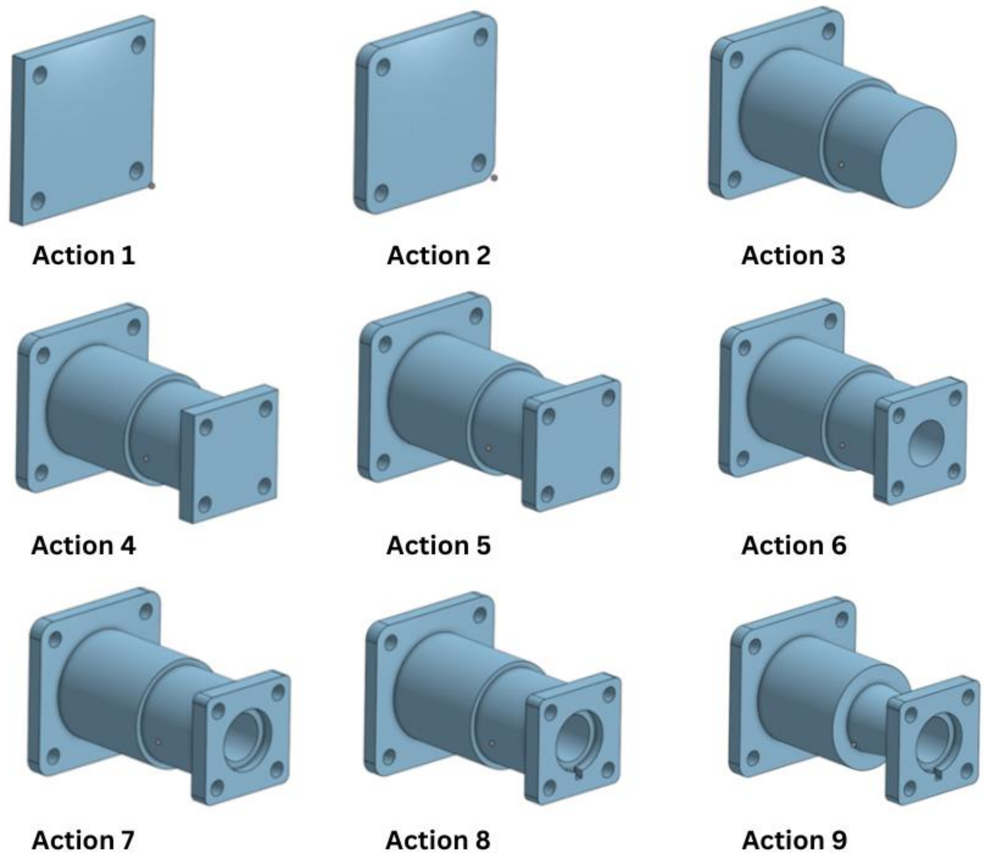


Figure 4.8: Participant 1's Subtractive Process for Step 1 of the CAD Task

As seen in Figure 4.8 above, Participant 1 did include some detail in their sketches. For example, in their first action they included the through holes but extruded the sketch first and then added in the fillet details in their next action. However, Participant 1 does have the characteristics of a subtractive modeler. They completed the basic shape as they see it in action 5 and then began adding in more details like the recessed keyhole and centre hole then angled the cylinder after. While they did not get Step 1 completely correct as their angled cylinder feature is incorrect, it is an excellent example of a novice subtractive designer's process. For comparison, Participant 6's additive CAD process is below in Figure 4.9.

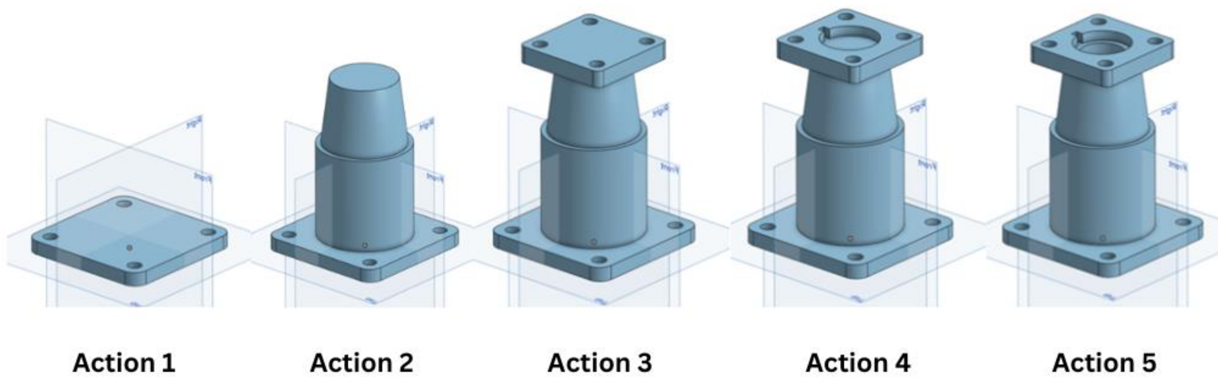


Figure 4.9: Participant 6's Additive Process for Step 1 of the CAD Task

As stated earlier, Participant 6 utilized a "bottom-up" approach. They oriented the model so that they would have a "base plate" to build on. They added in all details to their base sketches and only used subtractive actions if:

- The detail could not be added into the base sketch as in action 4 .
- The detail went through multiple sections of the part as in action 5.

The main differences between Participant 1 and Participant 6's CAD process are their orientation of the model, the detail included in their sketches and the order they added details in. By details we are referring to fillets, through holes, angle of cylinders and keyhole features. Both participants are mechanical engineering students at the University of Toronto, so they have had identical formal training in CAD and Manufacturing. However, besides the second year UofT manufacturing course they've had very different experiences in manufacturing that could explain their different approaches to CAD. We further elaborate on this in the Discussion section 5.2 below.

4.3.2 Affect of New Additive Manufacturing Processes on Current Engineering Students

The majority of student participants described the model in a bottom-up manner. They constantly referred to the part having a base plate and orienting the model in a similar manner. Beyond their

CAD style when asked what manufacturing process they are most familiar with and how they would manufacture these parts, the majority tended to prefer 3D printing. For example, even though Participant 8 has a primarily subtractive modeling style they stated that their "first choice is always 3D printing, because it's so easy". However, this preference for 3D printing could potentially raise concerns about whether it limits their overall design abilities. In response to this, Participant 6 made an insightful comment when asked whether they felt that having a bias towards 3D printing limited their overall design prowess. Their response conceded that it could restrict one and be "seen as a pigeonhole but [one] could also see it as a way to be more creative in the method [they're] choosing". That by finding workarounds and ways to make certain manufacturing processes work for their designs it can "lead to innovation and different ways of thinking". While the majority of student participants expressed a preference for 3D printing as their primary manufacturing choice, Participant 4 did not have such a strong inclination towards this method. They still preferred traditional manufacturing methods, like casting. They stated that 3D printing seems to have "less effect" on them because "someone else is doing it for me". They feel removed from the actual manufacturing process as their "hands are not on it". This preference towards 3D printing and the potential lesser effect of it on current CAD modellers is further elaborated on in the Discussion section 5.2 below.

#### 4.3.3 Influence of Manufacturing on Professional Engineers CAD Style

All participants were asked whether they consciously thought about how to potentially manufacture the part from the CAD task, all participants said that they did not. However, when asked if knowing how the part was to be manufactured would change their process, all participants responded no, except for Participant 10.

Participant 10 is the most experienced engineer of the group with 25+ years of experience in the engineering industry. Participant 10 responded that while it would not change greatly change their process it would be something they kept in mind. They elaborated that to them, a good design is "easy to manufacture, easy to use and easy to assemble" so when they CAD they're always trying to "preserve the intent of the design" so that they're CAD-ing with "critical dimensions that can easily transfer to a 2D drawing" to make manufacturing easier. This confirms what Participant 5 said in their interview about their experience with senior mechanical engineers who "cannot start designing a part without knowing how it's going to be manufactured". This form of intentional manufacturing influence in one's CAD style seems to only be present in the most experienced of professional engineers who have most likely experienced negative consequences when manufacturing is not actively considered during the CAD modeling stage of product design. The need to fully understand a part's lifecycle seems to come from years of experience designing parts that end up not being manufacturable.

Furthermore, Participant 5 compared their own experience to a colleague to describe how their CAD process may have been affected by previous manufacturing experience. Participant 5 began their professional engineering career in fixing technical issues on existing products for customers while their colleague began in the R&D department. In Participant 5's initial years as an engineer they had a "tiny box to work in" with "a lot more constraints". They had had constantly think about backwards compatibility issues and ensure that any design changes made would not change the existing manufacturing process. While their colleague had "no boundaries" and only had to consider potential manufacturing processes at the end of the design process. In Participant 5's opinion their journey after undergraduate education was "a bit backwards". They believe when a student comes "out of school out of school you start in design to build your intuition of what works and what does not. And then you move to an area where you're working with tighter constraints, because you've got that intuition”. When they eventually worked together on projects this led to wildly different approaches. Neither approach is worse or better it’s simply a different way of considering how manufacturing fits into the overall design process.

Overall, all novice participant interviews confirmed that their style of CAD lined up with the manufacturing process they are most familiar with. It important to note that this style is not set in stone, given experience with a completely different type of manufacturing their style may change to match what is now the new normal to them. Furthermore, similarly to the professional experienced engineer participants, they may begin to consciously consider manufacturing processes while modeling in CAD.

## 5.0 Discussion

Quantitative results from the experiment showed that even novice engineers tend to have a bias towards either subtractive or additive modeling, qualitative analysis of participant interviews showed that this bias can be linked towards manufacturing processes that the participant is most familiar with. Participants with primary experience in additive manufacturing like 3D printing or injection molding tended to be an additive modeler while participants with primary experience in milling or machining tended to be a subtractive modeler. This bias did not come from their idea of how the part would be manufactured but instead from their own personal preference of manufacturing.

### 5.1 Subtractive versus Additive CAD Processes

As seen in Section 4.2, when comparing the additive and subtractive CAD processes, it is not just the type and frequency of actions that are different, it is the overall approach. Additive modelers tend to break up the part into different sections, add in all necessary detail to that part and then move along sequentially to the next part. Unless they notice an error, they are unlikely to return to a previous section as in their mind it's complete. In comparison subtractive modelers tend to look at the part as a whole. They attempt to finish what they consider to be the general shape and then go back and model in the details. The definition of general shape or details is specific to each modeler but it in general Figures 4.3 and 4.4 are a standard look at the process of an additive and subtractive modeler. In this study, it was seen that whether a participant was an additive or subtractive modeler depended on which manufacturing process they were most familiar with.

### 5.2 Affect of Minimal Manufacturing Experience in Novice Engineers

The majority of the student participants described the part in a very additive way, confirming Chen's observation in their MASc thesis that a younger generation of CAD designers are less inclined to prefer traditional manufacturing processes with the ease and access of 3D printing. However, building off Participant 4's idea that manufacturing fixation in one's CAD process comes from the hands-on nature of certain manufacturing processes, would it be easier to sway novice engineers to a new style as rarely are current engineering students setting up the 3D printing process unless they themselves own a 3D printer? As previously stated, Participant 6 owns their own 3D printer and 86% of their actions during the CAD task were additive. In comparison, only 57% of Participant 4's actions were additive. The distance Participant 4 feels from 3D printing could potentially mean that while they are currently a primarily additive modeler given more experience with a different style of manufacturing their style could be easily swayed.

### 5.3 Differences in Outlook between Student and Professional Engineers on Manufacturing's Influence in CAD

Compared to the eight student participants in this study, the two working engineers had an extremely different outlook on how manufacturing processes should, in their opinion, affect a designer's CAD process. Most student's when asked about how the manufacturing of the part would affect their CAD process said it would not; however, when the working engineers were asked, they explained that it would affect their entire process as they would be focused at every step on ensuring that the part could actually be manufactured. Both professional engineers, did state that the awareness for preserving the manufacturing intent came from years of making mistakes and learning from them, something that even the most experienced student engineer in this study does not have.

It seems that there are two ways manufacturing can influence an engineer's CAD process. The first being an unintentional bias towards either additive or subtractive modeling which comes from previous experience with a specific type of manufacturing. The other seems to only be present in the most experienced of engineers, where manufacturing is actively considered and actively influences one during the CAD stage of product design. This type of influence most likely comes from years of making mistakes during the CAD modeling stage that rendered parts unmanufacturable.

## 5.4 Future Work

While Brennan et al. and Abdellal et al.'s study focused on how manufacturing bias can affect the overall design process, this study focused on how manufacturing bias can affect a designer's CAD process. This study has shown a link between a designer's past experience in manufacturing and their current CAD style, even if their past experience in manufacturing is minimal. Going forward, it would be interesting to research how these different styles of CAD could interact and work together in a group setting. For example, if a subtractive and additive modeler were paired together to design or CAD a part what roadblocks or what innovations could come from that. Furthermore, the manufacturing bias in experienced engineers seems to come from previous mistakes made that rendered a part un-manufacturable. Building upon Participant 6's idea that creative solutions could come from manufacturing bias, would having engineers work with manufacturers earlier on in the product design process lead to less fear about un-manufacturable parts and towards finding creative solutions. Finally, given the easy-access and accessibility of 3D printing to a younger generation of engineers it would be interesting to research how manufacturing bias can present in different generations. Not only whether modelers from the current generation of engineering students are potentially more easily swayed due to the hands-off process of 3D printing but how two additive modelers would work together if one was extremely familiar with injection molding and the other more familiar with 3D printing. Going forward, the presence of manufacturing bias should be studied in a group setting to better understand how different styles can interact and work with each other, because engineering and designing are rarely solo activities.

## 6.0 Conclusion

This study aimed to find if there was manufacturing bias in CAD-ing for novice engineers. Participants were mainly found from current University of Toronto mechanical engineering students with two participants being working professional engineers. Participants were asked to CAD a part from 2D engineering drawings and then were interviewed about their CAD process and background in manufacturing. Participants also filled out a pre-experiment survey so that the investigators had a complete background on each participant.

The results support that there is a link in a designer's CAD process and their manufacturing background. Even in novice engineering students who have had identical educational backgrounds in CAD and design can have opposite CAD styles that line up with their manufacturing backgrounds. It was found that a participant's CAD style can be categorized as additive or subtractive and that this style and their way of approaching CAD and design mirrors the manufacturing process they are most familiar with. Furthermore, it was found that this current generation of engineering students tend to have a preference for 3D printing due to how accessible it is. This led to six of the eight student participants to having an additive CAD style. Finally, all of the student participants have stated that the manufacturing process of a part they are designing does not affect their CAD style and they view it as a separate challenge to consider when the CAD modeling is done. Comparatively, the working engineers in this study stated that they are constantly thinking of the manufacturing process when modeling in CAD. Through mistakes and trial and error they found that not considering the manufacturing process can render parts un-manufacturable.

This study confirms the findings of previous work in manufacturing fixation in design. It reinforces that no matter how inexperienced an engineer can be in manufacturing even limited exposure to a certain process can shape their CAD style. Going forward, now that this link has been identified in novices and intermediates, the following topics could be interesting research areas:

1) Explore how designers with additive and subtractive styles work together.
2) Given the seen preference of newer manufacturing processes like 3D printing in the current generation of students, does MFD in different generations present differently?
    i) Does this affect how younger generations and current working professional collaborate?
    ii) Given the typical hands-off approach of 3D printing as a manufacturing process in this younger generation of engineers will it have a long lasting impact on CAD modelers or will it be easily replaced by a different manufacturing process?

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[3] J. B. Brennan, W. B. Miney, T. W. Simpson, and K. W. Jablokow, "Manufacturing Fixation in Design: Exploring the Effects of Manufacturing Assumptions on Design Ideas," *Proc. ASME Des. Eng. Tech. Conf.*, vol. 6, Nov. 2021, doi: 10.1115/DETC2021-70361.

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[6] E. S. Abdelall, M. C. Frank, and R. T. Stone, "A Study of Design Fixation Related to Additive Manufacturing," *J. Mech. Des. Trans. ASME*, vol. 140, no. 4, Apr. 2018, doi: 10.1115/1.4039007.

## Appendices

### Appendix A - Participant Recruitment

### A1. Participant Recruitment Message

The Ready Lab at the Faculty of Applied Science & Engineering from the University of Toronto is looking for participants for our computer-aided design (CAD) study in a paid, 2-hour study. The purpose of the study is to analyze the actions of CAD users as they complete a series of tasks to better understand how biases can affect a user's CAD process. The study will take place during the Winter 2023 semester.

To be eligible, you must:

- Be comfortable creating moderately complex CAD models given an engineering drawing using Onshape
- Have access to a computer, microphone and reliable internet if participating through Zoom

You will be asked to:

- Attend a 2-hour session either in person at the University of Toronto's St. George Campus or through Zoom
- Perform a series of CAD activities (create CAD models) using Onshape
- Complete a pre-experiment survey
- Partake in a post-experiment interview

As a token of appreciation, participants will be compensated $7.50/half hour (either CAD or USD depending on participant location) for participation in the study. Any personal identity information will be anonymized in any external-facing documents (i.e. publications and presentations).

Your participation will be tremendously helpful for developing a better understanding of CAD usage and will be used to develop better CAD training in the future. If you are interested, please sign up here at: https://bit.ly/CAD_StudySurvey. We will provide more information through email!

If you have any questions, please email Victoria Velikonja at victoria.velikonja@mail.utoronto.ca with the subject line "Ready Lab CAD Experiment".

A2. Participant Mailing List Signup

**Mailing List Signup**

**Thank you for your interest in the Ready Lab's CAD study!**

**We are interested in studying the actions and preferences of CAD users with different skill levels.**

**If you are interested in becoming a participant in this experiment, please put down your name and email below. We also ask that you answer a few quick questions to help us understand your level of familiarity with CAD!**

**We anticipate the experiment to take between 1 to 2 hours. As a token of appreciation, we plan to provide a gift card for your participation in the experiment.**

**We will reach out to you very soon with more information!**

If you have any questions, please do not hesitate to email victoria.velikonja@mail.utoronto.ca with the subject line "Ready Lab CAD Experiment"

Please provide your first name:

Please provide your last name:

Please provide your email:

Are you currently a student or a professional?

- Student
- Professional
- Other

What level of 3D CAD user would you consider yourself to be? Please select the level that closest represents your CAD experience level

- ○ Novice (I understand the basics of CAD, have made a few simple parts, and followed some CAD tutorials. I have used CAD for course labs/personal projects/team projects)
- ○ Intermediate (I am comfortable making medium to high complexity parts that include multiple sketches, datums, and features. I have used CAD for personal and/or team projects and made meaningful contributions to the models)
- ○ Advanced (I have extensive experience using CAD in a professional setting or teaching CAD to students, with a good mastery of CAD principles and regularly work with large CAD models with complex geometries and high feature-counts)

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How many months of experience do you have in CAD (across all CAD programs)?

____________________

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How many months of experience do you have in Onshape? (if none, type "0")

____________________

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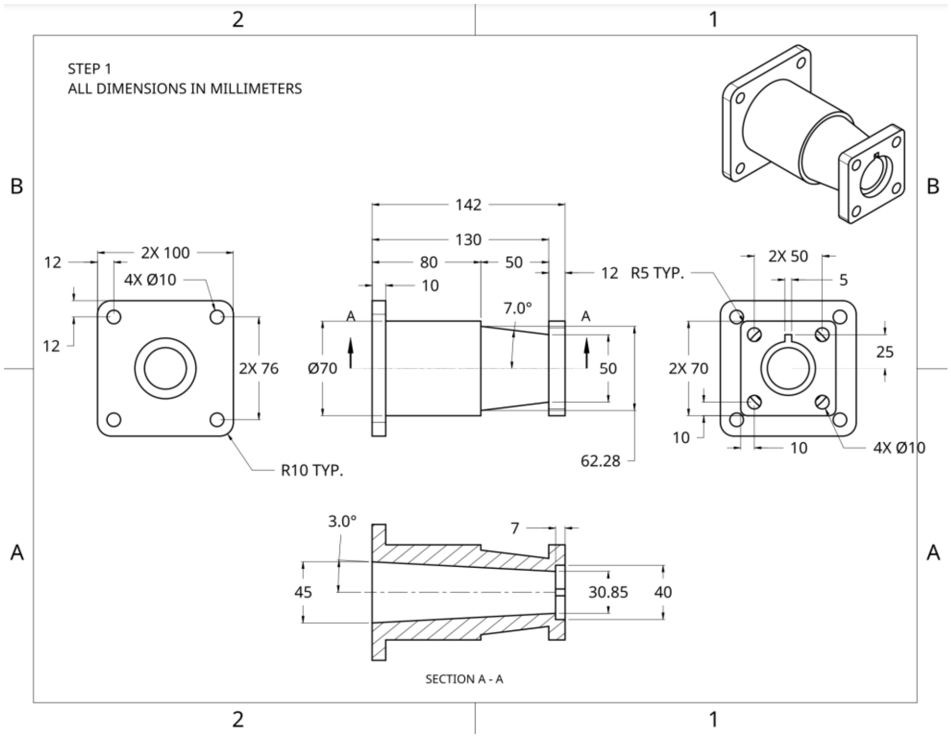
Is Onshape the main solution you use for CAD?

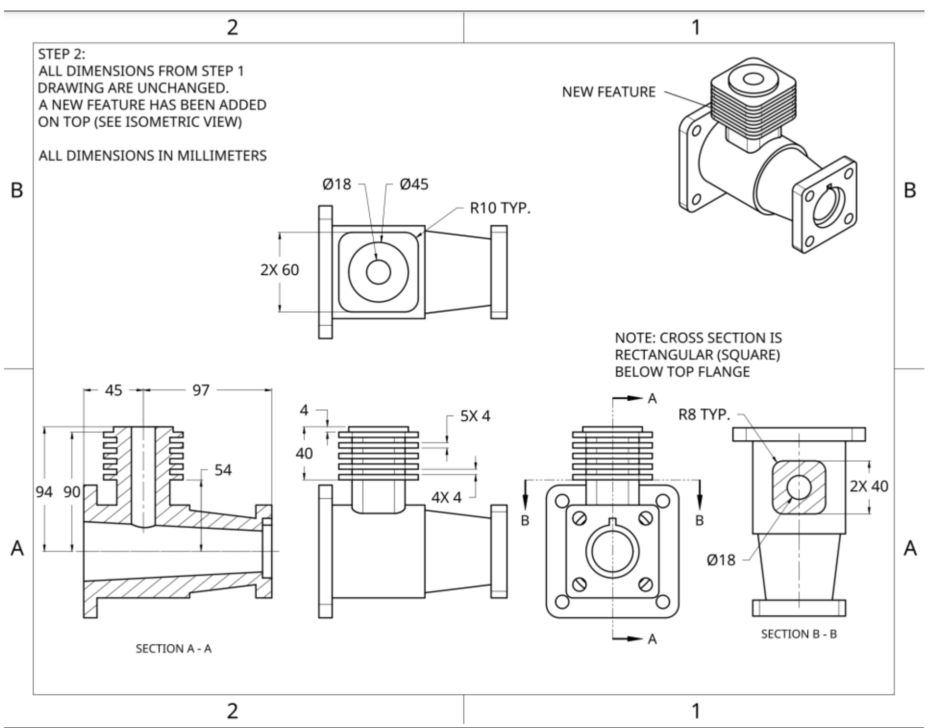
- ○ Yes
- ○ No

<u>Appendix B – 2D Drawings of Participant CAD Task</u>

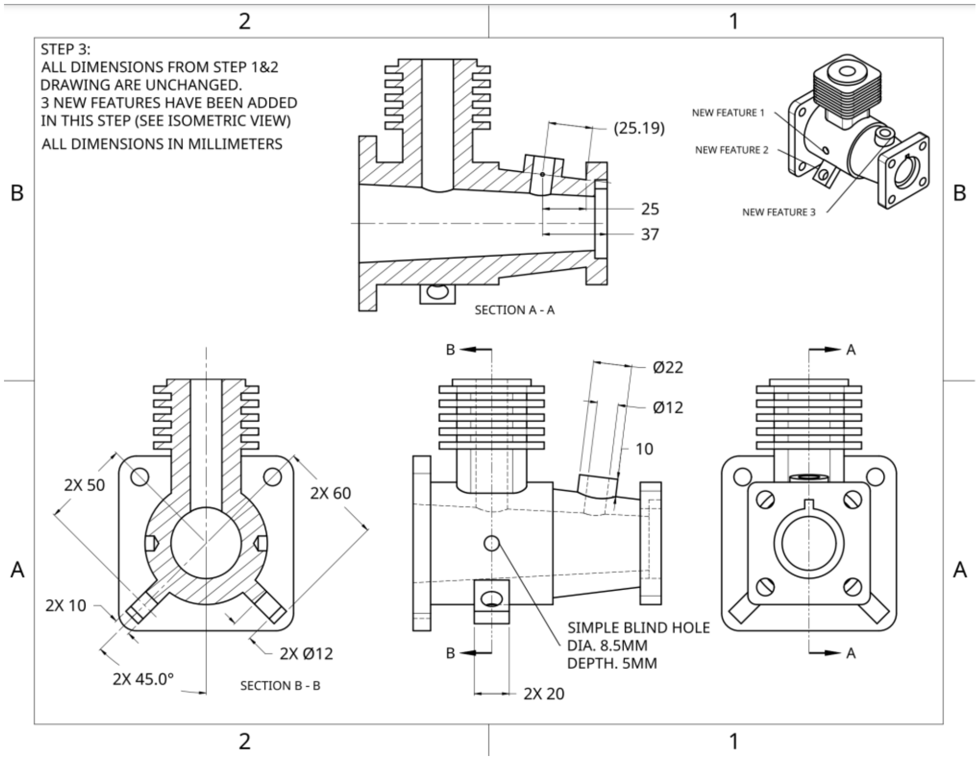
Appendix B.1 – 2D Drawing of Step 1 for the Participant CAD Task



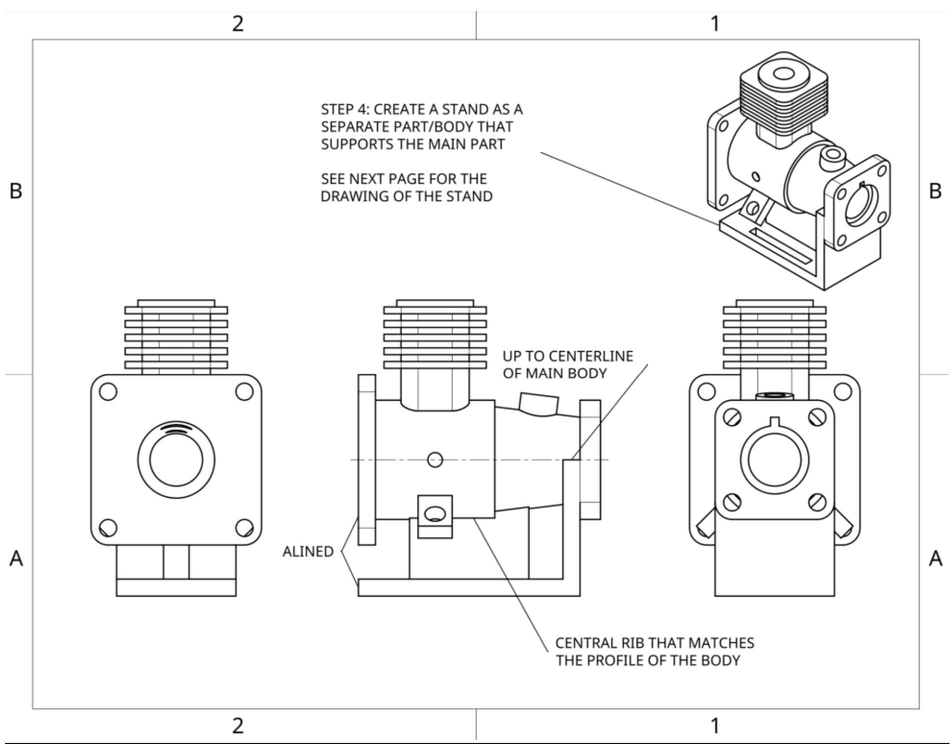

Appendix B.2 – 2D Drawing of Step 2 for the Participant CAD Task



Appendix B.3 – 2D Drawing of Step 3 for the Participant CAD Task

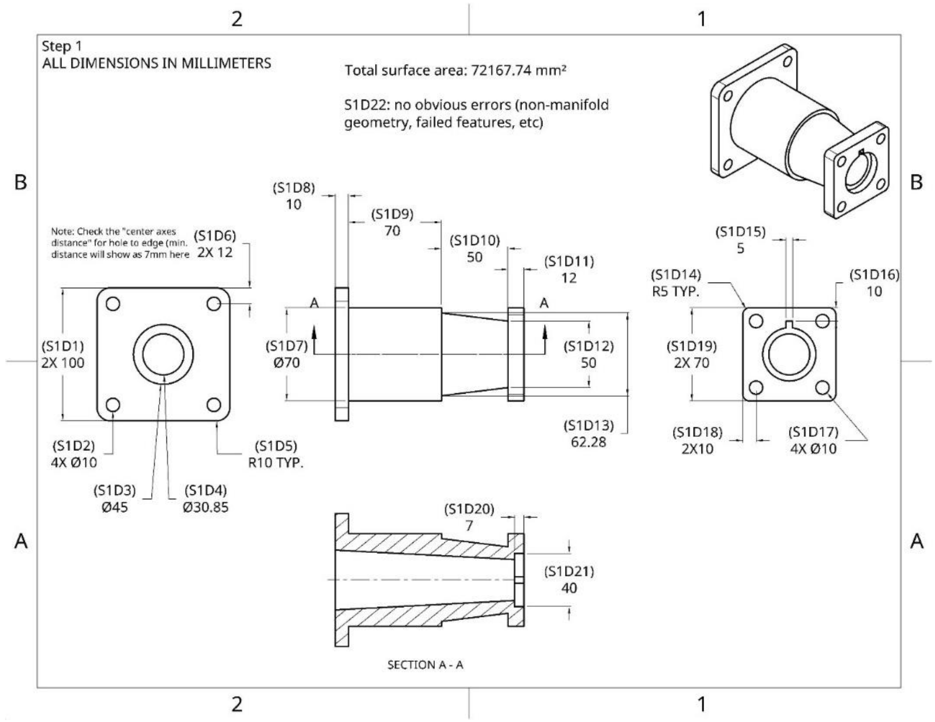



Appendix B.4 – 2D Drawing of Step 4 for the Participant CAD Task

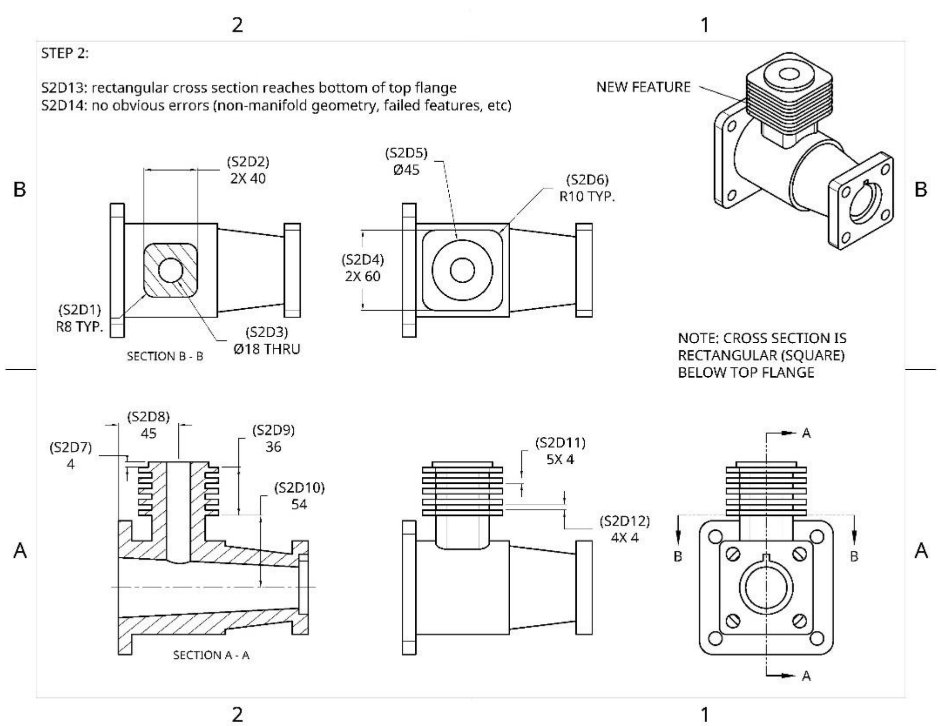


Appendix C – Grading Scheme for Participant CAD Task

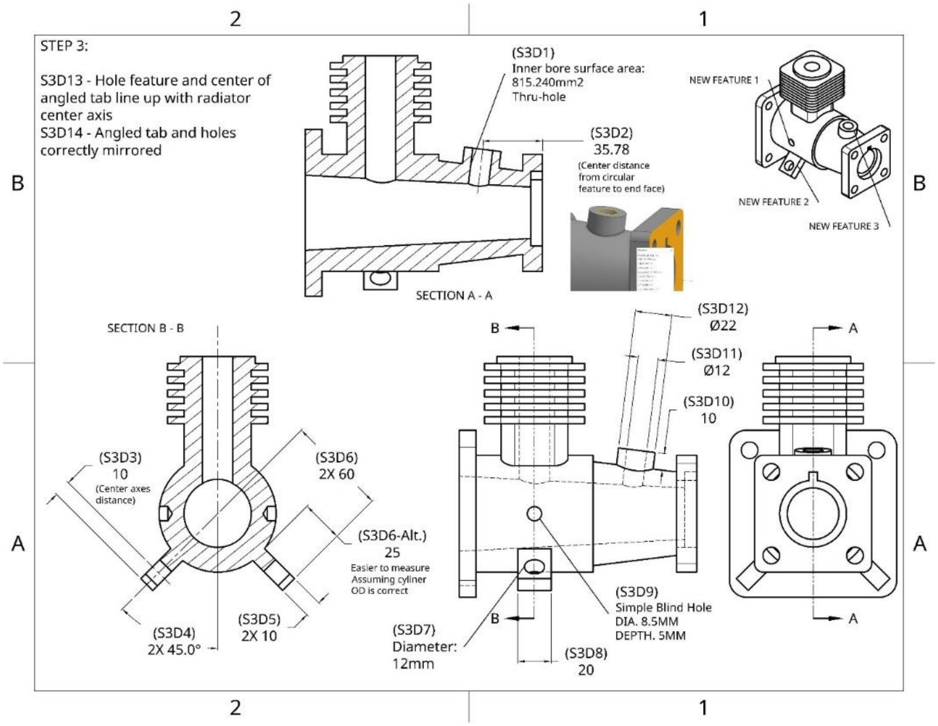
Appendix C.1 – Grading Scheme for Step 1 for the Participant CAD Task




Appendix C.2 – Grading Scheme for Step 2 for the Participant CAD Task



Appendix C.3 – Grading Scheme for Step 3 for the Participant CAD Task




Appendix C.4 – Grading Scheme for Step 4 for the Participant CAD Task