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A Comparative Analysis of Computer-Aided Collaborative Design Tools and Methods

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ABSTRACT

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Collaboration has always been critical to the success of new product development teams, and the advent of geographically dispersed teams has significantly altered the way that team members interact. Multi-user computer-aided design (MUCAD) and crowdsourcing are two results of efforts to enable collaboration between geographically dispersed individuals. In this research, a study was done to investigate the differences in performance between MUCAD and single-user CAD teams, in which teams competed to create the best model of a hand drill. This was done across a three-day period to recreate the scenario found in industry. It was found that MUCAD increases awareness of teammates' activities and increases communication between team members. Different sources of frustration for single-user and multi-user teams were identified, as well as differing patterns of modeling style. These findings demonstrate that MUCAD software has significant potential to improve team collaboration and performance. A second study explored a number of potentially significant factors in MUCAD team performance, including leadership, design style, unfamiliar parts, knowledge transfer, individual experience, and team composition. In this study, teams of undergraduate mechanical engineering students worked together to complete tasks using NXConnect, a MUCAD plugin for NX developed at Brigham Young University. A primary finding was that having an appointed leader for a MUCAD team improves performance, in particular when that leader works with the team in creating the CAD model. It was also found that creating a framework to aid in organizing and coordinating the creation of the CAD model may decrease the time required for completion. In the final study, the possibility of using crowdsourcing to complete complex product design tasks was explored. In this study, a process for crowdsourcing complex product design tasks was developed, as well as a website to act as the platform for testing this process. A crowd consisting of engineering and technology students then worked together on the website to design a frisbee tracking device. The crowd was able to collaborate to accomplish some detailed product design tasks, but was not able to develop a complete product. Major findings include the need for more formal leadership and crowd organization, the need for better decision making mechanisms, and the need for a better model for engaging crowd members on a consistent basis. It was also found that crowd members had a greater willingness to pay for the product they developed than individuals who had not worked on the project. Results also show that although crowd members were often frustrated with the collaboration process, they enjoyed being able to work with a large group of people on a complex project.

Keywords: Multi-user CAD, collaborative design, virtual teams, crowdsourcing

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NOMENCLATURE

CAD	Computer-aided Design
MUCAD	Multi-user Computer-aided Design
PSVT:R	Purdue Spatial Visualization Test - Visualization of Rotations
MU	Multi-user
SU	Single-user
UI	User Interface
IBR	Integrally Bladed Rotor

CHAPTER 1. INTRODUCTION

1.1 Problem Statement

Over the years, geographically dispersed design teams have become increasingly common. This phenomenon has many advantages, such as involvement of a wider range of expertise, better connections with new international markets, and lower development costs in comparison to companies who use traditional colocated teams [2]. However, the virtual interactions of team members present challenges in collaborating effectively, communicating, and establishing strong team relationships [2]. In order to enable these teams to succeed, new processes and tools are needed.

The current computer-aided design paradigm is one in which designers work individually on a part or assembly, which limits the potential for collaboration [3]. Geographically dispersed design teams need to find ways to create a more collaborative environment and enhance the sharing of design information [4–6]. This geographically dispersed design team paradigm has recently expanded to a new level with the advent of internet-based crowdsourcing, which brings together the contributions of hundreds or thousands of individuals from around the world.

This progression, from single-user design to multi-user design, and finally to crowdsourced design, can be represented by an expanding pyramid of design team scale as shown in Figure 1.1, where each successive level builds on the theories and techniques developed for previous levels. This is an increasing scale not only in the sense of greater numbers of people, but also in the complexity of interactions and the diversity of individuals involved. New approaches must be developed in order to capture the potential benefits of this expanding scale. Substantial research is needed to understand these different design team paradigms, and how the strategies, advantages, and disadvantages differ from one paradigm to another.

In response to the need for a more collaborative design environment, multi-user computer-aided design (CAD) software has been developed by researchers at BYU. Now that this tool, called NXConnect, has been developed and proven technically feasible, there exists a need to better un-

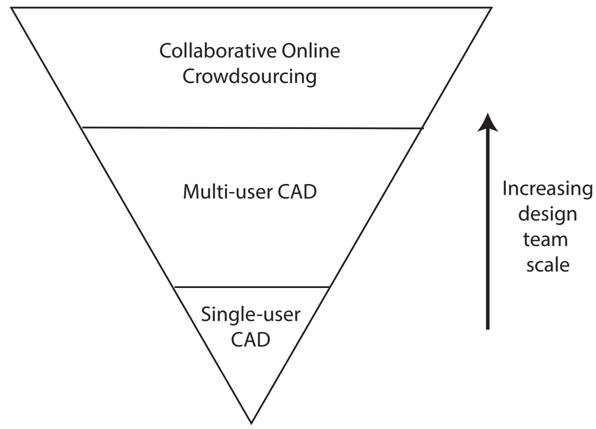


Figure 1.1: The increasing scale of product development teams

derstand the benefits and challenges of using this software, as well as the best practices for maximizing team performance within the software environment. Little is known about the differences in performance between design teams using traditional single-user software and teams using the new multi-user software, and as indicated by Lurey et al., simply having more advanced technology is not sufficient to make teams more effective. Teams also need effective processes and team dynamics in order to perform well [7]. Many questions also need to be answered regarding the organization and management of multi-user CAD teams. These include questions of leadership, design style, and team composition. Researching these topics will allow industry to make informed decisions about implementing multi-user CAD software.

Crowdsourcing, at the top level of the pyramid in Figure 1.1, has the potential to bring together hundreds of dispersed individuals into the design process, bringing people with diverse backgrounds and interests. Crowdsourcing has been used with great success in a number of areas, including scientific research and data collection [8, 9]. It has also been used for product development, which usually takes the form of a design competition in which the sponsor selects a winning design. Depending on the competition rules, designs are submitted either by individuals or by teams formed offline from individuals who choose to work together. However, little work has been done to develop effective methods for collaborative, crowdsourced product design. Great potential exists in combining the ideas and expertise of many different people to design new products. If a process can be developed to allow this to be done, then the benefits of geographically dispersed teams can be taken to a new level by involving the expertise and ideas of thousands, even those outside the organizational boundaries of a company, leading to greater innovation [10].

A number of crowdsourcing platforms have been created for developing new products. Each employs a slightly different method for engaging a crowd in the product development process; however, none of them have crowd members collaborate to complete subsystem engineering level tasks such as CAD, printed circuit board (PCB) design, or prototyping. As mentioned, many of them are based off of a competition-style rather than a collaborative approach. Although some platforms have capabilities for detailed product design, most focus on the concept generation and selection stage of the development process. The question remains, can the crowdsourcing community collaboratively design an entire product? The potential benefits of doing so include decreased development costs, higher-quality designs, and greater customer buy-in. In order to accomplish this, a process needs to be developed for decomposing, distributing and coordinating complex product design tasks so that they can be completed through small contributions of crowd members.

1.2 Summary of Research Objectives

Crowdsourcing and multi-user CAD, while distinct facets of technology-aided collaborative design, rely on many similar principles for effective implementation. This makes these topics ideal for studying in conjunction with each other. The overall objective of this thesis is to develop methods for improving collaborative engineering design and to understand the factors affecting performance of design teams in these collaborative settings. This thesis will first investigate the factors affecting the performance of multi-user CAD teams, then build on this base to explore the possibility of using crowdsourcing to involve dispersed individuals in the design process at a much larger scale. This will be accomplished through the following research objectives.

1. Determine the differences in performance between single-user CAD teams and multi-user CAD teams. The hypothesis for this objective is that team performance will improve when using multi-user instead of single-user CAD (Hypothesis 1).

2. Determine the effect of several factors on the performance of multi-user CAD teams. These factors are: leadership, design style, unfamiliar parts, knowledge transfer, individual experience, and team composition. The hypotheses to be explored for this objective are as follows:

- There will be a difference in performance between a team that self-organizes and a team that has a leader appointed (Hypothesis 2).
- Some design styles will be more effective in multi-user CAD than others (Hypothesis 3).
- Some design styles currently used in industry will not be conducive to working in a multi-user environment (Hypothesis 4).
- Multiple users in the same environment will be able to solve new or unfamiliar problems better than in isolation (Hypothesis 5).

3. Develop a process for decomposing, distributing, and coordinating detailed design tasks in a crowdsourced commmunity

4. Develop a process for iteratively obtaining market validation of a product design, and integrate this process with the detailed design process

5. Evaluate the quality of a crowdsourced product design created using the process developed by this research. The research hypotheses relating to this objective are:

   - Complex product design tasks can be successfully completed by the coordinated work of crowd members (Hypothesis 6)
   - A leader or leaders will emerge from among the crowd members (Hypothesis 7)
   - Crowd contribution patterns will be distinct from those observed on other crowdsourcing platforms (Hypothesis 8)
   - Contribution patterns will vary between crowd members, with some completing a significantly larger portion of the work (Hypothesis 9)
   - Crowd members will have awareness of other crowd members' activities similar to that of MUCAD team members (Hypothesis 10)

6. Verify the proposed benefits gained by using the new process for product development. The corresponding hypotheses are:

- Crowd members will be willing to pay more for the product than individuals who do not work on the project (Hypothesis 11)
- The product designed by the crowd will have a lower development cost than if the product were designed by professional designers (Hypothesis 12)

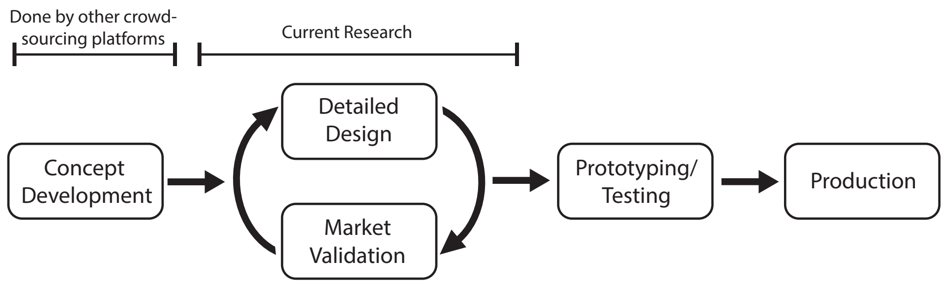


Figure 1.2: A simplified product development process, showing the focus of the current research

To completely develop a new product by crowdsourcing will require understanding how to crowdsource a series of development stages, including concept development, detailed design, prototyping and testing, market validation, and production. While many of these stages could likely be crowdsourced, the focus of this research is on the stages mentioned above, as shown in Figure 1.2.

Objective 1 will be discussed in Chapter 3, Objective 2 will be discussed in Chapter 4, and Objectives 3-6 will be discussed in Chapter 5. A discussion of the crossover between the findings from Chapters 3-5 will be presented in Chapter 6, along with the conclusions of the research. Background for all subjects covered will be discussed in Chapter 2.

CHAPTER 2. BACKGROUND

2.1 Multi-user Computer-Aided Design

Multi-user computer-aided design (MUCAD) is a tool that allows individuals to collaborate on the creation of CAD models. Users can simultaneously modify the same CAD model from different computers and see each others' updates in real time. Potential benefits of this software include decreased calendar time for creating CAD models, increased ease of identifying errors, enhanced collaboration for non-collocated teams, and involvement of multiple stakeholders in the design process [11].

In contrast, current practices with computer-aided design in industry are inherently single-user in nature. CAD, CAM, and other CAE applications are set up to allow one person at a time to work on a particular part or assembly. The editing permissions for these parts are controlled through the use of Product Lifecycle Management (PLM) software such as Teamcenter, which allows one person at a time to check out and work on a particular part. Because of the non-collaborative nature of these design tools, a variety of non-engineering communication tools (such as email, screen share, and video conference) are commonly used in industry to achieve the collaboration necessary for modern new product development [12].

These limitations in current computer-aided design applications have led to the research and development of a number of multi-user alternatives both at universities and at companies such as Onshape [13] and Autodesk [14]. Over the past several years, researchers in the BYU CAD Lab have developed NXConnect, a multi-user CAD plugin for NX [11, 15]. As the software has been developed, studies have been conducted in an attempt to better understand the benefits of this software as well as how to best utilize it [16, 17]. Stone et al. studied the performance of three-person teams that completed a 25 minute design task using NXConnect (Figure 2.1). They found that NXConnect does decrease calendar time required to complete CAD models as compared to individuals working in traditional CAD software, and also identified a number of other topics for

Figure 2.1: MUCAD teams using NXConnect for the study by Stone et al. [1]

future research, including comparing teams of single-users to MUCAD teams, analyzing collaboration patterns such as communication, and investigating the most effective methods for modeling in a MUCAD environment [1].

Another exploratory test with MUCAD involved two teams, one using MUCAD and the other using single-user CAD, working separately to design an escape pod. In this experiment, the team using MUCAD experienced fewer turn backs, designed better interfaces, and created a more detailed model than the team using single-user CAD. Although these results seem to indicate that MUCAD software increases productivity and model quality, additional repetitions are needed to identify if these differences were primarily due to the difference in CAD software or some other factor.

An important part of past studies involving MUCAD has been evaluating the CAD skill level of participants. The Purdue Spatial Visualization Test - Visualization of Rotations (PSVT:R), created by Guay in the 1970s [18] has been used for this evaluation. This test examines ones ability to mentally rotate geometric figures and determine their orientation. Scores on the test have been shown to be highly positively correlated with success in learning and using CAD software [19–21]. Use of a new, revised version of the PSVT:R is administered by Dr. Yoon of Texas A&M, who has validated the tests psychometric properties [22].

2.2 Virtual Teams

A virtual team is one in which team members' interactions are mediated by time, distance, and technology [23]. Based on these criteria, multi-user CAD teams can be considered virtual teams. Although crowdsourcing generally involves more people than can be considered a team, crowds have several important similarities to virtual teams. These include the use of communication technology, non-collocated members, and asynchronous work. The shift towards the use of virtual teams has dramatically impacted the way companies function. This shift is due to a number of factors including globalization of the marketplace, mergers and acquisitions, and competition [7]. With this change comes the need to understand whether traditional team dynamics and strategies hold true or if new techniques and tools are needed. Substantial research has been done on various factors affecting virtual teams, including leadership emergence, creativity, knowledge management, diversity, and awareness. This research is discussed in the following paragraphs.

Leadership emergence in teams is one area that has been studied extensively [24–26]. It has been found that when no leader is appointed, one will generally emerge, although this may be based on characteristics that are unrelated to effectiveness [23]. A study of leader emergence in virtual teams found that factors affecting leader selection include trust of team members, power distance of culture compared to that of other team members, and perception by team members of performance [27]. Charlier et al. also found that in virtual teams, individuals who communicate more frequently are more likely to be perceived as leaders by their teammates [24].

Research has shown that in cases where creativity is needed and ideas need to be generated, virtual teams can be more effective than traditional teams. It has been found that traditional teams where members interact verbally produce fewer ideas than nominal groups, where individuals work in isolation and then pool their ideas. However, in a virtual team setting where individuals can interact and see the ideas of others while generating their own, the idea generation outperforms even that of nominal groups. This is in part due to the collaboration technology minimizing production blocking, allowing team members to contribute ideas simultaneously while receiving stimulus from the ideas of others . Levi also states that as the size of a virtual team increases, the number of creative ideas actually increases rather than being reduced, as is the case in traditional teams [23, 28, 29].

Knowledge management has become an important part of product development as more and more design teams become geographically dispersed. Providing designers with appropriate and sufficient knowledge is essential for product success [30]. Regli et al. discussed the need for a new generation of product development software tools that will enable the effective exchange of design information between all partners in the development process [31]. Argote and Ingram present research showing that effective methods for knowledge transfer can create competitive advantage for firms, and that organization members as well as software tools are important reservoirs of knowledge [32].

Diversity in teams can be beneficial or detrimental depending on the type of diversity and the task being accomplished. Deep-level diversity (knowledge, abilities, skills) tends to have a positive effect, especially in cases where problem solving and creativity are required [23]. In fact, this is one of the strategic reasons for using virtual teams, as they allow for a much more diverse group of people to be involved in a project. However, Hertel et al. point out that in virtual teams, restricted communication opportunities may increase misunderstandings, limiting the constructive use of diversity [33].

Improved situation awareness and awareness of teammates' activities has been shown in multiple areas to positively impact team performance [34]. Software development, which bears some similarities to multi-user CAD in that simultaneous work is being done by multiple people on the same project, requires shared task knowledge for effective coordination [35]. In the context of an operating room, a study by Parush et al. showed that information loss during communication could be reduced through an augmentative display, improving team situation awareness [36]. In both cases, computer technology was able to improve team awareness.

2.3 Crowdsourcing

Crowdsourcing has been defined as "the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and generally large) network of people in the form of an open call" [37]. This process has been shown to be beneficial both by academic research and implementation in industry [38–40]. Crowdsourcing has been applied in many areas from scientific research to graphic design, and has successfully been used for new product development [41, 42].

Examples of crowdsourcing applications abound in these and other areas. Foldit, in the realm of scientific research, is a multi-player online game that has been used to predict protein structures more effectively than computational algorithms alone [8]. Litterati, an app for mapping litter in cities [], and Waze, a navigation app using community-provided traffic and route details [], are both examples of crowdsourced data collection. Zooniverse is one example of crowdsourced data processing. This website hosts many projects that require human analysis of millions of photos to classify features such as galaxy shapes, a task that would be infeasible for a small group of researchers [43]. Companies have also used crowdsourcing to bring new ideas into their innovation processes. IBM's Innovation Jam is one example of this, in which tens of thousands of IBM employees, clients, and partners were involved over the course of 72 hours in an online debate about new business opportunities [44].

The feasibility of using a crowd to match the results of experts has been explored in a number of studies. Rosenberg showed that the collective intelligence of a random group of 75 sports fans was able to out-perform experts in predicting outcomes of College Bowl football games [45]. A study by Staffelbach et al. used crowd members to analyze wind simulation data. They found that with a sufficiently comprehensive tutorial, crowd members were able to complete these tasks with a competence comparable to that of graduate students with expert-level knowledge. While recognizing that crowds can not entirely replace trained experts, they showed that crowd workers can be used to complete preliminary analysis of complex data [46]. The value of crowds in idea generation has also been explored in a study by Poetz and Schreier. They conducted a contest where crowd members and professionals generated new product ideas. After company executives evaluated the ideas, without knowing who created them, it was found that crowd members' ideas scored significantly higher in terms of novelty and customer benefit than those of the professionals [42].

The challenges and benefits of using crowdsourcing in complex projects have been explored both by academia and industry. A number of articles discuss the challenge of decomposing complex tasks so that they can be completed by crowdsourcing. Grace et al. explain that crowdsourcing creative design tasks is difficult because these tasks are not easily decomposable, and that a better understanding of how to distribute dynamic and irreducible tasks to a crowd is needed [47]. Kittur et al. address the general issue of decomposing complex and interdependent tasks, developing a method for doing so and showing how it can be used for writing an article and researching a purchase [48]. This method consists of three steps (partition, map, and reduce), where larger tasks are first broken down into subtasks, tasks are completed by workers, and then the results are merged into a single output. The method discussed in this article has the potential to be applied to product development crowdsourcing which consists of complex and creative tasks, though this is not the focus of their research.

2.3.1 Product Development in Crowdsourcing

As mentioned previously, a number of crowdsourcing platforms for product development exist. Quirky.com is a website where people can submit an idea for a product, and then receive input on their idea from other users. If the idea is selected by the Quirky employees, the design work and production will be completed by the company. The community is involved only in the concept generation and selection stages of the development process. CrowdSpring.com is another platform that crowdsources a variety of design projects, including logo design, graphic design, and product design. However, this platform uses a competition approach in which many individuals create and submit their own designs. The best design is selected by the sponsor and prize money is awarded to the winning designer. CADCrowd.com uses the same approach, but focuses on creating CAD models and renderings.

The development of the Fiat Mio is an impressive example of crowdsourced design discussed by Saldanha et al. This project by Fiat Brazil involved more than 17,000 volunteer participants in the concept development of a new car. Based on their analysis of the process used by Fiat, Saldanha et al. proposed a new approach to crowdsourcing called "the accordian model." This model proposes that the crowd be involved throughout the design process through a series of opening and closing periods, in which the crowd responds to a challenge, their responses are synthesized by an expert design team, and then new materials based on this synthesis are presented to the crowd for another stage of input [49]. Though extremely effective at obtaining input, this approach was limited in that the only tasks that participants engaged in were answering questions about their preferences or rating different concepts. The bulk of the design work was again done by the expert design team.

Mladenow et al. explored ways in which crowdsourcing communities can be integrated into the new product development process, showing that they can be integrated into any stage of the process, including idea generation, conceptualizing, design and engineering, and testing. This is only explored theoretically, however, referencing existing crowdsourcing platforms that incorporate some aspect of these design stages. Detailed methods for crowdsourcing new product development are not discussed. Mladenow et al. emphasize that more in-depth research needs to be done into how companies can integrate crowds into their product development processes. There are a number of benefits of doing so, including elevating market acceptance or customer buy-in of new products. People tend to be more satisfied with products that they help design themselves, and the quality of products designed by customers are comparable to those suggested by experts [50].

From these industry examples and academic research, it can be seen that crowdsourcing has potential for enhancing certain aspects of product design. Further work is needed to extend existing theories to product design, and to expand the extent to which the design of a new product can be crowdsourced. A number of factors need to be addressed in order for work to successfully be done in a collaborative, crowdsourced design setting. These include decomposing and assigning tasks, making decisions, and coordinating efforts. Research done on these factors outside of product design can shed light on processes that may work in a product design setting.

Decomposing and assigning tasks effectively is essential for a large project to be completed by many crowd members. In their research on using Amazon Mechanical Turk (an online crowdsourcing marketplace) to accomplish this decomposition, Kulkarni et al. found that having crowd members decompose the tasks and create workflows does not usually work well unless expert workers are used or the requester is able to monitor and intervene in the process. The system that they developed, Turkomatic, is based on a price-divide-solve algorithm where workers subdivide tasks until they are small enough to be solved [51].

A recent study by Valentine et al. [52] demonstrated a concept called "flash organizations." This is a method of organizing crowd members into an organizational structure with specific roles. The study shows that crowds need to be able to define new tasks as needed in order to be successful. Unlike past attempts where the tasks and workflow are set from the beginning, this approach allows the crowd to rapidly adapt as the need for new tasks arises. Doing so allows the crowd to complete much more complex and interactive projects than would otherwise be possible.

Schmidt et al. [53] investigated the effectiveness of decision making in new product development, comparing individuals, face-to-face teams, and virtual teams. For the virtual teams, they used a discussion database where team members created threaded conversations about the advantages and disadvantages of different options before making a decision on whether or not to proceed with the development of the product. The study found that virtual teams made more effective decisions than either face-to-face teams or individuals, which may be due to the technology-mediated interactions allowing for more objective decision making. It is possible that crowds could similarly make more effective decisions that face-to-face teams or individuals due to the similarities they share with virtual teams.

Coordinating efforts can prove to be a major challenge for geographically dispersed crowd members collaborating online. One solution to this issue was explored by Klein et al. [54], where they created subdivided networks by dividing the design into subsystems with predefined standardized interfaces, so that subsystem changes can be made with few consequences for the design of other subsystems.

CHAPTER 3. COMPARING PERFORMANCE IN MUCAD AND SINGLE-USER CAD TEAMS

For the past several years, the BYU CAD Lab has been developing collaborative computer-aided design (CAD) software. As this software is being developed, industry seeks to better understand the differences in performance between teams using multi-user CAD and single-user CAD to make informed decisions about implementing this new software into their engineering processes. In order to better understand the differences in performance between teams, an experimental study was conducted in which four multi-user teams and four single-user teams competed to create the best model of a hand drill.

3.1 Methods

This study was setup to simulate virtual teams found in industry. Industrial virtual teams often have limited contact with each other due to large distances, multiple projects, or time zone differences. The study strove to simulate some of these conditions by requiring team members to collaborate together on a three day project physically distributed from one another, communicating only through audio or text. Team members in general were not familiar with members of their team, contributing to the sense of team members being from separate locations, time zones and even cultures. Figure 3.1 is an example of the schedule participants would have experienced over the simulated industrial projects period of performance. Although the schedule permitted multiple teams competing during the same week, they were never working at the same time (i.e. morning or afternoon teams). A description of the participants involved is given in Section 3.1.3 below.

On the first of three days all participants were given identical team training on single-user NX 8 CAD software, used in the study via a recorded video training. The 11 minute video addressed several basic functions of the NX 8 software. If the team being trained was designated as "multi-user" they would receive additional training specific to NXConnect (the MUCAD software

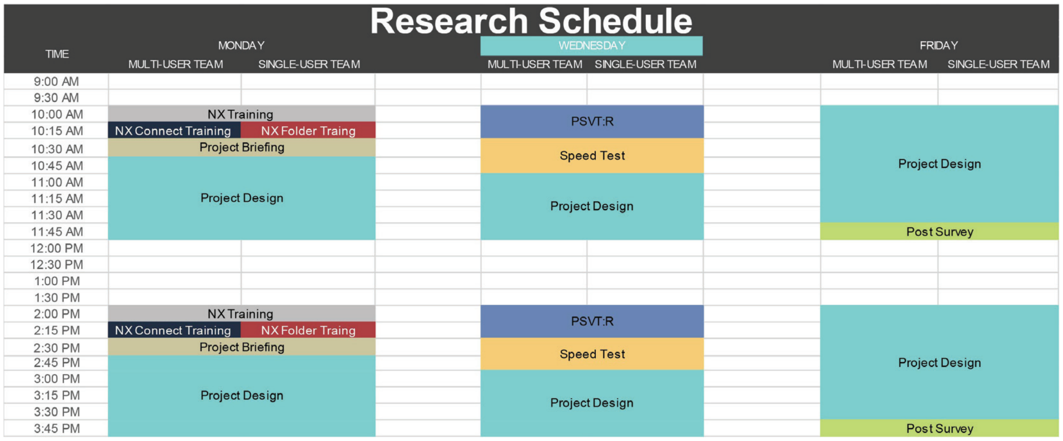


Figure 3.1: Typical study setup for a given week

they would be using). This MUCAD video was 9 minutes long and gave two brief examples of how teams may use NXConnect and troubleshoot problems likely to occur while modeling. Teams designated as “single-user” were given information on how to access the email server for transferring files. At the end of the training, all teams were given an identical 15 minute project briefing. During this briefing each team was asked to design a hand drill in the CAD software they were assigned (NXConnect for multi-user and NX 8 for single-user). Each team member was given a hard copy of instructions for mirroring halves of the drill handle, as well as pictures of different drills, with one drill showing an exploded view and listing all of its parts. Each team member was also given a rubric, which they were to use as a guide in their design.

After the training, proctors guided participants to assigned seats where they were tasked to design a drill with their team beyond physical sight and hearing of each other. Each team member was placed in a different portion of the lab where other projects in the lab continued on as normal. Proctors were instructed to record observations, address software challenges, and refrain from giving design help. The one exception was that proctors could assist in mirroring the handle of the drill by using a detailed set of instructions (which were given to participants during the training). After an hour and ten minutes of modeling participants were asked to stop modeling. Proctors then saved all progress and reset the computers for the next team.

On the second day the team was given the first hour to complete two tests individually. Each participant was asked to take thirty minutes or less to complete a PSVT:R test, and thirty minutes or less to complete a speed modeling test. In between these tests, team members were asked to wait for their teammates to finish before moving on. Both tests were also completed at participants assigned seats away from teammates and were to be done on their own. After the entire team had completed the two tests they were given thirty minutes to continue modeling the drill. At the end of the thirty minutes proctors again asked participants to stop modeling, saving the progress as participants left.

On the last of the three days, team members were given one hour and fifty minutes to model with a five minute break half way through. Proctors had participants return to assigned seats taking careful notes as the team modeled. After an hour and fifty-five minutes proctors asked participants to stop modeling. Each team member was asked to follow a link to fill out a final survey about their experience and to a form that allowed the lab to reimburse them for their time. The following subsections discuss further details of how the study was carried out and techniques applied to mitigate bias from the study.

3.1.1 Judging

The screen shots from the final models were put into a standard three page format for each team and given to a panel of judges. The judges were university engineering faculty and staff with significant CAD modeling and product design experience. Each team's model was represented by a sheet with each component modeled, the most current assembly of the model, and the two sides of the drill handle. An example of the components sheet given to the judges is shown in Figure 3.2. Judges were not given information regarding who was on which team, or if a team was multi-user or single-user. The judges rated each model based on the same rubric given to competing teams on the first day (see Appendix D). Judge ratings were averaged and used to compare different teams.

3.1.2 Software

This study used NX 8 CAD software produced by Siemens, a company previously known as Unigraphics. This study also used NXConnect, research software that has been recently developed at the BYU Site in the NSF Center for e-Design. At the time of this study, the currently version of NXConnect had some deactivated features.

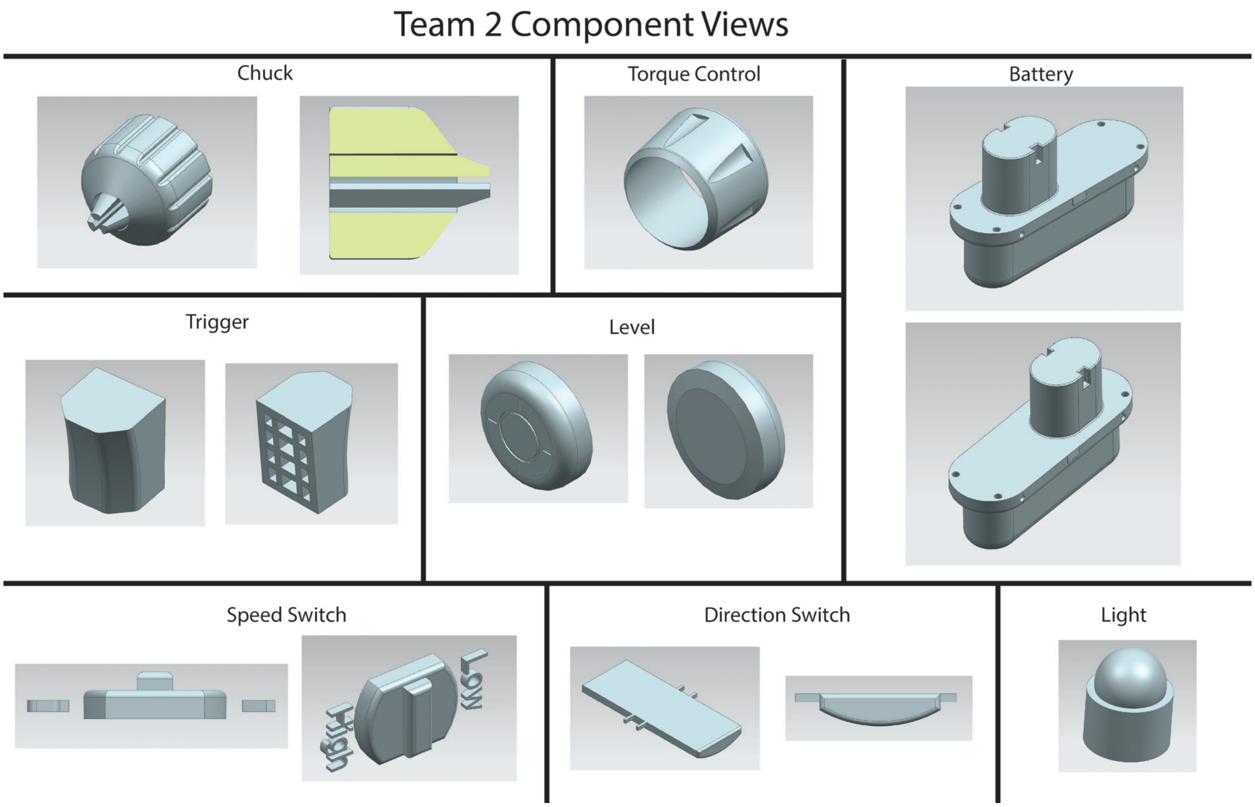


Figure 3.2: Example of material presented to judges from a single team

To help keep performance comparable between NXConnect and single-user NX 8, a handicap was placed on single-user NX 8. This handicap simply deactivated and grayed out all of the buttons that were not supported by NXConnect. Deactivated buttons in NXConnect were also grayed out. Despite software glitches that occurred, the limitation generally prevented any participant from using a feature not available to any other participant.

Multi-user and single-user teams both were allowed to use Skype. Only the single-user teams were allowed to use Gmail, encouraging multi-user teams to use NXConnect to share files.

3.1.3 Data Collection

We recorded comprehensive data through video and audio of facial expressions, modeling styles, and team chats. Because of the nature of this type of data we obtained IRB approval (Institutional Review Board) and had participants sign an approved consent form at the beginning of the study. This form gave a brief review of the study layout, the purpose of the study, how personal data would be kept confidential, and IRB contact information. Personally identifying data collected came in the form of video, audio, and survey data.

Video

Video was recorded of each team member from a Webcam mounted to the screen of each computer used during the study. Screen capture software also recorded the screens of each computer. Video was recorded while participants were modeling. During the recording, proctors would indicate the start and stop times of the video either by a verbal signal or by blanking the screen. This video data allowed us to study modeling methods, potential software issues, nonverbal forms of communication, team dynamics, and participant involvement.

Audio Data

Audio data was primarily recorded via a microphone in each participants headset. The headset mics filtered out most background noise making it easier to distinguish which team member was speaking. Secondary audio data came from each computers webcam. This data was used when the headset mic was muted, unused, or not recorded. The secondary audio did not filter as well as the headset mic and so picked up a lot of background noise. Audio data was used in studying team communication. By listening to the team as a whole we could approximate planning session lengths and identify team strategies.

Survey Data

Two surveys assisted in better comparing teams performance. The first survey was focused on finding the skill level and availability of potential participants. The survey asked questions such as:

- "How familiar are you with NX?"
- "Have you taken ME EN 471 or an equivalent advanced CAD course?"
- "Can you dedicate 6 hours (in three two-hour blocks) to participate in this study?"

This survey was used to filter candidates and organize them into feasible teams. Preference was given to those who had experience with NX, and questions regarding CAD experience were used to organize participants into balanced teams. The question "How familiar are you with NX," as well as the question "Have you taken ME EN 471 or an equivalent advanced CAD course?" were used to determine the level of experience that potential participants had with CAD software in general, as well as NX specifically. This information was used by the researchers to ensure that all teams were of comparable skill level. A discussion of the effectiveness of using this survey for creating teams of comparable skill level occurs in later sections of this paper. The second survey was filled out by participants who completed the study. This survey asked questions about team member experience with the study, their familiarity with other teammates, and how they felt their team performed. Some examples of these questions include:

- "What about the collaboration process was frustrating, if anything?"
- "How well did you know Team Member A before the competition?"
- "In thinking about your team as a whole, how would you rate your team in the following categories? [NX modeling skill]"

Data from this survey was used in evaluating several research questions. Overall, it gave us insight into the minds of teammates above and beyond what we could glean from the video and audio data.

Participants

Participants were solicited via posters, fliers, and announcements in various engineering classes. Incentives in the form of prizes and compensation were also advertised. Most applicants had stated they had taken an introductory course in CAD and have had additional experience with CAD modeling. The proctors found that most of the participants were engineering students. All accepted participants were compensated the same if they were in attendance for their entire project. To incentivize high performance, teams received additional rewards if they performed better than the others. However, some participants may have been motivated to come for the monetary compensation for participation only, and may have not been interested in the physical prize. This lack of interest in a prize could result in a decreased motivation to perform well, which would introduce a confounding factor although an assumption is made that this impacted all teams equally.

Those who wanted to participate in the study completed an online survey that included an availability calendar. After applicant schedules were filtered, four person teams were then manually selected. This was done using estimated team skill levels from survey responses to create a list of teams with relatively similar skill levels. Teams were further organized so that no one person participated more than once. In most cases, we successfully avoided putting participants with significant past NXConnect experience on multi-user teams as it would give such teams an unfair advantage when competing against other multi-user teams. As discussed later the methods for organizing teams could be improved in future studies.

3.2 Results

3.2.1 Team Performance

A major motivation for this study was to better understand how performance varies between teams using multi-user CAD and single-user CAD, as measured by model quality and productivity. General team performance is expected to be higher when using multi-user instead of single-user CAD. The average score of each team is shown in Table 3.1. The completed CAD models for each team can be seen in Figure 3.3, shown in order of decreasing score and separated into multi-user (on the bottom) and single-user teams (on the top). To evaluate performance as measured by the judges scores, a multiple regression using model effects of average team speed test score, minutes lost due to bugs, and team type (i.e. single-user vs multi-user). By doing this, we hoped to compensate for skill level differences between teams and bugs caused by the beta software NXConnect. The results for the team level comparisons did not give statistically significant results, and thus the performance improvement when using MUCAD is inconclusive. At least two factors limited this significance. The relatively small sample size (eight teams) impacted the results but another factor that may have caused problems was the teams being unbalanced in skill level. Some teams had a much higher skill level as determined by speed test scores, making it difficult to directly compare the model quality between teams. More details about findings regarding skill level are discussed later in the Skill Level Prediction section.

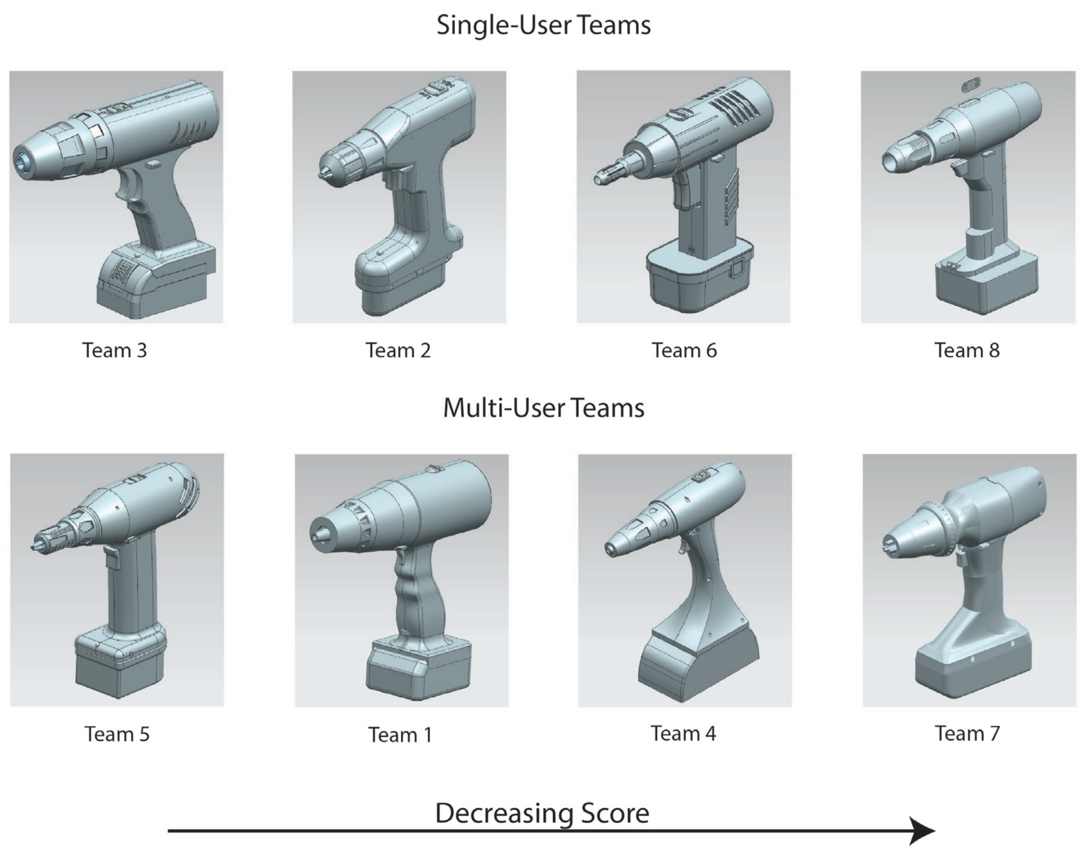


Figure 3.3: Assembly views of all teams completed models

Table 3.1: Average Judges' Scores

MU/SU	Average Score	Team ID
SU	95.3	3
SU	78.3	2
SU	74.7	6
SU	65	8
MU	87.3	5
MU	78.3	1
MU	70	4
MU	66.3	7

Although significant results for performance based on judges scores were not found, other observations and statistical analyses were made that can be used as metrics to compare performance between multi-user and single-user teams. These provide insight into some of the benefits that can be gained through using MUCAD software. The remainder of this paper will discuss these observations and analyses, which include user experience, awareness, communication, skill level prediction, and UI Analytics.

3.2.2 User Experience

Each team was expected to have a different experience based on whether the team was assigned multi-user or single-user software. Because MUCAD software allows for an increase in collaboration, we expected MUCAD teams to become more familiar with their teammates than single-user teams. In order to collect this data, each participant was asked to rank their familiarity with each of their teammates on a scale of familiarity from 0 to 4 (where 0 corresponded to none or very low familiarity and 4 corresponded to very high familiarity). This question was asked in reference to the participants familiarity before the experiment and after the experiment. By taking the difference between each participants responses, we were able to analyze the data using a two-sample t-test. Statistically significant evidence was found that through the experience multi-user teams were 0.33 more familiar with their teammates than single-user teams. (MU-SU = 0.33 on a scale from 0 to 4; p-value of 0.0008).

Due to the opportunity for enhanced collaboration, the hypothesis was made that multi-user teams would be more satisfied with their team than single-user teams. In order to measure the user experience, a post-survey question was asked that stated, “Overall, how satisfied were you with your team?” Participants could then rate their satisfaction on a scale from 0 to 4. However, a two-sample t-test analysis found no statistically significant evidence that multi-user teams were more satisfied than single-user teams (MU-SU = -0.067 on a scale from 0 to 4; p-value of 0.60). A larger sample size of teams would be required to extract significance and reject the associated null hypothesis.

In addition to team satisfaction, team frustration data was also collected. In order to measure the user experience, a post-survey question was asked that stated, “How frustrated were you with the collaboration process?” Participants could then rate their frustration on a scale from 0

Table 3.2: Percent of total frustration caused by different categories

Category	Percent of Total Frustration		
	Multi-user	Single-user	Combined
Communication	11	44	55
Software Bugs	19	4	23
Inexperience	4	7	11
Team Members	7	0	7
Software Limitations	0	4	4

to 4. Analyses found no statistically significant evidence suggesting multi-user teams were less frustrated with the collaboration process than single-user teams (MU-SU = 0.53 on a scale from 0 to 4; p-value of 0.097).

A second post-survey question was then asked, "What about the collaboration process was frustrating?" This question was designed to better target the source of frustration for virtual MU-CAD teams. The responses were then placed into six main categories. Table 3.2 shows the percent of the total frustration caused by each category and shows that multi-user and single-user teams experienced frustration for very different reasons.

Interestingly, single-user team members had four times more communication-based frustration than multi-user team members. Single-user team members expressed that frustration was due specifically to communication dealing with component interfaces and the communication of dimensions. Multi-user team members expressed specific frustration with being unable to have an initial non-virtual planning session. This response is consistent with the literature on virtual teams, which recommends that virtual teams have a face-to-face kick-off meeting [13]. Of the 11% frustration due to communication in the multi-user teams, there were no complaints about communication within the virtual environment (i.e. it was regarding other communication media).

During the course of the study, the multi-user teams experienced a number of software bugs. 19% of the total frustration was due to the experimental beta software. In particular, participants reported specific frustration due to "random" work deletion and previous modeling state reversion. Some frustration was expected in this particular area. Although the beta software has many advantages, the current state of the software is limited as described previously. These limitations include deletion, state reversions, and system freezing. As MUCAD is further developed, these limitations may be resolved.

Frustration with team members, expressed by multi-user team members, contributed to 7% of the total frustration. An explanation for this could be that although both multi-user and single-user software required team cooperation, the multi-user environment required a more close-knit collaboration. With a required increase in the level of collaboration, frustration with team members likely arose due to increased expectations. The multi-user teams were continuously aware of the state of every component, and when those did not meet their own expectations, individuals expressed frustration.

On the other hand, single-user team members expressed frustration due to NX software limitations. As expected, team members felt that they were unaware of other teammates progress due to the nature of the single-user environment. There were no complaints on software limitations from the multi-user team members.

An analysis of satisfaction with the collaboration processes between multi-user teams and single-user teams was also performed. Each team member was asked "How much did you enjoy the collaboration process?" The data suggests that multi-user teams were generally more satisfied with the way in which they were able to communicate throughout the study over those users who used single-user CAD (MU-SU = 0.8895 on a scale from 0 to 4).

3.2.3 Awareness

Physical separation of teammates during this study meant that all communication about each teammates work was digital. Participants were not allowed to collaborate in person at any point. It was hypothesized that MUCAD, with its capability of allowing all users to see and work on a part simultaneously, would increase awareness of teammates activities.

A two-sample t-test was done comparing the responses of multi-user and single-user participants to the question "Overall, how aware were you of your teammates activities throughout the project?" This test showed that on a 0 to 4 scale, MUCAD teammates rated their awareness of their teammates activities 1.13 points higher than single-user teammates with a p-value of 0.0008. This result is summarized in Figure 3.4. This increased awareness proved to be beneficial because it reduced extra work needed to fix problems with part interfaces and allowed all users to better understand the current state of the model. Although this increased awareness did not directly correlate with the performance differences (which was not significant described previously), there are

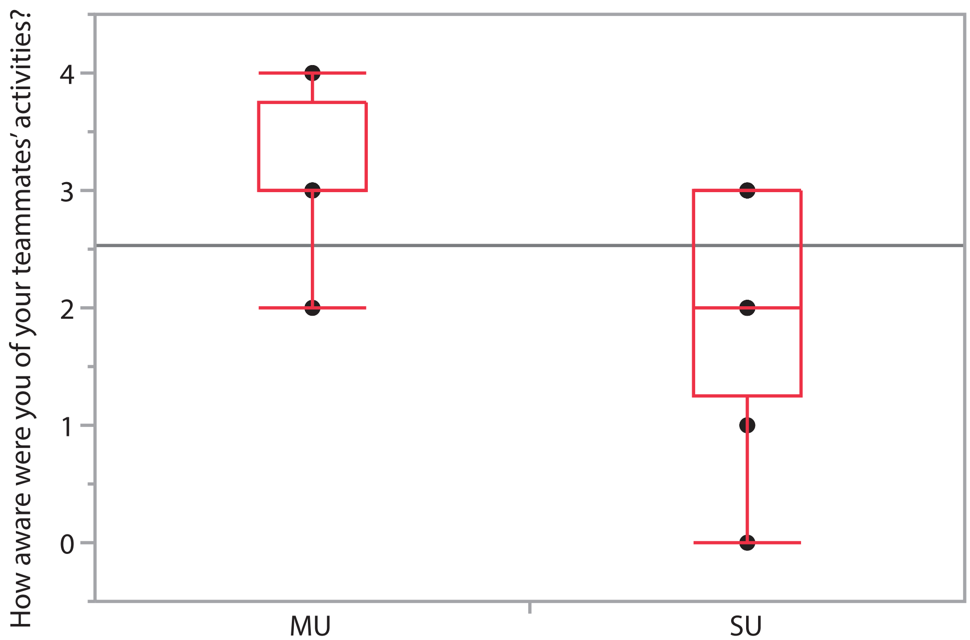


Figure 3.4: Plot showing quantiles for multi-user and single-user team awareness

some interesting case studies that show ways which MUCAD, when used properly, could enhance the collaboration process.

Interface Awareness

On single-user teams, teammates modeled individual parts and then sent them to one teammate who assembled the parts. Sometimes when the parts were assembled it was found that parts did not interface correctly and had to be modified, wasting design time. Two case studies, one from a multi-user team and one from a single-user team, help illustrate the benefits of increased interface awareness. In both cases, the handle and the battery were modeled by different team members. The battery needs to be able to fit into the base of the handle, and poor design of the two parts could result in interference or a poor fit.

In Team 2 (single-user), difficulties occurred with the battery/handle interface. One teammate was modeling the handle, while another teammate was modeling the battery. When the two parts were put together in the assembly, the battery did not properly match up with the base of the

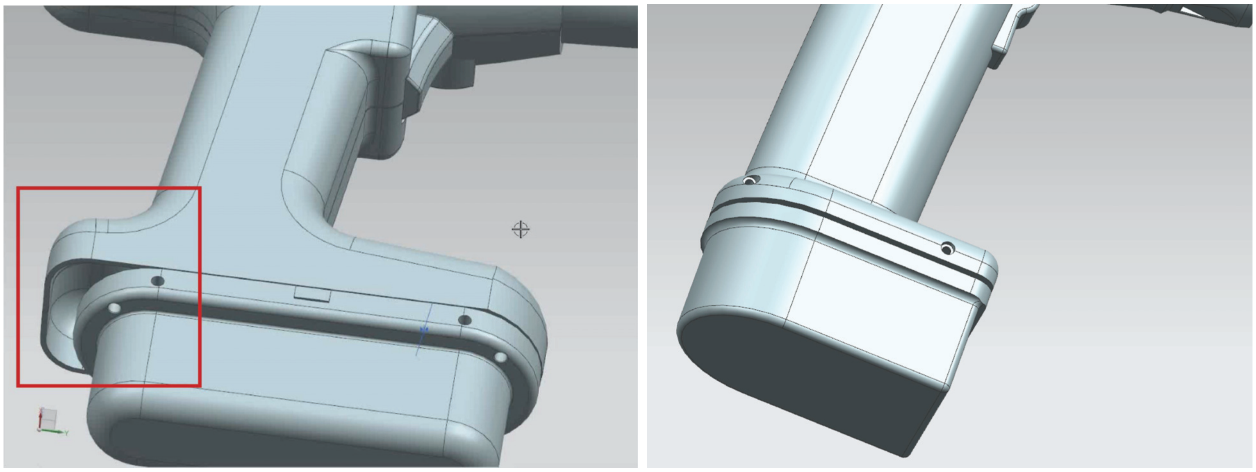


Figure 3.5: Battery-handle interfaces for two teams, Team 2 (single-user left) and Team 5 (multi-user right)

drill handle, leaving the gap marked by the box in Figure 3.5. Although an attempt was made to modify the battery, the team was unable to complete this in time.

In Team 5 (multi-user), two different teammates also worked on the handle and the battery. However, each person was able to see the other teammates part as they were working to assure that the interface dimensions matched. At one point these two teammates had a conversation in which they were both able to look at the current drill model and discuss how they would coordinate their efforts to make the parts successfully interface.

Current State Awareness

Differences in how aware teammates were of the current state of the model were also observed. This included awareness of what was being worked on by each person and what still needed to be done. Without this awareness, teammates at times did not know what needed to be worked on next or how their part related to the rest of the assembly. Team 1 (multi-user) and Team 2 (single-user) both had team conversations through Skype about the state the model and what still needed to be done. However, the multi-user team seemed to do this more easily because everyone on the team had access to the full assembly at all times. Multiple team members made suggestions on what still needed to be done.

Team members on single-user teams managed this state awareness by using screen-sharing or emailing parts, and one team member generally led out when having team conversations about remaining tasks. An interesting observation is that the highest performing team, Team 3, which was single-user, emailed parts to each other frequently, which created an effect similar to multi-user in that they were frequently updated on the current status of the model and could see how their parts needed to fit in. This demonstrates that it may be possible to achieve a needed level of awareness in a single-user CAD team with additional overhead activities. In other words, a significant amount of extra work is required to share parts back and forth. This indicates that having access to the actual CAD data facilitates awareness more than screen sharing or other methods of transferring this information between team members.

3.2.4 Communication

When analyzing the data recorded from participants communicating in teams we focused mainly on high-level patterns in the data. We hypothesized that multi-user teams would in general communicate more than single-user teams and specifically would have longer planning sessions than single-user teams.

The left and right plots in Figure 3.6 show the average communication per minute of all the multi-user teams and all the single-user teams respectively. While the study was broken into three different days, audio data recorded during team modeling is presented here as one continuous stream. The data supports our supposition that multi-user teams would communicate more than the single-user teams. For this study, the average percentage of time the multi-user teams were actively communicating through audio was 8.36% which was about 60% more than the single-user team average which was 5.22%.

From previous research, communication has been found to impact productivity. Clampitt and Girard found that several forms of communication had an impact on productivity [5]. While all the types studied had a significant impact on productivity, they found that "the Personal Feedback factor was perceived as having the most significant impact on employee productivity" and that "Co-worker Communication, Media Quality, and Corporate Information" had less of an impact. Essentially, more communication does not directly correlate with increases in productivity, but it can have a significant impact. Clampitt and Girard found that communication was corre-

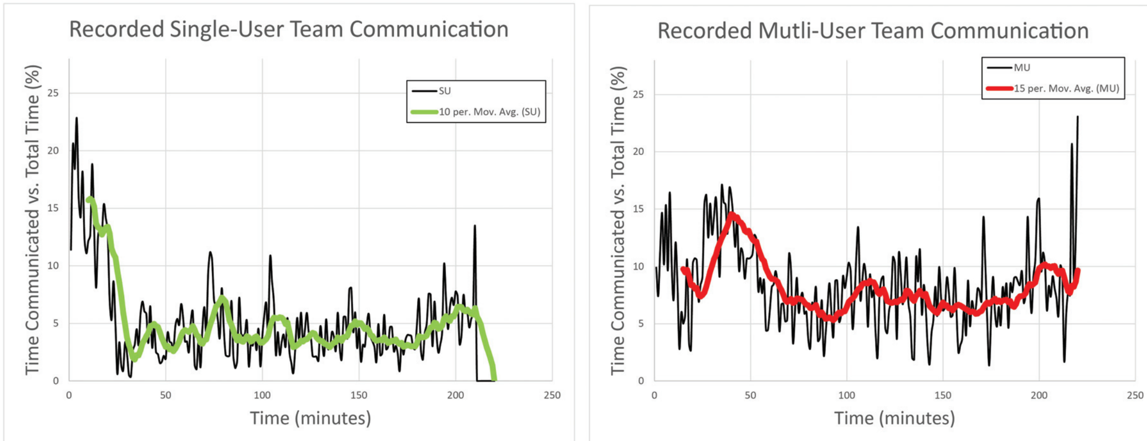


Figure 3.6: Audio communication trends

Table 3.3: Initial planning time

MU/SU	Planning Time	Score	Team ID
SU	11	95.33	3
SU	12	74.67	6
SU	14	65	8
SU	20	78.33	2
MU	11	87.33	5
MU	14	70	4
MU	15	78.33	1
MU	16	66.33	7

lated with job satisfaction which they suggested could be correlated with productivity, since job satisfaction can have an accumulative effect [5]. Although in this current study the connection was indeterminate.

The average initial planning session times for multi-user teams versus single-user teams had no significant difference, being within 30 seconds of one another. Timing of the team planning sessions was somewhat subjective and so are expected to be accurate within 2-3 min. The data collected is presented in Table 3.3. While there does not seem to be any correlation between the team type and initial planning length, longer planning time does seem to be correlated to poorer overall score, perhaps due to the total length of the project, though this correlation is not statistically significant.

3.2.5 Skill Level Prediction

An important part of this study was accurately accounting for the differing NX skill levels of the study participants. All study participants had some previous CAD experience, but some were very proficient with NX while others struggled with basic features. In order to understand the effectiveness of different methods for predicting skill level, we performed analyses comparing PSVT:R score, speed test score, and self-rating. These comparisons showed that PSVT:R is not as effective as the speed test at predicting skill with a specific CAD package, and also showed that people are not good at predicting their own skill level.

As mentioned in section 2.4, we attempted to create teams with similar overall skill levels. The metric for determining skill level was a pre-survey question asking "How familiar are you with NX?" which was answered on a scale from 0 to 4. Although the teams created were well balanced according to these self-ratings, it was seen during the study that certain teams were much more proficient with NX than others. We expected that self-perception of individual CAD proficiency would generally match evaluated individual proficiency. However, a statistical analysis showed that there is no correlation between these two metrics. From this analysis we conclude that a persons self-perception of CAD skill is not always accurate and should not be used as a primary means for determining skill. A similar phenomenon has been observed in other areas, for example, in the realm of second language self-assessment. Studies show that individuals are inaccurate when evaluating their own second language skills, unless they have had recent experience practicing the language skills that are being assessed [19]. Similarly, better self-assessments of CAD skill level would be expected if the assessment is done after participants have completed a CAD modeling task.

As mentioned in the Methods section, the PSVT:R and a speed test were administered to study participants to evaluate their CAD modeling skill. We expected that single-user CAD skill would be positively correlated with PSVT:R score, but a regression between these two scores showed no correlation. The lowest PSVT:R score of any of the participants was 22 out of 30 with an average score of 26.75, meaning that two thirds of the resolution of the scale was not utilized, making it more difficult to distinguish skill differences. A histogram showing the distribution of PSVT:R scores can be seen in Figure 3.7. This data comes from a population of individuals who already had a certain level of CAD experience, indicating that the PSVT:R may not be the best test

Table 3.4: Skill measurement comparison

Team ID	Average Self-rating (0-4)	Average PSVT:R (0-30)	Average Speed Test (minutes)	Judges Score
1	2.75	28	28.1	78.3
2	2	25.3	24.3	78.3
3	2.75	26.5	24.1	95.3
4	2.25	27	36.1	70
5	2.75	26.8	33.4	87.3
6	3.25	28.3	21.2	74.7
7	2.75	24.8	27.3	66.3
8	1.75	27.5	38.8	65

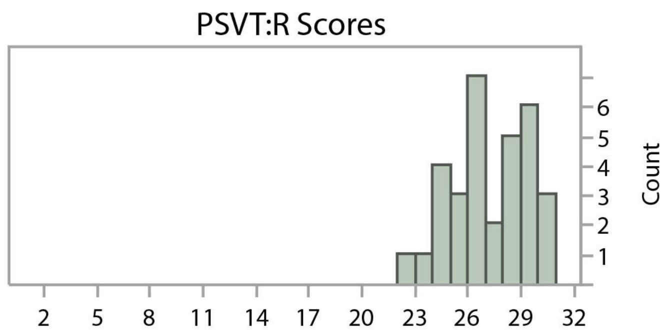


Figure 3.7: Histogram of all PSVT:R scores

for evaluating CAD skill in a population where all individuals are familiar with CAD software. The PSVT:R has typically been used to predict students ability to learn 3D modeling software in an introductory engineering graphics course [22]. Because nearly all of the study participants had successfully completed an introductory engineering graphics course, they were expected to perform, and did perform, quite well on this test.

In order to further investigate the accuracy of the speed modeling test for predicting CAD skill, we performed a regression of individual speed test scores and individual skill as evaluated by a persons teammates in the post-survey. In doing this, we assumed that after working together as a team for the 3.5 hours of modeling time, teammates would have gained a good sense of each teammates relative skill level. This regression did yield a statistically significant correlation, indicating that the speed test is a good indicator of individual CAD skill.

3.2.6 User Interface Analytics

In order to better understand the modeling styles of multi-user CAD versus single-user CAD, user interface analytics were collected. These analytics contain a variety of useful data including the time stamp for all buttons pressed, the name of each button pressed, and the part file in which the user modeled. Analyses can be performed on team modeling style by comparing and contrasting this team data.

The winning team, Team 3, received a score of 96.33 from the judges while Team 8 scored the lowest with a score of 65. Both teams used single-user software. Figure 3.8 shows the user-interface analytics for both Team 3 and Team 8 for all three days of the study. On day one, Team 3 started eight of the nine components whereas team 8 only started two of the nine components.

Distinct modeling styles are seen between the two top teams, Team 3 and Team 5. The winning team, Team 3, received a score of 96.33 from the judges while Team 5 came in second with a score of 87.33. Figure 3.8 shows the user-interface analytics for both Team 3 and Team 5 for all three days. On day one, Team 3 started eight of the nine components whereas Team 5 started all nine components. Members on Team 3 worked nearly exclusively on individual parts for the length of the study, only working on the same component occasionally. Members on Team 5 worked simultaneously on components near the end of the study, but initially "specialized" in a certain part or parts. There was no simultaneous work from multiple team members on any component on day 1. This trend carried into day 2, where there was only slight collaboration on the largest part, the handle. However, even this collaboration was not performed simultaneously. On day 3 there was extensive simultaneous work on components. All three users modeled simultaneously during various instances during the last day of the study. The most simultaneous component assistance occurred in the handle. It should be noted that the handle was also used as the assembly file for the drill.

From these observations it is seen that Team 5 largely used MUCAD as if it were a single-user software on the first and second day. The power of MUCAD comes in part from the ability to work simultaneously on the same component. By not exploiting this strength of the MUCAD software, Team 5 placed itself at a disadvantage. It is possible that Team 5 could have performed better than Team 3 had they better known how to take advantage of the strengths of MUCAD.

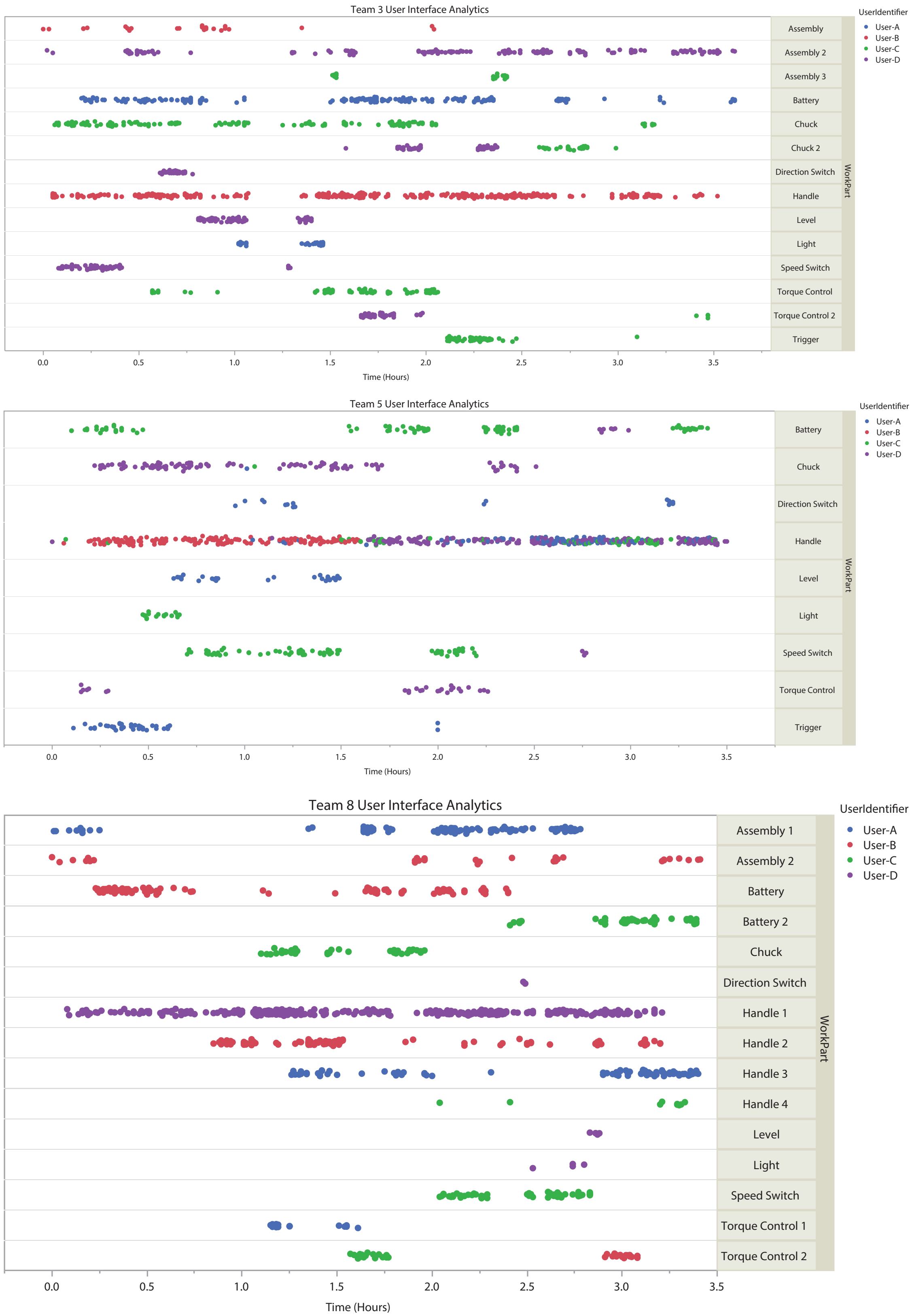


Figure 3.8: User interface analytics data for Team 3 (top), Team 5 (middle), and Team 8 (bottom)

CHAPTER 4. TEAM FACTORS IN DESIGNING WITH MULTI-USER CAD

4.1 Methods

4.1.1 Combined Factors

The Combined Factors experiment explored the effect of three of the factors on multi-user CAD teams: Team Leadership, Team Composition, and Individual Experience. In this experiment, teams of three students worked together to create a model of an Integrally Bladed Rotor (IBR). An IBR is an aeroengine component consisting of a rotor disk and multiple blades. It is machined from a solid piece of material, eliminating the need to assemble the blades onto the disk [55]. Six teams participated in the experiment. Each team started with an STL file of one blade of the IBR (obtained from GrabCAD) [56]), and was required to complete the following tasks:

1. Create a solid model of the blade
2. Model a center hub for the IBR
3. Pattern the blade around the hub
4. Fillet the edges where the blades join the center hub

The team members worked together in NXConnect to complete these tasks and were given 25 minutes to work. The researchers assigned each team a different leadership style (observing leader, participant leader, or no leader) which will be discussed in depth in the Leadership Styles section. Teams also had different compositions of NX skill level, which will be discussed further in the Team Composition section. Each team member took a survey at the end of the experiment.

Leadership Styles

The leadership styles that were tested were observing leader, participant leader, and no leader. ”Observing leader” means that the leader was not helping in the development of the CAD models, but was present during the work time and offered guidance. ”Participant leader” means that the leader was one of the three team members developing the CAD models. The other two team members were cognizant of his position as the designated leader. ”No leader” means no official leader was designated, but natural leadership was able to form among the three team members.

Scoring

After all of the teams had completed the experiment, their completed CAD models were scored using a rubric. This rubric was based on completeness of each feature of the IBR model, and more points were given for more complex features (see Appendix B). Each team's model was scored by three individuals, and these scores were averaged to obtain a raw score (RS) for each team.

The scores were then adjusted to account for differing skill levels on different teams and time lost due to NXConnect bugs. This adjustment was done using the following formula:

$$\text{Adjusted Score} = (\text{RS}) \times (\text{SSF} + \text{TSF}) \tag{4.1}$$

The skill scaling factor (SSF) was obtained by dividing the speed test time of the least-skilled person on the team by the average speed-test time of all participants. The time lost due to bugs scaling factor (TSF) was obtained by dividing the teams total time lost due to bugs by the average time lost. This adjustment resulted in the scores shown in Figure 4.4.

4.1.2 Unfamiliar Parts

The purpose of the Unfamiliar Parts experiment was to determine if users in a collaborative CAD environment could solve new and unfamiliar problems better than in isolation. To determine this, we first had teams of three students work together in NXConnect to model a part which none of them had previous experience with, which was the inner part of a combustor case. Each team

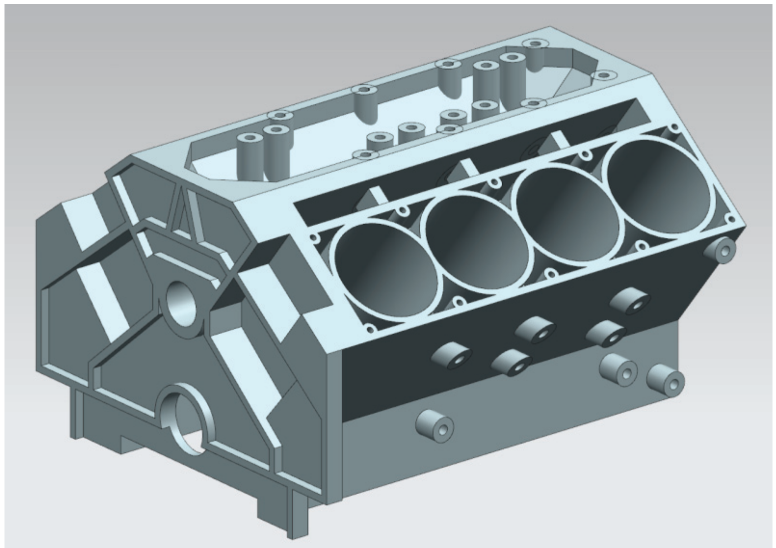


Figure 4.1: The engine block model shown to engineers in industry

modeled the part once, using one of three levels of information about the part: a written description of the part, Google images of the part, or dimensioned screen shots of the CAD model. Six teams completed this experiment, with two teams being given each level of information. The teams were given 30 minutes to complete the task. This experiment was repeated with six individuals independently completing the same task in single-user NX. The individuals were given one hour to complete the task.

4.1.3 Design Style

The Design Style experiments focused on understanding the design styles currently used in industry with traditional single-user CAD software and how these styles may need to change in a multi-user CAD environment. In order to do this, we created a survey that was sent to BYU mechanical engineering alumni working at a variety of companies.

In the survey, participants were shown screenshots of an engine block CAD model (see Figure 4.1), and asked to describe the steps they would take to model the part in CAD.

The Design Style experiments used some insights from this survey and tried to determine what constitutes a superior modeling style for teams working together in multi-user CAD software. The experiments specifically tested whether having the team members work together to create an

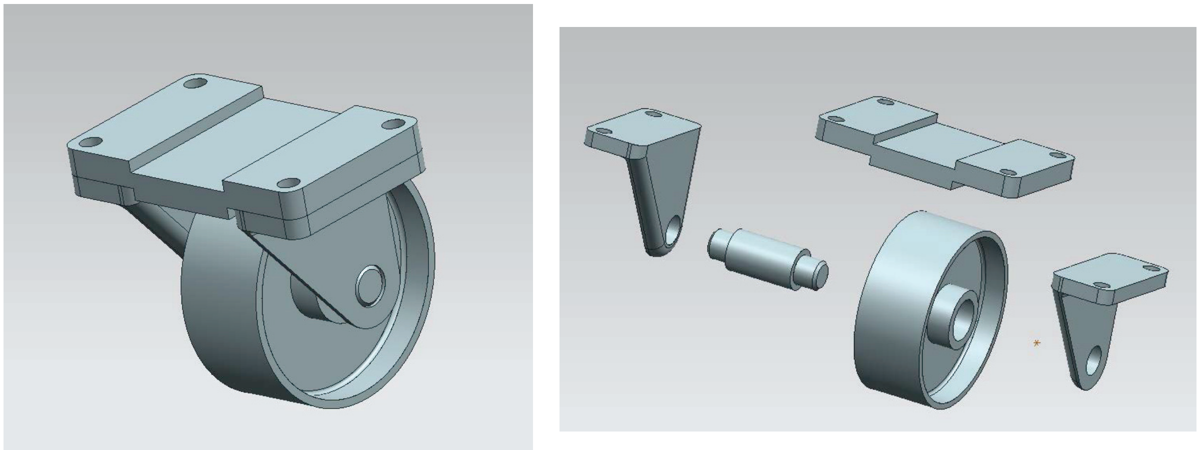


Figure 4.2: Caster model screen shots given to teams as a reference

initial framework of sketches and datums in the CAD part would allow the team to work more quickly and produce better results than a more ad-hoc organization method.

In order to test this, we had two teams create a model of a caster, both in NXConnect, using Figure 4.2 as a reference. All pieces of the caster were modeled in a single part. The first team was told to create an initial framework of sketches and datums in the part that would allow them to define all of the interfaces and relative positions of the caster parts so that each team member could go off and work on their assigned portion of the model. The second team was simply told to create the model, with no additional instructions indicating how to structure their work.

4.1.4 Extended Leadership

During the Team Leadership experiments, it was proposed that leadership may not have as significant of an impact in a one-time 25 minute session as in a longer, multi-phase project. In order to explore the impact of leadership in a longer, multi-phase setting, we designed an experiment in which teams competed to design a trebuchet machine with the longest throwing range.

Experiment Steps

For the extended leadership experiment involving the trebuchet machine construction and competition, two teams of three students:

1. Received instructions on the materials available to them and rules for the competition.
2. Watched an introductory video showing a trebuchet in use.
3. Used an online trebuchet simulator to experiment with basic dimensions of construction and optimize their designs.
4. Modeled their design in NXConnect.
5. Returned a second day after their parts were 3D printed.
6. Assembled their 3D printed trebuchet.
7. Tested their trebuchet to throw maximum distance.

Each team had a different leadership style. For the first team, one of the team members was assigned to be the leader and worked with the other two to design the trebuchet. This team member had the greatest CAD skill on the team as measured by the speed test. On the second team, a fourth student who is experienced with NXConnect was assigned to be a supervisor of the three person team. The supervisor did not work on the design with the team, but observed the team during the simulation stage and then gave assignments to team members for modeling the trebuchet. He then went back to his desk in another part of the lab and called in via Skype every 20 minutes to verify the progress of the team and make new assignments as needed. While talking with the team on Skype, he also opened the CAD model that they were working on in NXConnect, allowing him to see the team's current status.

4.1.5 Knowledge Transfer

The Knowledge Transfer experiment was designed to examine how an experienced CAD designer/engineer gives directions to a more novice designer/engineer. The transfer of knowledge was examined through three different methods. All tests were performed with both the senior and junior engineers in different locations, thus requiring Skype communication for instruction transfer.

1. Single User - Both engineers were in a single-user CAD environment. This meant the senior engineer began with a part open on his computer and shared his screen through Skype as he gave instructions to the junior engineer to modify the part. Once the instructions were given, the senior engineer closed the part, thus allowing the junior engineer to open the single-user part and begin the modifications from the instructions.

2. Multi User - Both engineers were in a multi-user CAD environment. This meant both engineers had the same part open at the same time during instruction and work time. Due to the part file used not being compatible with NXConnect, the multi-user environment was simulated by having both individuals open local copies of the part in regular NX to avoid any interference from extant bugs and still get an accurate knowledge transfer.

3. Multi User with Screen Share - Both engineers were in a multi user CAD environment while the senior engineer shared his computer screen with the junior engineer over Skype. This meant that both engineers had the same part open during both instruction and work time, and the senior engineer could point out part details to the junior engineer through his shared screen.

Scoring of the Knowledge Transfer participants was based on the following equation:

$$\text{Adjusted Score} = (CS) * (TSF) * (SF) \tag{4.2}$$

where CS (Completion Score) is based on how complete their model was at the end of testing, TSF (Time Scaling Factor) is their time to complete the task divided by the average time in that method of testing, and SF (Skill Factor) is their speed test score divided by the average speed test score of all the participants in that method.

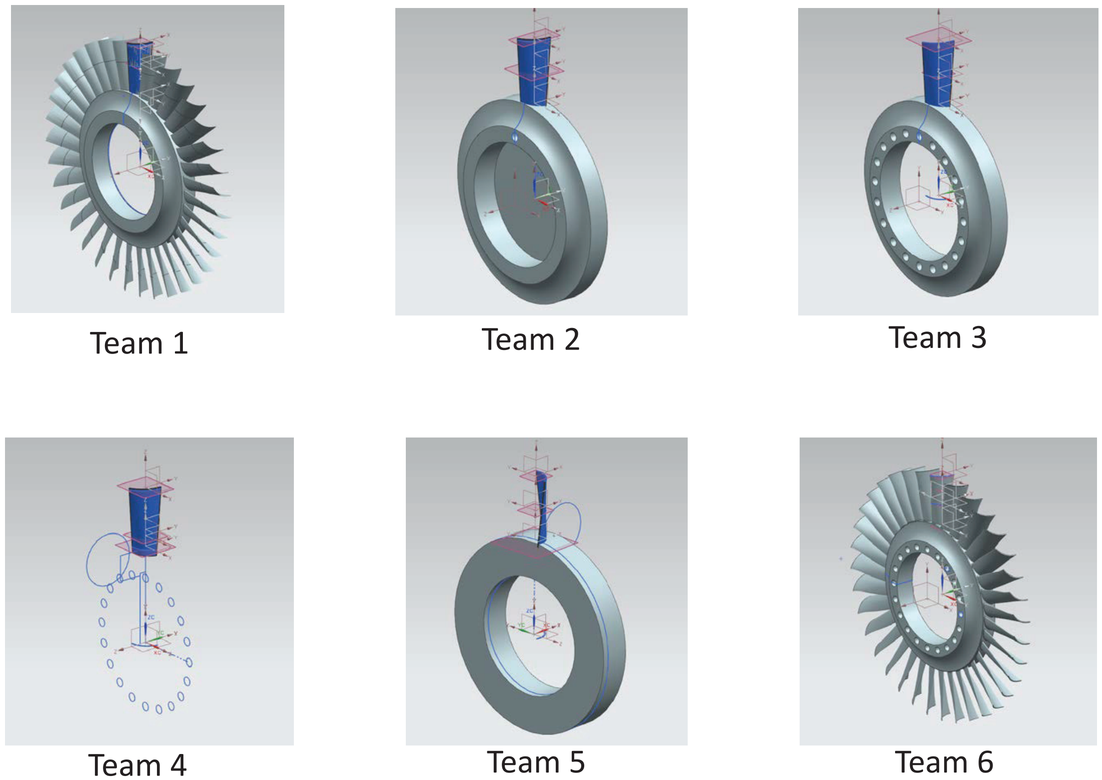


Figure 4.3: Completed IBR models for the six teams

4.2 Results

4.2.1 Team Leadership

The three leadership styles mentioned in Methods were evaluated through participant survey responses and statistical analysis of the Combined Factors experiment. In the analysis of how leadership styles affected the final adjusted score, the average score for teams with a participant leadership style was the highest, followed by the average for teams with an observing leader. However, this difference was not statistically significant (p-value 0.43). A larger sample size of teams would be needed to find statistically significant results. Figure 4.4 shows the final adjusted scores for the six teams. The results of this analysis can be seen in Figure 4.5. While the two teams with a participant leader had very similar scores, there was a large disparity between the scores of the two teams with an observer leader. The proctor notes from the Combined Factors experiment indicate

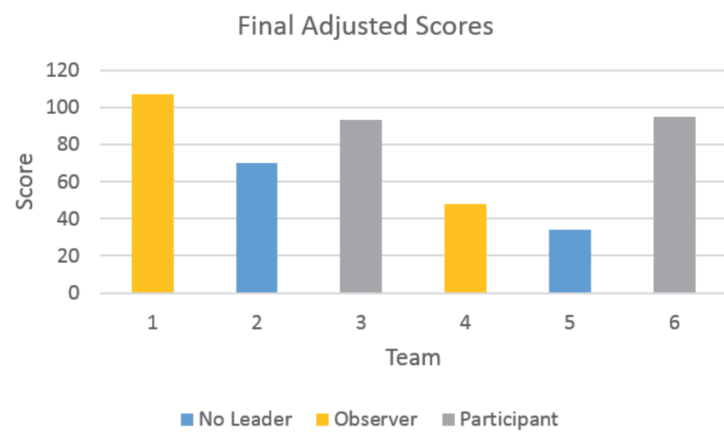


Figure 4.4: Final adjusted scores for the six Combined Factors teams

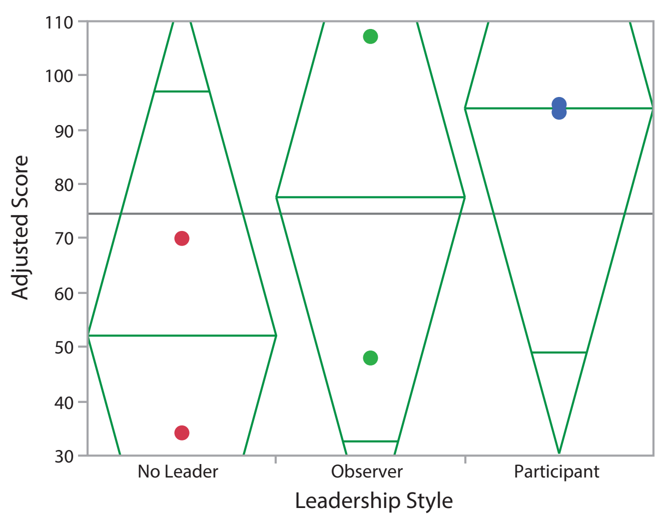


Figure 4.5: Comparison of mean scores for the three leadership styles

that this disparity may be due to a greater level of autonomy and proactivity observed among the members of the higher-scoring team. In contrast, the members of the lower scoring team relied heavily on their leader for direction.

The findings from the Combined Factors experiment were supported by findings from the extended leadership experiment, in which two teams with different leadership styles designed trebuchets as described in Methods. A few interesting observations can be made about the team dynamics with these two leadership styles. On the team with the supervisor, one of the three team members seemed to emerge as a leader even though there was leadership present in the form of a supervisor. This emergent leader helped other team members with their CAD modeling when they struggled, and the other team members often deferred to him when decisions needed to be made. It seems that because of the dynamic and interactive nature of the multi-user CAD environment, there needs to be leadership directly involved with the design process, or leadership will naturally emerge.

It also seems that leadership is more significant at certain stages of the process. During exploratory stages, such as when the team was doing the online trebuchet simulation, all team members were contributing and the leader did not demonstrate a clear leadership role. Later on, when details were being figured out and decisions were being made, a leader was helpful in facilitating these tasks.

The relationship between score, difficulty working with the team, and leadership style was also analyzed. Participants were asked ”How difficult was working with your team to complete the task?” The analysis showed that there was no statistically significant correlation between difficulty and adjusted score.

Awareness

One aspect of leadership styles tested was team member awareness. Two fits were made in an attempt to find a relationship between awareness and team score: linear and exponential. For the linear fit, the intercept p-value was 0.0107 and the slope p-value was 0.129. In comparison, the exponential fit yielded an intercept p-value of <0.0001 and a p-value for the slope of 0.1044. From this analysis an exponential fit seems to best explain the trend in the data, indicating increased score with increased awareness, although the evidence is inconclusive.

4.2.2 Design Style

Responses to the engine block modeling survey were received from 12 individuals working at 7 different companies. The graphs in Figure 4.7 and Figure 4.8 show data about years of industry experience and frequency of CAD usage for the survey respondents.

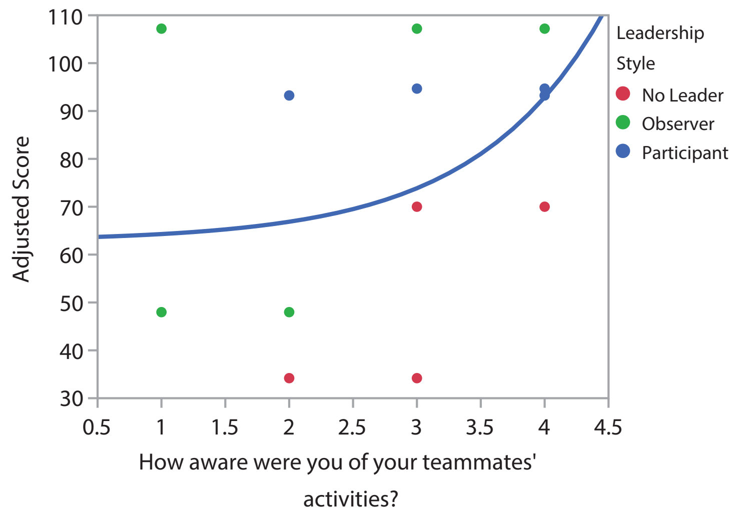


Figure 4.6: Exponential fit of awareness vs. adjusted score

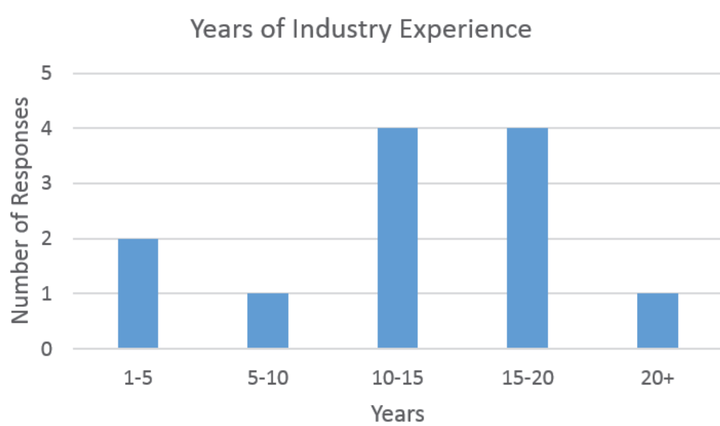


Figure 4.7: Years of Industry Experience for survey respondents

Two individuals agreed to actually model the part and provided a video taken of their screen while working. The remainder simply described in writing the steps that they would follow. Nearly all participants described a subtractive modeling style, starting with an extrude in the general shape of the engine block and then cutting features out of it.

Participants were also asked how working in a multi-user CAD environment would change their modeling style. In our past observations of teams working together in NXConnect, we have seen that team members will generally briefly discuss basic dimensions for the part, divide up

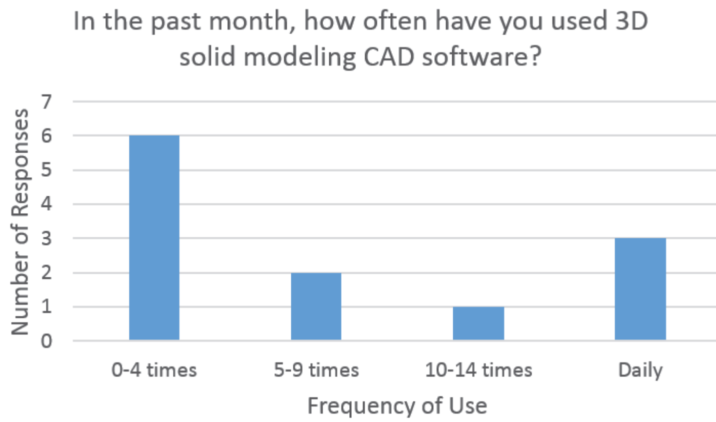


Figure 4.8: Frequency of use of CAD software by survey respondents

the work, and then begin modeling. While working, they continue to discuss dimensions and other details as needed. In the survey, however, many people commented that planning, good organization and datum references would be needed in order to ensure that people would be able to work efficiently in a multi-user CAD environment.

The caster modeling experiment provided an interesting preliminary investigation of this idea. During the experiment, the first team spent 8 minutes, 15 seconds on the process of creating their initial framework. The second team was simply told to create the model, with no additional instructions indicating how to structure their work.

The resulting CAD models can be seen in the images shown below. Figure 4.9 shows the framework created by Team 1, and the team's completed model. Figure 4.10 shows the completed model of Team 2. The wireframe views allow us to see the sketches and datums used by each team. As can be seen, both teams were able to create a complete caster model that closely resembles the reference images. However, some differences can be seen by comparing completion times and average speed test times of the two teams, shown in Table 4.1. Team average speed test time for Team 2 was 58% shorter than Team 1, indicating that Team 2 was much more skilled, but caster completion time for Team 2 was only 20% shorter than Team 1 without having created an initial framework to aid organization. With only two teams we cannot establish a trend, but the data indicates that there may be some value to creating an initial framework to aid organization in a multi-user CAD environment.

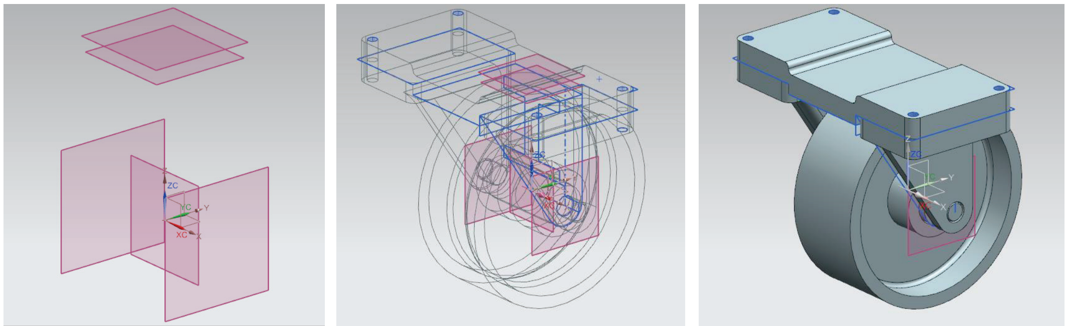


Figure 4.9: Team 1 initial framework, wireframe view, and solid view of completed model

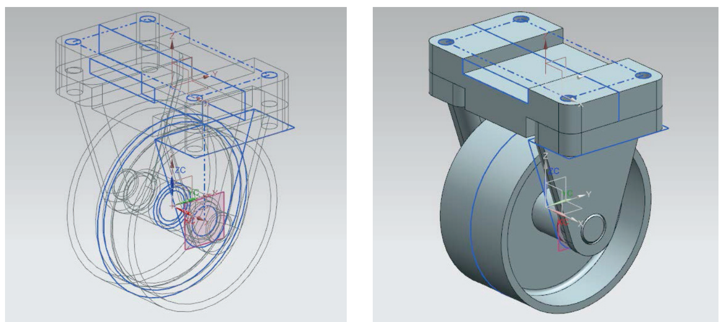


Figure 4.10: Team 2 wireframe view and solid view of completed model

Observations of Team 2 showed that they had to make many adjustments later on in their modeling time to make all parts of the model interface correctly. However, they were able to coordinate these adjustments well, showing that the multi-user environment in itself facilitates coordination and allows for adjustments to be noticed and resolved quickly.

4.2.3 Unfamiliar Parts

Comparing the resulting CAD models of the teams and of the individuals seems to indicate that teams were able to arrive at a more creative and detailed solution than the individuals when

Table 4.1: Caster completion times and team average speed test times

Team	Caster CompletionTime	Team Average SpeedTest Time
1	30.5 minutes	29.7 minutes
2	24.3 minutes	12.5 minutes

there was a low level of familiarity with the part. This finding is in contrast to much of the literature regarding creativity in teams, which states that individuals working separately and then pooling their ideas can come up with a larger number of, and more creative, ideas than a group can [23]. However, research of computer-based groups, such as that of Valacich et al., shows that groups using a computer-based idea generation system can outperform an equal number of individuals working alone. This is due to the elimination of production blocking, or the phenomenon where only one person in a group can speak at a time [28]. MUCAD team members, working together in a computer-based system, seem to experience a similar effect to that observed by Valacich et al. Team members can simultaneously create new concepts, while also viewing the concepts of their team members, further stimulating their creativity.

For the tasks where more information (such as CAD screenshots) was given, there were more mixed results. In some cases the team models were higher quality, while in other cases the individuals produced higher quality models. A comparison of a team's model and an individual's model when given only a written description of the part can be seen in Figure 4.11.

These results seem to show that a multi-user environment may be particularly useful in new design scenarios or in situations where some or all team members are unfamiliar with the task at hand. Although model quality is not likely to improve substantially in cases where a well-defined part needs to be modeled, decreased calendar time is still a benefit of multi-user CAD that was observed in this experiment.

4.2.4 Knowledge Transfer

In the analysis of the Knowledge Transfer experiment, it was found that the method of knowledge transfer does not have a statistically significant effect on how well the participants performed (one-sided p-value was 0.86). As the data collected was limited in scope and quantity, it is recommended that this area be investigated more extensively in order to determine whether there truly is a significant effect caused by methods of knowledge transfer.

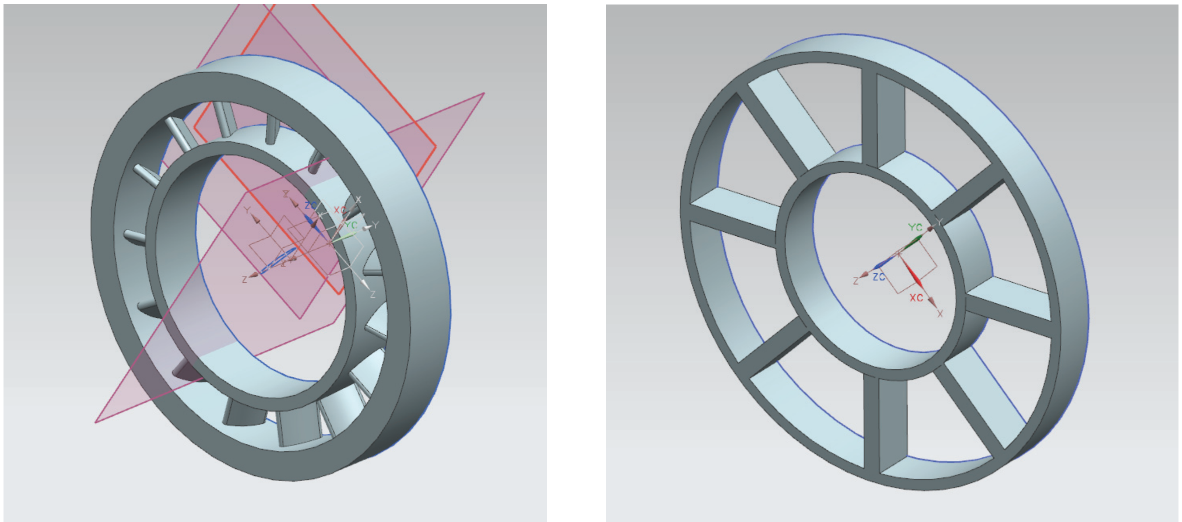


Figure 4.11: From left to right, the CAD models of Team 6 and Single-user 2

4.2.5 Individual Experience

The design style survey sent to BYU alumni also asked about working in a multi-user CAD environment. When asked how comfortable they would be working in this environment, the average response was 1.92 on a 0-4 scale (Figure 4.12). However, when asked "How much would knowing that others can see your work in progress negatively affect your inclination to work in a collaborative CAD environment?", the majority of respondents said it would have no negative effect (Figure 4.13).

Reasons for not feeling comfortable included concerns about dealing with different modeling styles of other users, changes made by others affecting an individual's work, time lost waiting for others, and the lack of a need for multiple people working on a simple part. Reasons for wanting to work in a multi-user environment included having a collaborative environment to create better ideas and completing work more efficiently. These findings seem to indicate that training and positive experiences with the multi-user software will be important for ensuring that users can transition into a multi-user environment and feel comfortable in this setting.

To understand individual preferences for working in NXConnect, study participants were asked a few survey questions. Participants were asked "If provided with this software in a work or class project setting, would you use it? (assuming it were bug-free)". All participants responded

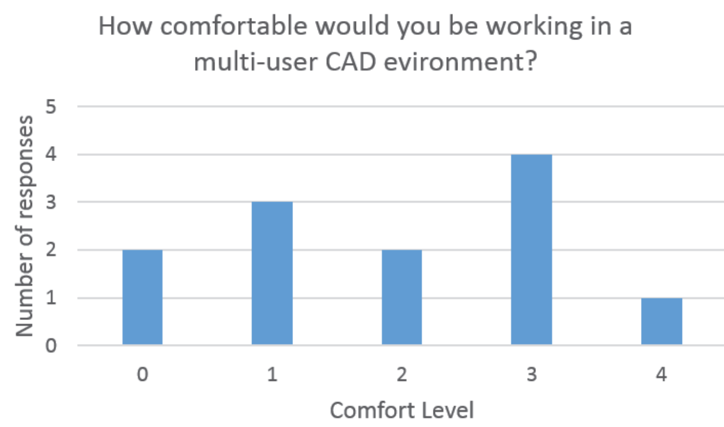


Figure 4.12: Comfort with working in a multi-user CAD environment

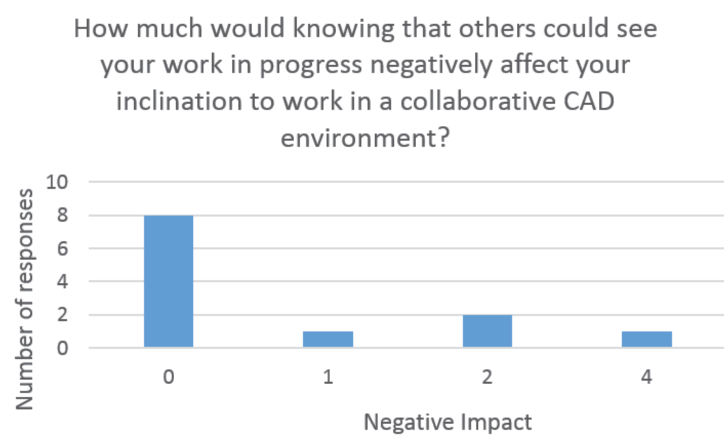


Figure 4.13: Impact of others seeing work in progress

affirmatively. Reasons for wanting to use it include being able to collaborate more easily with team members, completing CAD models more quickly when time is limited, eliminating the need for checking in and checking out parts, and improving problem solving abilities. Participants were also asked how comfortable they were with other people seeing their work in progress. As can be seen in Figure 4.14, most people were very comfortable with this.

4.2.6 Team Composition

Team composition consisted of observing the effect of having team members with differing CAD skill levels working together in NXConnect and whether teams composed of equal or variable

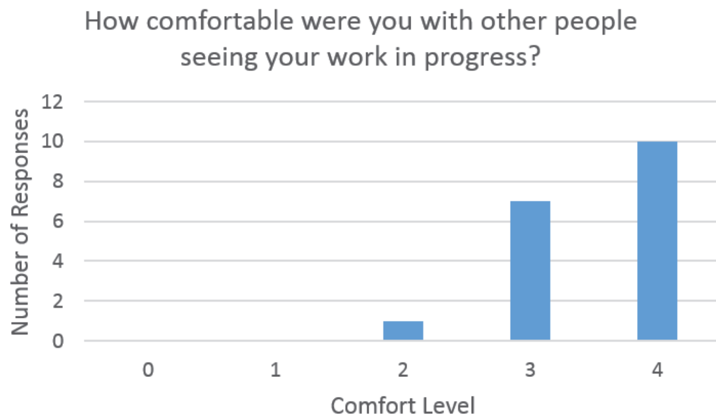


Figure 4.14: Comfort level with others seeing work in progress

skill CAD modelers is more desirable or effective. In order to understand how team composition affects team performance, each team's score was correlated to the mean, standard deviation, and skew of the team members' speed test times. Score was also correlated to the speed test time of the least-skilled member of the team and to the speed test time of the most skilled team member. It was found that there was a statistically significant correlation of team score to the speed test time of the most skilled team member, with a p-value of 0.03. The shorter the speed test time of the most skilled member, the higher the teams score.

It was also found that there was a statistically significant correlation of team score to the standard deviation of a team's speed test times, with a p-value of 0.01. The higher the standard deviation, the higher that team's score. However, this result is opposite to what was found by Stone et. al in a similar experiment [1], as can be seen by comparing Figure 4.15 and Figure 4.16. This discrepancy could be due to the fact that skill was measured with different metrics in the two experiments, but also indicates that more in-depth research will be needed to definitively determine the effect of standard deviation of team member skill on team performance.

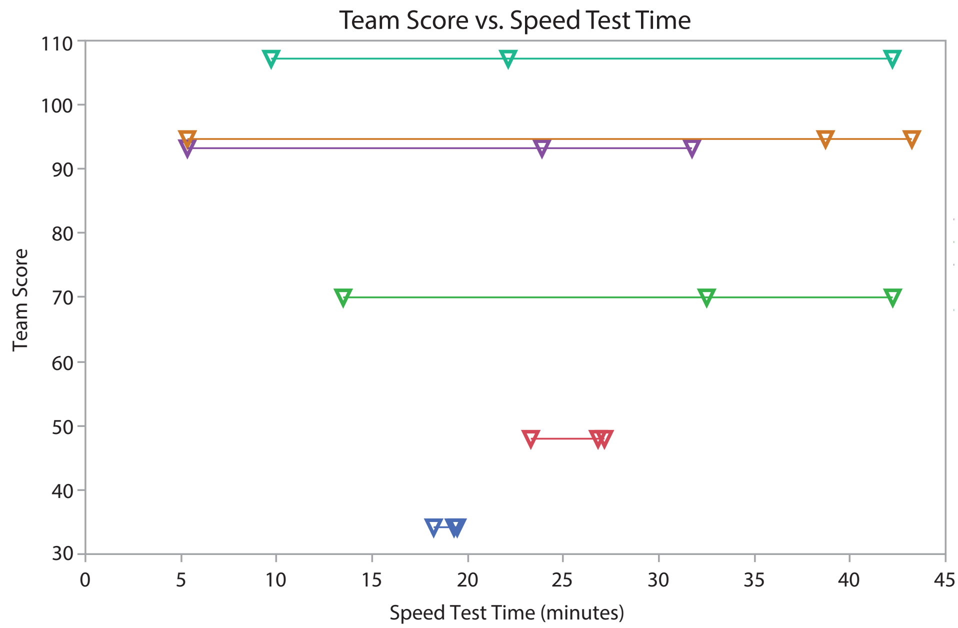


Figure 4.15: Team score vs speed test time

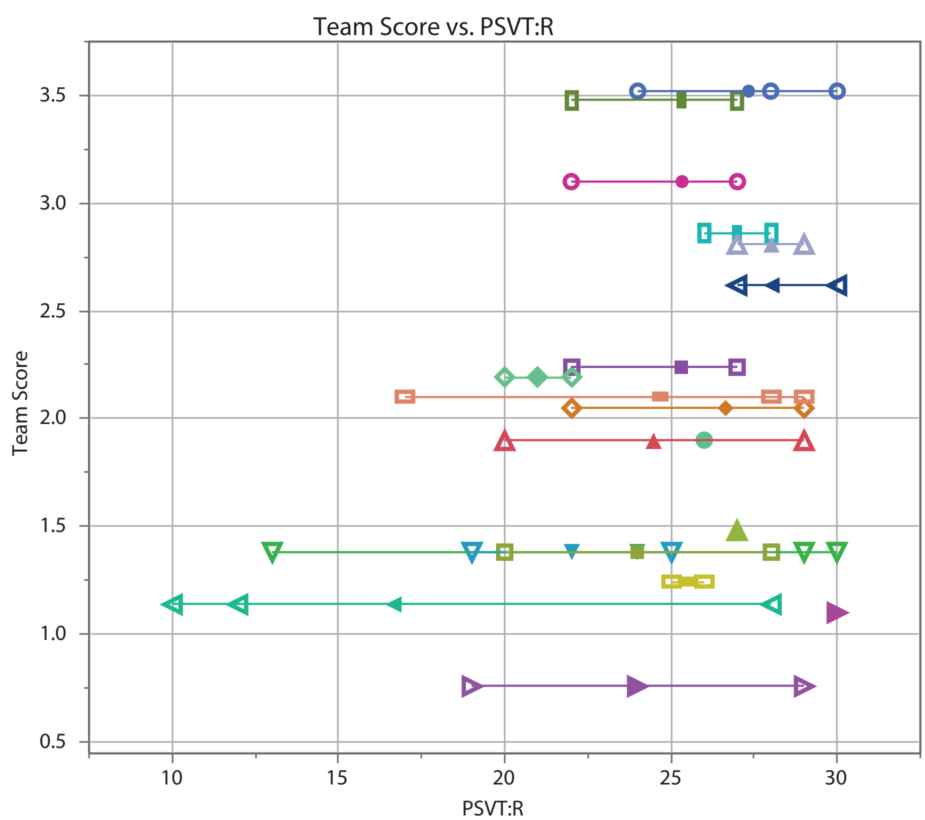


Figure 4.16: Team score vs PSVT:R score from the experiment by Stone et. al [1]

CHAPTER 5. CROWDSOURCING PRODUCT DESIGN

Crowdsourcing has been used with great success in a number of areas, including scientific research and data collection [8, 9]. It has also been used for product development, which usually takes the form of a design competition in which the sponsor selects a winning design. However, little work has been done to develop effective methods for collaborative, crowdsourced product design. Great potential exists in combining the ideas and expertise of many different people to design new products, but a new, collaborative crowdsourcing process is needed to effectively accomplish complex product design tasks. This chapter discusses this process, the platform developed to implement the process, the experiments used to evaluate the process, and the results of these experiments.

5.1 Methods

5.1.1 Collaborative Crowdsourcing Process

A proposed collaborative crowdsourcing process for product development was developed by taking elements from existing theories and practices in the broader crowdsourcing literature. Many of these are mentioned in Chapter 2. The process developed is shown as a block diagram in Figure 5.1. As discussed, the factors that need to be incorporated to make this a successful process are decomposing and assigning tasks, making decisions, and coordinating efforts, which are accomplished by the various elements represented in the diagram. The main sources that served as motivation for the inclusion of these elements are as follows.

The elements for decomposing and assigning tasks were based on research by Kulkarni et al. and Valentine et al. [51, 52]. These sources provided insight that led to allowing crowd members to have complete control over the creation of tasks and the workflow, rather than the project requester pre-defining them. This allows an iterative process to occur, in which crowds

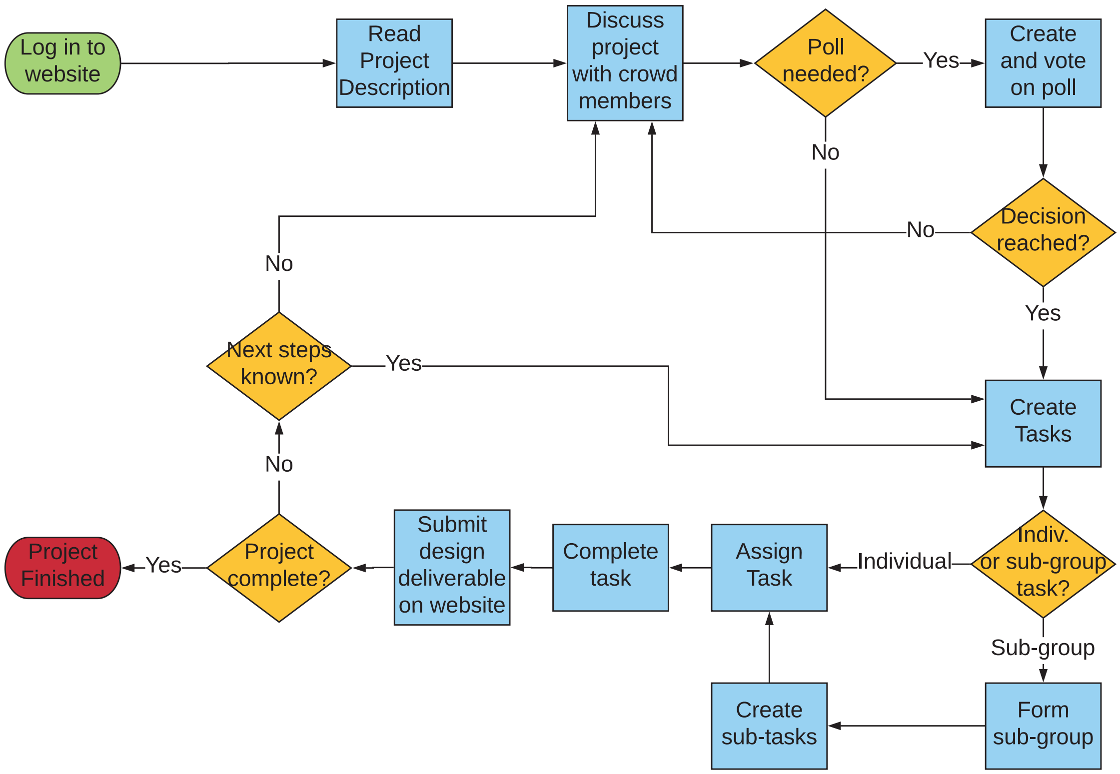


Figure 5.1: The collaborative, crowdsourced product development process

have the ability to define new tasks and adapt to changing needs. Lessons learned from the study by Kulkarni et al. also led to allowing the moderator to intervene when needed to keep the crowd within the bounds of the project description. The formation of subgroups was drawn from the study by Valentine et al., as well as a study by Klein et al. [54]. This is an important concept that allows the crowd to better accomplish local problem solving.

The group discussion and polls arose from the need to give the crowd information sharing and decision making abilities that were often not present in other crowdsourcing studies. While in many studies these capabilities were not needed, it was recognized that these capabilities would be important for crowd members to work together on complex product development tasks.

The combination of these key elements make the process uniquely suited to crowdsourced product development. All crowd members can communicate with each other, enabling information sharing and a wide range of insights. This communication, along with file sharing, enable crowd members to collaborate as they work on interrelated product design tasks. Crowd members have the ability to create new tasks, allowing them to control the work-flow, modifying it throughout the project in response to changing needs. Market validation, an important part of developing a new product, is built into this process. As crowd members contribute and vote on ideas, the crowd will converge on the most desirable design.

5.1.2 Collaborative Crowdsourcing Platform Overview

After developing the process, a website was developed as a platform to enable this process. This website has several tools to enable collaboration between crowd members, including a group chat, one-on-one chat, file repository, poll feature, task management system, and forum.

The group chat allows all crowd members to participate in discussions about the design and what needs to be done. One-on-one chat allows any two individuals to communicate with each other, and a messaging feature allows small groups to communicate. The file repository is a file system where crowd members can upload and download files in order to share them with other crowd members. These files can include images of concepts, CAD files, or text documents, among other things. With the poll feature, any crowd member can create a poll which can then be voted on by any other crowd member. All crowd members can see the poll results so that they can all be aware of the opinion of the crowd. The task management system allows crowd members to create tasks, assign them to a specific person, and specify other information such as task status and priority. The forum allows any crowd member to create a new topic which can then be discussed by the crowd. This is also a place to keep a record of information that needs to persist for future reference. The open permissions built into these tools allow for all crowd members to have equal input to the process. A link to a short tutorial video demonstrating how to use the various collaboration tools is included on the Tools page, and participants were asked to view this video prior to participating. Screenshots of several of the website's pages are shown in Figures 5.2-5.6.

The website also contains features to aid individuals' awareness of the current status of the project and what still needs to be done. The first of these features is an activity feed on the main page. This is populated with new tasks, polls, and forum topics, with the most recent item at the top, so that crowd members can easily scroll through and see these new updates. The second feature

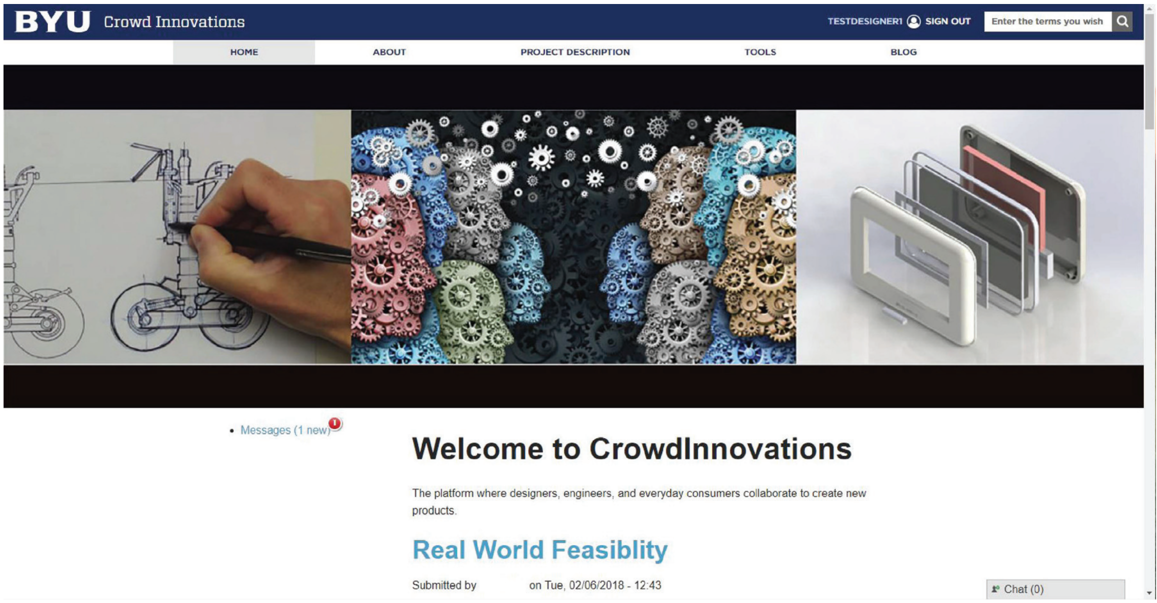


Figure 5.2: The Home page of the crowdsourcing website

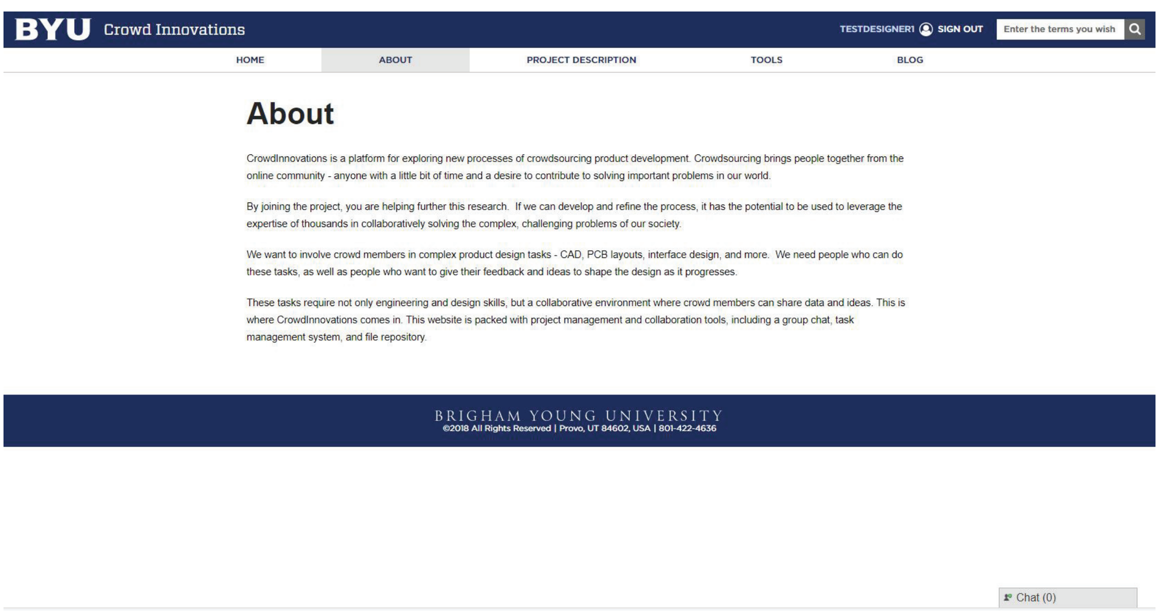


Figure 5.3: The About page of the crowdsourcing website

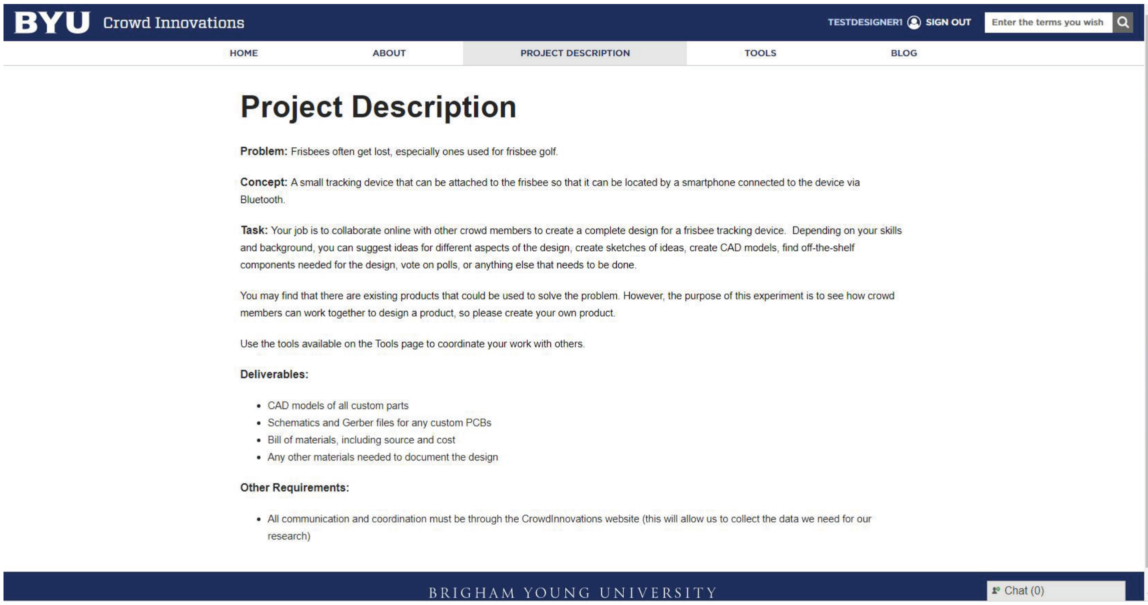


Figure 5.4: The Project Description page of the crowdsourcing website

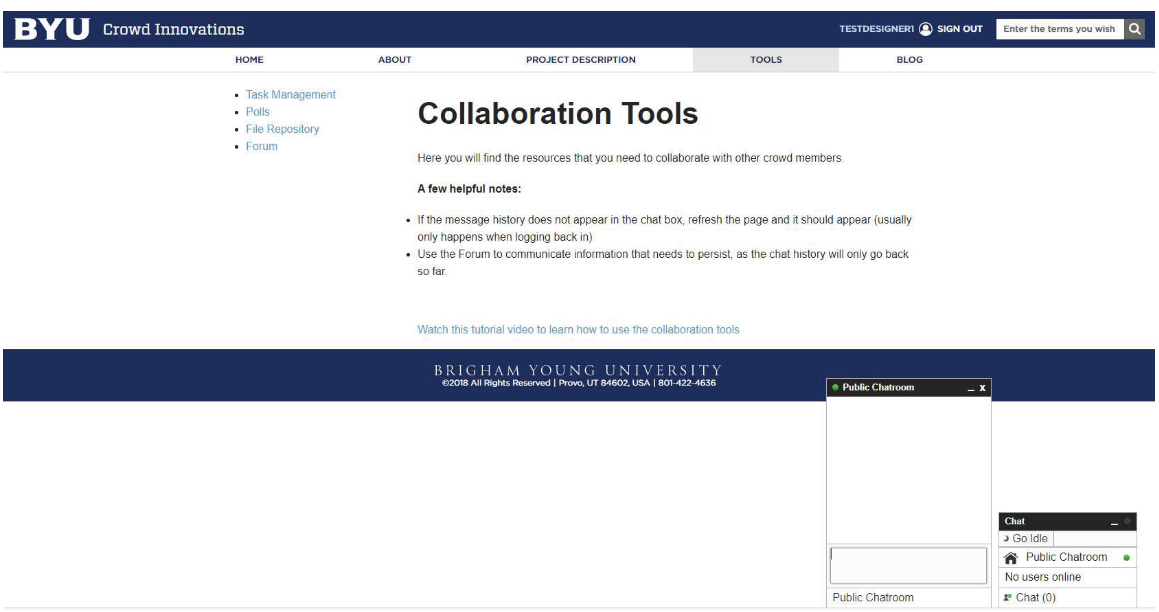


Figure 5.5: The Tools page of the crowdsourcing website. The group chat window is also shown

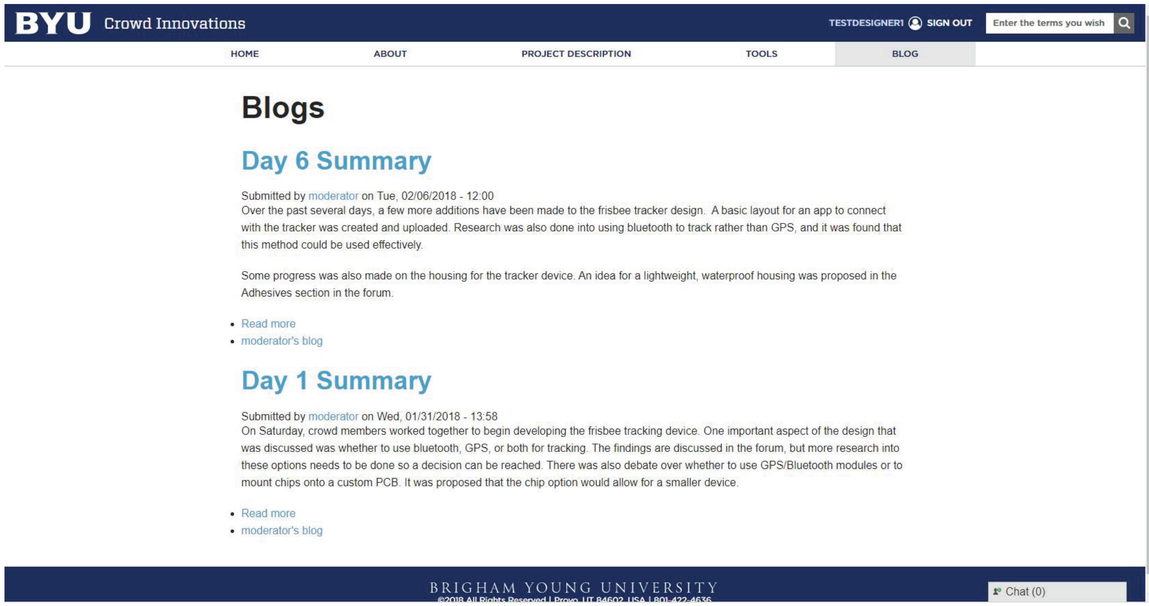


Figure 5.6: The Blog page of the crowdsourcing website

is a blog where regular updates are posted with summaries of the project's progress. This allows crowd members who haven't been on the website for a while to see a more condensed version of work completed throughout the project. These blog posts are created by the website moderator. The website also has a project description page that details the problem to be solved, the concept to be developed, the expectations for crowd members, and the expected project deliverables.

The website moderator was a research assistant familiar with the website and the project being completed. This moderator was online during all experiments in order to provide any needed clarification and resolve technical issues with the site. The moderator did not participate in the project, only assuring that crowd members did not do anything outside the guidelines set by the project description.

5.1.3 Preliminary Testing

A number of preliminary tests were done to evaluate the usability of the crowdsourcing platform. Lessons learned from each test were documented, and changes were made until the website was deemed ready for the full product design case study. These preliminary tests were conducted with the same group of mechanical engineering students. Each test, with its results and corresponding changes, are discussed in section 5.2.1.

5.1.4 Product Design Case Study Setup

Once the preliminary testing was complete and all desired modifications to the process and platform had been made, the same experiment was conducted, this time in a true crowdsourcing setting by putting out an open call to all students in the School of Engineering and Technology at BYU. A one-hour design session was held first, where a large group of students collaborated virtually on the website. For this case study, the crowd members asked to design a frisbee tracking device, described on the project description page as: "a small tracking device that can be attached to the frisbee so that it can be located by a smartphone connected to the device via Bluetooth." The full project description given to participants can be seen in Figure 5.4. At the end of the session, all participants completed a post-survey.

After this session, all students who had signed up (which included many that did not participate in the one-hour design session) were asked to work on the project for up to two hours each on their own time. On the last day of the study, another one-hour collaboration session was held. Throughout the course of the study, participants logged on to the website from whatever computer they had available, and were not in the same physical location. This created the type of crowdsourcing environment that would be anticipated in a real-world scenario, where individuals join an online community and interact virtually from anywhere in the world. All interactions between study participants happened by means of the crowdsourcing website. At the end of the study, each participant was compensated according to the number of hours that they spent working on the product design.

5.1.5 Evaluation

After the Product Design Case Study, some additional data was collected for comparison. As mentioned previously, it was hypothesized that one of the benefits of crowdsourced product design would be greater customer buy-in for those directly involved with the design versus those who did not participate. To verify this, a survey was sent out on Amazon Mechanical Turk asking respondents to state how much they would be willing to pay for a frisbee tracking device. Respondents were restricted to people in the US, and the responses were filtered to only include those who were in the same age range as most college students (18-34).

It was also hypothesized that development cost can be lowered by developing a product with crowdsourcing. In order to evaluate this, a survey was sent out on Amazon Mechanical Turk asking for respondents to view a progress report showing the work accomplished by the crowd and then give their best estimate for how many man-hours were spent completing that work. The respondents were restricted to people in the US whose job function is engineering in order to obtain responses from people with enough experience to give a reasonable estimate.

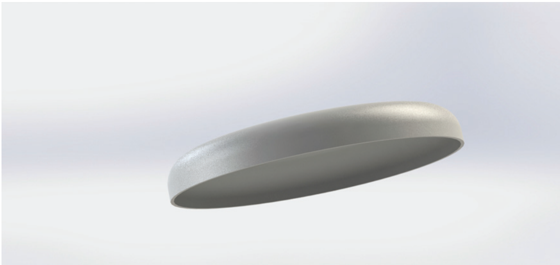
5.2 Results

5.2.1 Preliminary Test Results

The first test was one hour long and involved 10 students which worked together to design a new product. During this test, it quickly became apparent that communication between crowd members was very difficult. The tool for communication was a forum; however, this did not notify users when new comments were added, and it was difficult to follow the conversation. Users requested a chat be added for instant messaging capability, which was integrated into the website before the next test. A number of bugs with the website were also found and corrected.

For the second test, crowd members were asked to work on the project for two hours during the course of one week. Each person was free to choose when they would work on the project. However, due to the asynchronous nature of the work done by different people, crowd members had a difficult time knowing what the status of the design was and what needed to be done. As a result, only a few people did any work, with one person making most of the contributions. After discussing their experience with several test participants, it was found that some new features were needed on the website to aid awareness of what had been done recently and what the current state of the design was. The update feed on the main page was implemented to display new content such as polls, tasks, and forum topics, and the blog page was added to give condensed summaries of daily progress.

The final preliminary test had the same form as the Product Design Case Study, involving 13 individuals from the same group as before. For this test, all individuals participated in a one-hour design session, after which each individual worked on the project for an additional two hours



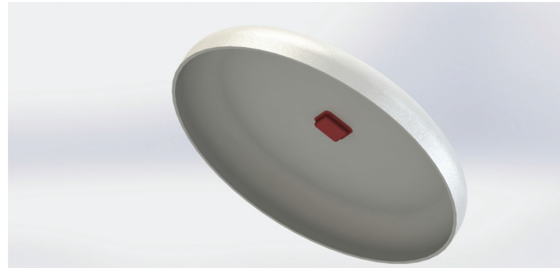


Figure 5.7: CAD renderings of the frisbee tracker concept

on their own time during the following week. Participants were able to communicate well and made substantial progress on the new product design.

5.2.2 Product Design Case Study Results

For the product design case study, 18 students participated in an initial one-hour design session. During the following week, 8 students continued to work on the project at different times, contributing one or two hours each. By the end of the study, the crowd had come to a conclusion about the various pieces of hardware that would be integrated into the design. This included selecting a bluetooth module, microprocessor, adhesive, waterproof battery holder, and waterproof mini speaker. These conclusions came after the crowd had researched and discussed a wide variety of options for each of these components, weighing how well each met the project objectives. Other deliverables produced by the crowd include simple CAD models (Figure 5.7), a list of requirements (Table A.1), and a simple mobile app layout (Figure 5.8). The full results are included in Appendix A. Participants were asked to complete the post-survey at the end of the one-hour session, and responses were received for 16 of the 18 participants.

Although the crowd was not successful in the sense that they did not complete the design, the study demonstrated that unfamiliar crowd members responding to an open call can come together in an online platform and work together to complete tasks necessary for the detailed design of a new product. The study also points towards a number of important lessons that can be the focus for future research of crowdsourced product development.

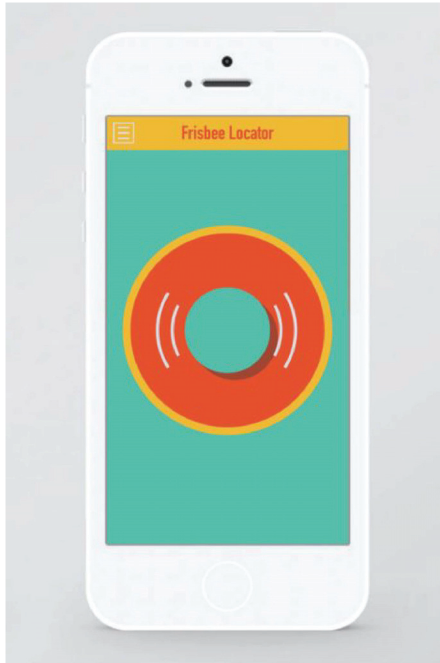


Figure 5.8: The app layout created by the crowd

Table 5.1: The list of requirements created by the crowd

Requirements
Trackable by different devices
Not interfere with Frisbee flight
Must be able to easily remove from Frisbee
Low cost
Usable across Frisbee types
Attachment resilient to vibrations and shock
Lightweight
Reasonable battery life
Withstand the elements water, dirt, humid/arid climate
Attachment doesn't corrode over time

Lessons Learned

Because the participants were students, they lacked the design expertise necessary to take the design to a fully developed product. Although it was clear from this study that inexperienced individuals can make important contributions to the design of a new product, individuals with design expertise are also needed. An interesting topic for further research is what ratio of expert to novice crowd members is optimal for completing a new product design.

Lack of direction and decision making were two related issues that presented another significant challenge for the crowd. Although some leadership did emerge as discussed later, the crowd never had a well-formulated plan for completing the project. Substantial discussion occurred about a number of design considerations, but these did not always turn into concrete decisions. Decision making is discussed more in depth in a following section.

Inconsistent participation was also problematic for the progress of the design. Beyond the initial one-hour design session, participation was sporadic, and multiple individuals were rarely on the site at the same time. This inhibited collaboration and decision making, because individuals with key expertise were not always present at the right times. In the future, a different participation scheme will be needed. This would likely involve regular collaboration sessions with all crowd members or sub-groups, interspersed with people working on their individual tasks.

Leadership Emergence

In order to understand the crowd's perception of the existence of leadership, study participants were asked three questions in which they identified the crowd member best fitting each description. These questions were adapted from a study by Bendersky and Shah [57]. The questions were, "Which individual do you think made the most valuable contributions to the group?", "Which individual do you think had the most influence on the group's decisions?", and "Which individual had the greatest status (social respectability) in the group?"

As shown in Figures 5.9 - 5.11, User 1 received the most votes for status and influence, while User 15 was ranked highest on contribution. User 15 was also ranked second on status. This indicates somewhat of a dual leadership, with one individual shaping the direction of the crowd and the other making the greatest contributions. This dual leadership is somewhat reminiscent of corporate management where different individuals, such as the chief executive officer (CEO) and the chief technology officer (CTO), take charge of different aspects of the organization. Although these results show some indication of leadership, the lack of a majority of votes for these individuals indicate that the leadership was not strongly recognized. Based on these results and the observed lack of direction in the crowd that was discussed earlier, it is predicted that appointing leaders in the crowd will be more effective than allowing leadership to emerge organically.

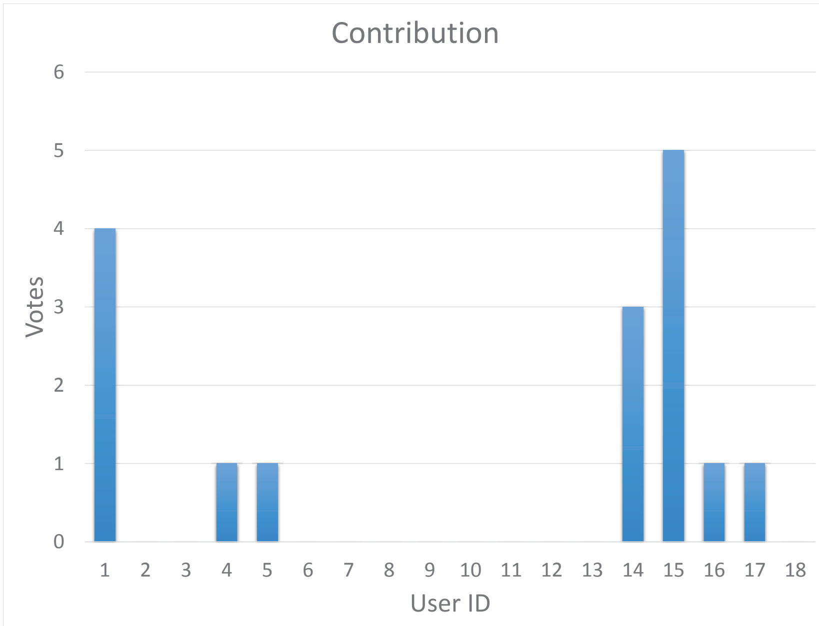


Figure 5.9: Crowd members' votes of greatest contribution

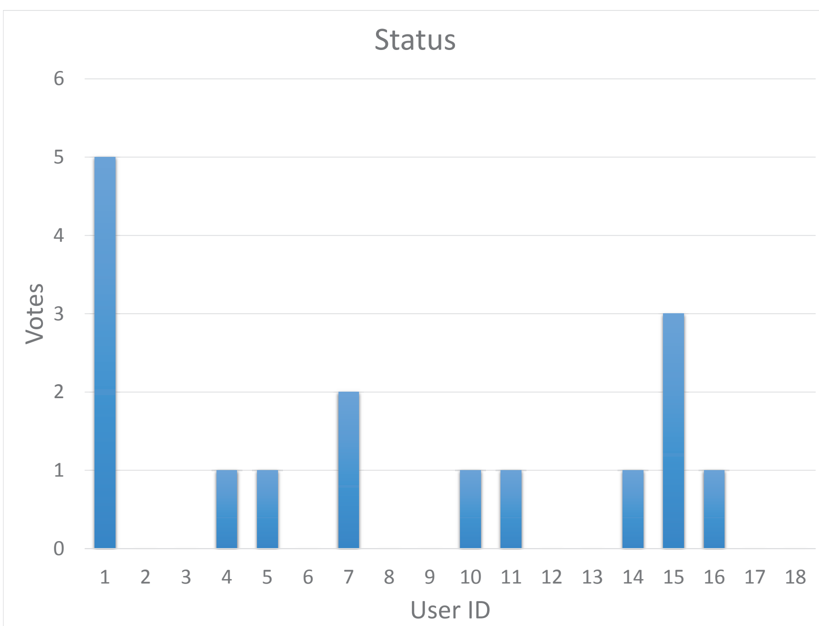


Figure 5.10: Crowd members' votes of greatest status

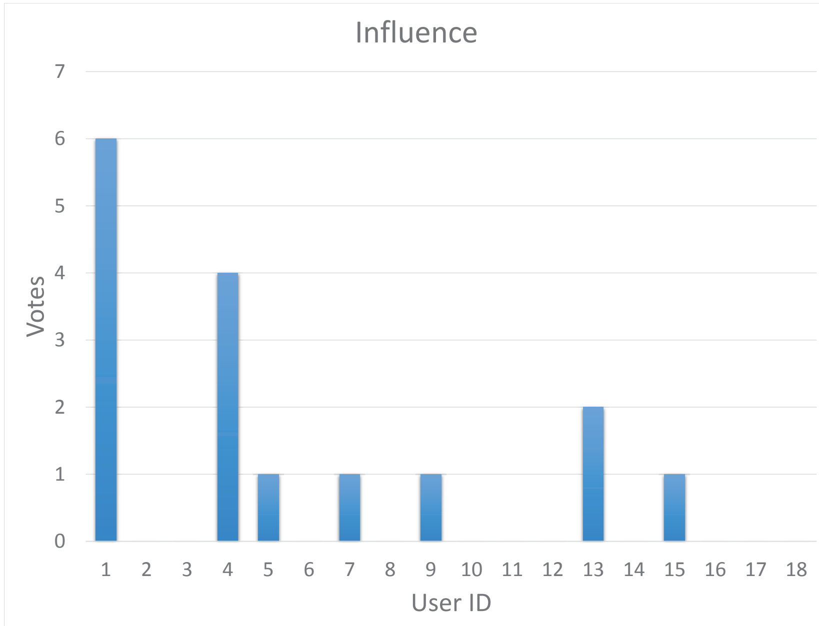


Figure 5.11: Crowd members' votes of greatest influence

Decision Making

In order to understand the effectiveness of the decisions made by the crowd, participants were asked a series of 11 questions about the decision making process (see Appendix B for the list of questions). These questions were drawn from a study by Dean and Sharfman [58]. Each of these questions was answered on a scale from 1-7, with a score of 7 indicating the best decision making processes.

On average, the crowd rated their decision making quality as just above the median point on the scale, indicating that they struggled to make effective decisions. According to the survey results, crowd members felt that as a group they did the best at looking for information in making decisions, being open about their preferences, and being primarily concerned with the goals of the organization rather than their own goals. They did not do as well at using analytical techniques to aid decision making or completing the tasks necessary to implement decisions made. A possible approach to improve decision making would be for the crowd's input and recommendations to be reviewed by expert crowd members.

Figure 5.12: Crowd members' evaluation of the crowd's decision making quality

Contribution Patterns

User activity data from the website log was plotted across time to see contribution patterns during the study. It was hypothesized that contribution patterns would vary between crowd members, with some completing a significantly larger portion of the work. As seen in this chart, the data validated this hypothesis, with some users contributing significantly more than others. It is also interesting to note that most of the contributions were in the third quarter of the session, after the crowd had discussed their options and then started doing more specific tasks. Activities logged include forum comments, new forum topics, creating polls, and creating tasks. This activity can be seen for each user during the one-hour crowdsourcing session in Figure 5.13.

These patterns are similar to those observed in a study of various projects carried out on Zooniverse, a crowdsourcing website for citizen science. They found that most participants only contributed once and that the top 10% of contributors did approximately 80% of the work [43]. These findings indicate that in the case of crowdsourced product design, a different model for engaging crowd members is needed. A system where users are compensated based on the results they produce, as well as having a dedicated pool of workers working consistently would likely be more effective.

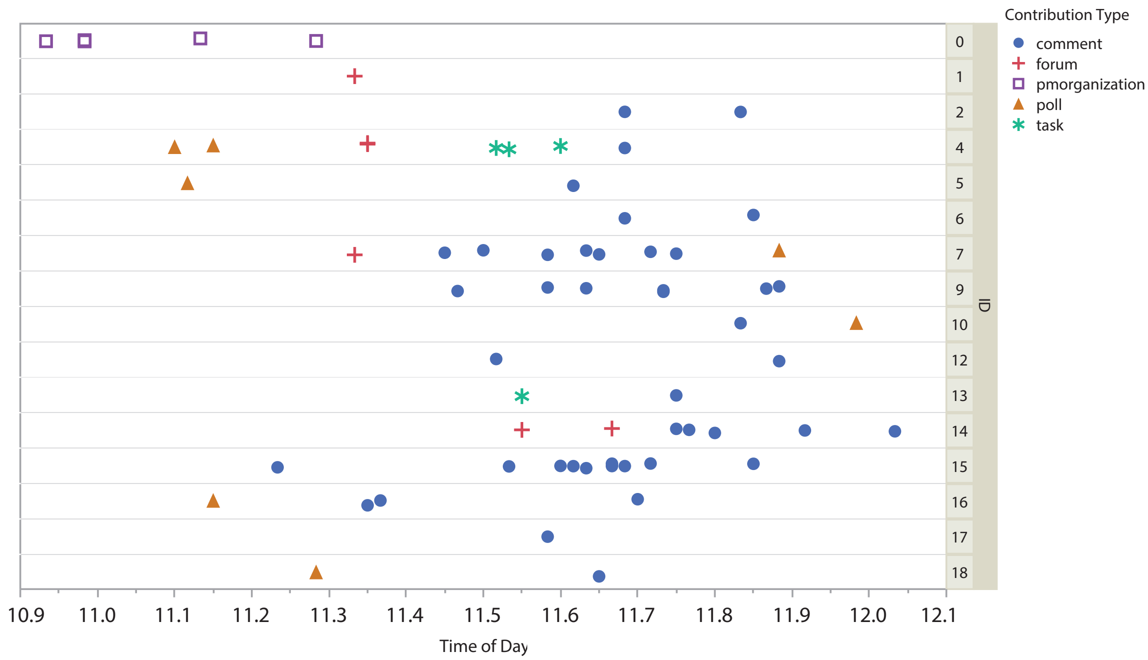


Figure 5.13: Contributions by crowd members during the one-hour design session

Hours Estimate

The survey results for estimated man-hours spent by the crowd were compared with the actual man-hours contributed by the crowd members during the study. The actual man-hours contributed were 30, and the average estimate was 170 man-hours, with a standard deviation of 373. The survey respondents were asked to justify the estimate that they gave, and based on these answers some responses were excluded for individuals who misunderstood the work that had been done, thinking that the crowd had actually completely developed and tested the product shown in the report, which resulted in an extremely large estimate. All comments from the survey are included in Appendix C. The distribution of estimated man-hours is shown in Figure 5.14. The majority of responses were reasonably close to the true value, but the high variance of the responses makes it difficult to draw any firm conclusions from the data. Further research will be needed to verify whether or not crowdsourcing product design can provide decreased development cost.

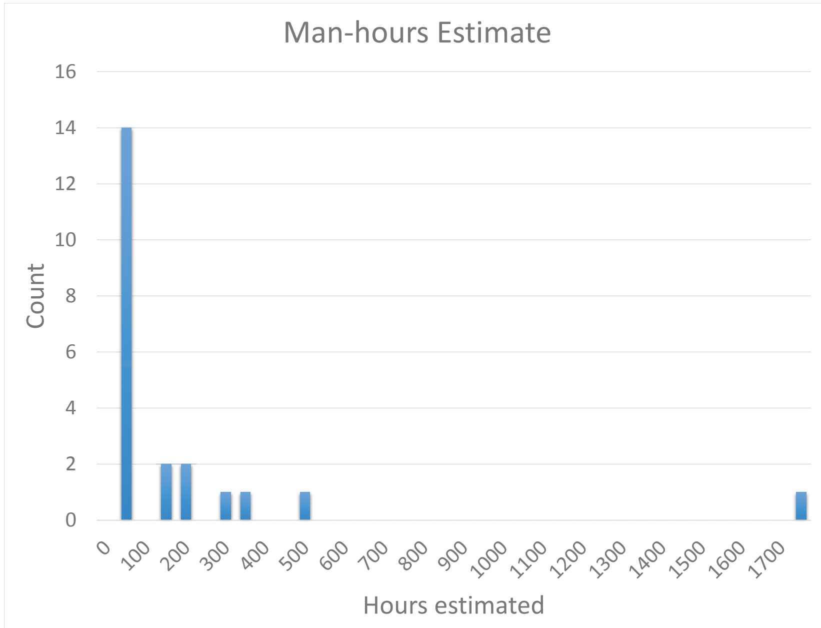


Figure 5.14: Estimated man-hours spent by the crowd.

Table 5.2: Average responses to questions about awareness

Question	Average Rating (n=16, 0-4 scale)
Awareness of other crowd members' activities	2.25
Awareness of the current state of the design	1.75
Awareness of what needed to be done throughout the project	2.00

Awareness

In the post-survey, respondents were asked about their awareness of other crowd members' activities, current state of the design, and what work needed to be done. On average, ratings were fairly low, as shown in Table 5.2. This indicates that further efforts need to be made to enhance awareness, as this is a critical factor for collaborative work to be successful. Additional collaboration tools or a better layout of the website would likely provide this enhanced awareness. Collaboration tools could include voice or video chat, file uploading built into the chat, or screen sharing. One improvement to the website layout would be a panel that allows users to access multiple tools simultaneously (such as chat, polls, and forum) instead of switching pages to view each one.

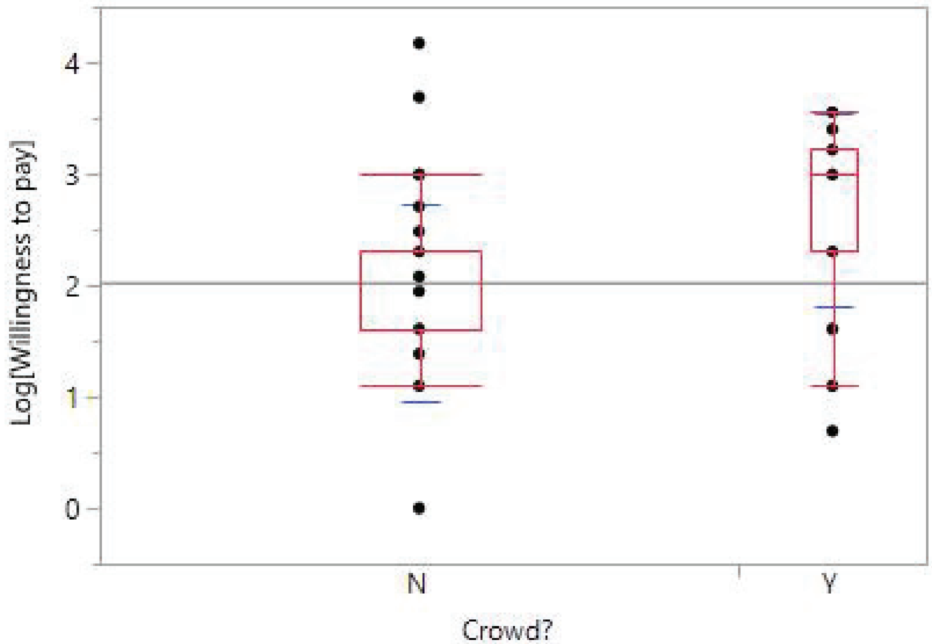


Figure 5.15: Comparison of willingness to pay for crowd vs. non-crowd members

Willingness to Pay

As mentioned previously, one proposed benefit of crowdsourcing product development is that it may increase customer buy-in [50]. In order to evaluate this, study participants were asked how much they would be willing to pay for the frisbee tracker if it were developed into a finished product.

The crowd members' willingness-to-pay data was compared to that of the Mechanical Turk survey respondents with a Welch's t-test, after taking a log transformation of the data. This test, shown in Figure 5.15, shows a statistically significant difference in the amount crowd members versus non-crowd members were willing to pay for the product (one-sided p-value = 0.0015). People who had participated in the design of the product were willing to pay on average $2.33 more than those who did not participate in the design. This finding is consistent with a similar study done by Norton et al. [59], where they studied the increase in valuation of self-made products. This finding indicates that crowdsourcing product design may be effective for companies wanting to promote greater market acceptance of their products.

Figure 5.16: Text analysis of what crowd members found enjoyable about the collaboration process

Participant Comments

In the post-survey, participants were asked how much they enjoyed the collaboration process and how frustrated they were with the collaboration process. They were also asked what was enjoyable and what was frustrating about the collaboration process. Their comments, summarized in the word clouds in Figures A.5 and 5.17, provide insight into what may motivate individuals to participate in crowdsourced product design, as well as what things need to be changed in order to have greater success. The larger the word in the cloud, the more frequently it was used by participants. The word cloud is also color coded, with red indicating the highest score and blue indicating the lowest score for both enjoyment and frustration. The responses were also placed into categories based on the general cause of enjoyment or frustration, as seen in Table 5.3 and Table 5.4. Note that in the case of Table 5.4, some individuals had more than one reason for their frustration.

Table 5.3: Categories that caused enjoyment

Category	Number of Responses
Working with others	10
Interesting project	5
Making contributions	1

The text analysis of enjoyment shows that people who enjoyed the collaboration process primarily enjoyed working with other people and the project that they worked on. This indicates that people will be motivated to participate in collaborative, crowdsourced product design because

Figure 5.17: Text analysis of what crowd members found frustrating about the collaboration process

Table 5.4: Categories that caused frustration

Category	Number of Responses
Lack of direction	7
Communication	6
Site navigation	4
Nothing	1

of the opportunity to work with a diverse group of people to complete an interesting project. The text analysis of frustration shows that people who were frustrated with the collaboration process were primarily frustrated by the chat window and a lack of clear direction. The frustration with the chat window stemmed from its small size and the resulting difficulty scrolling through to see the discussion. The comments about a lack of clear direction are consistent with the observations discussed earlier that no one created a plan for how the project objectives would be accomplished.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1 Crossover Discussion

Crowdsourcing and multi-user CAD, while distinct facets of technology aided collaborative design, rely on many similar principles for effective implementation. The preceding chapters have presented important findings relating to each of these areas individually, and further insight can be gained by discussing their similarities and differences.

6.1.1 Collaboration Process

How well team members could collaborate using the tools provided was one of the key questions for both MUCAD teams and the crowd. Based on survey results, it was found that crowd members were more frustrated with, and enjoyed less, the collaboration process than MUCAD team members. The survey comments show that this difference was mainly due to a greater difficulty on the crowdsourcing website with keeping track of what was being done and what needed to be done, as well as a lack of organization in the crowd.

In both cases, however, participants had a generally positive view of the project they were involved with. Their enjoyment stemmed from collaborating with other people and seeing a new product rise out of the collective contributions of multiple people. It seems that if participants have the appropriate tools to allow them to work together effectively, they can find great satisfaction in joining with virtual team members in new product development efforts.

6.1.2 Leadership

For both MUCAD teams and crowds, leadership or the lack thereof played a significant role in the success of these groups. In the case where MUCAD teams did not have a leader, performance was lower than in instances where leadership existed in some form. Similarly, the crowd had no official leadership and struggled to find clear direction and organization. This was a common complaint among the comments from the crowdsourcing study participants. Although clear leadership did not emerge from the crowd in this study, it is possible that over a longer project time span, a strong leader could emerge as crowd members continue to interact. If further research finds that this still does not occur, it is possible that crowd members working together to accomplish complex product design tasks need more established leadership, rather than relying on a leader to emerge from the crowd. As product development crowds grow larger, leadership will become increasingly critical, and an organizational structure such as that implemented by Valentine et al. [52], with subgroups to work on certain aspects of the design, would likely be necessary.

6.1.3 Awareness

Awareness was a critical factor for success since both MUCAD teams and the crowd members worked in a virtual team environment, with members collaborating from different physical locations and interacting with the aid of communication technology. Comparing responses from MUCAD team members and crowd members, average awareness of teammates' activites was higher for the former. This is likely due to the larger group size of the crowd resulting in a large amount of simultaneous activities being done by different people. Limitations of the website also made it difficult for crowd members to see what was being worked on by other team members.

Comments from the post survey indicate ways that the website could be improved to increase awareness in a crowdsourcing setting. Several participants mentioned wanting more features to be accessible simultaneously, such as being able to see the group chat, polls, and forum all on one page. Crowd members also requested that the chat window be larger so that they could more easily follow the discussion.

6.1.4 Design Spectrum

The research presented herein has demonstrated the use of MUCAD and crowdsourcing in a limited number of design activities. However, potential exists for expanding the degree to which these tools are used across the product development spectrum. As shown in Figure 6.1, a wide variety of design activities are required to take a product from an initial idea through production.

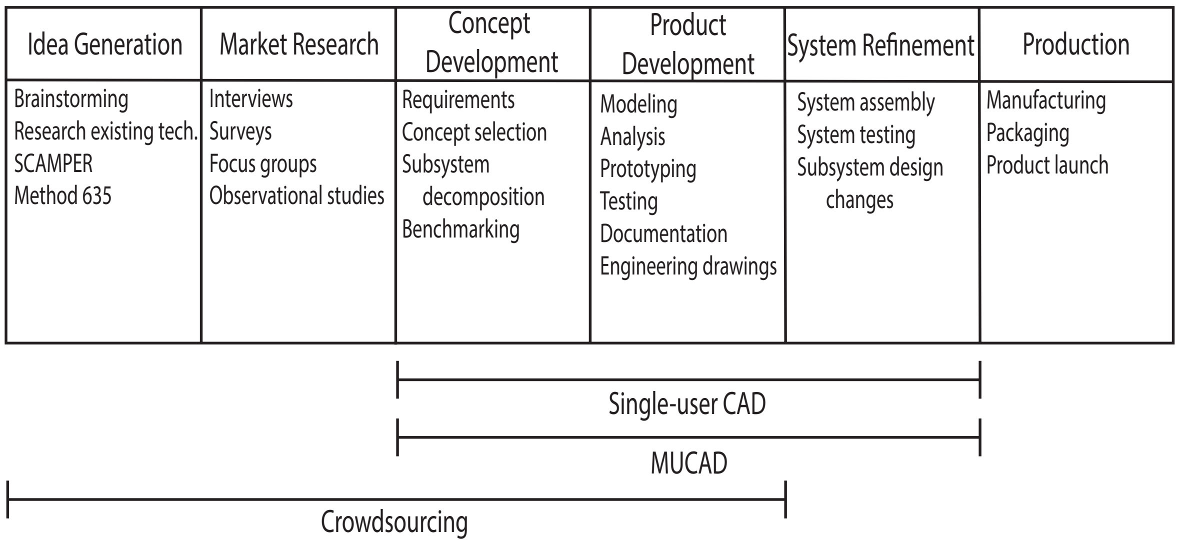


Figure 6.1: How single-user CAD, MUCAD, and crowdsourcing fit into the spectrum of product development activities

MUCAD and crowdsourcing are each suited to a specific subset of these activities as shown in the figure. The current research has shown that MUCAD can be used effectively in the product development stage of the process, and it is believed that MUCAD can also be advantageous during the concept development and system refinement stages.

Crowdsourcing, on the other hand, is well suited for many of the earlier stages, but also overlaps with MUCAD. It has been shown that crowdsourcing can be used for idea generation, market research, concept development, and some product development activities. With current technology, some product development tasks requiring advanced tools or extensive expertise are not feasible in a crowdsourced setting. However, it is possible that as technology advances, the realm of crowdsourcing in the product development spectrum could expand. Some activities are unlikely to ever fall under the realm of crowdsourcing, such as system testing and manufacturing, which require resources not generally held by individuals.

6.2 Conclusions

The overall objective of the research presented herein was to develop methods for improving collaborative engineering design and to understand the factors affecting performance of design

Table 6.1: Summary of research activities completed for each objective

Objective	Research Activities
Determine the differences in performance between single-user CAD teams and multi-user CAD teams.	Conducted user experiments with MUCAD and single- user CAD teams
	Evaluated CAD models created by each team
	Compared teams to find differences
Determine the effect of several factors on the performance of multi-user CAD teams.	Conducted user experiments for each factor
	Analyzed data from experiments
Develop the crowdsourcing PD process	Analyzed and evaluated other crowdsourcing methods
Develop a process for market validation	Developed a crowdsourcing website
	Conducted preliminary tests
Evaluate the crowdsourced product design	Conducted a crowdsourced product design case study
Verify the proposed benefits for crowdsourced product design	Evaluated the man-hours spent on the project
	Surveyed study participants
	Surveyed non-study participants

teams in these collaborative settings. This was accomplished by carrying out the six research objectives discussed in Chapter 1. The research activities carried out to accomplish these objectives are summarized in Table 6.1. The conclusions for each hypothesis are discussed below.

6.2.1 Multi-user CAD

Understanding the differences between teams using multi-user and single-user CAD is essential for those in industry making decisions about implementing MUCAD software. The research presented in Chapter 3 has made a preliminary investigation of those differences in a multiple-day, new design scenario. Significant differences in performance were not found, so a conclusive statement about Hypothesis 1 cannot be made. However, it has been found that MUCAD increases awareness of teammates' activities and increases communication between team members. Different sources of frustration for single-user and multi-user teams have been identified, as well as differing patterns of modeling style. These findings demonstrate that MUCAD software has significant potential to improve team collaboration and performance, and it is believed that future studies will further demonstrate this.

Factors affecting MUCAD design team performance is an area that has previously been relatively unexplored. The research presented in Chapter 4 has made an initial investigation into a number of potentially significant factors. These findings form the basis for understanding how to structure and train multi-user CAD teams for maximum performance. Results have been discussed regarding the influence of leadership, design style, unfamiliar parts, knowledge transfer, individual experience, and team composition. A primary finding was that having an appointed leader for a MUCAD team likely improves performance as proposed in Hypothesis 2, although the results were inconclusive. It was also found that creating a framework to aid in organizing and coordinating the creation of the CAD model may decrease the time required for completion, supporting Hypothesis 3.

Insight was gained into the perspective of engineers in industry about working in a multi-user CAD environment. These insights did not support Hypothesis 4, instead showing that the primary modeling style described by engineers in industry was identical to one style successfully used in multi-user CAD. No conclusive results were found for Hypothesis 5, but the results seem to indicate that teams working in multi-user CAD can produce more creative and detailed solutions to unfamiliar problems than individuals.

6.2.2 Crowdsourcing

Using collaborative crowdsourcing for complex product development tasks has potential to enhance the development process in a number of ways, although significant research is still needed before this can be successfully implemented on a large scale. In the research presented in Chapter 5, a crowd of engineering and technology students was able to collaborate to accomplish some detailed product design tasks, but not sufficient to completely develop the product. Hypothesis 6 was therefore partially supported, but more testing needs to be done with a broader range of tasks. A major finding was the need for more formal leadership and crowd organization. Contrary to Hypothesis 7, strong leadership did not emerge from the crowd, although results indicate this could occur given a longer period of time. The need for better decision making mechanisms was another important and related finding.

The need for a better model for engaging crowd members on a consistent basis was observed. Unlike the prediction in Hypothesis 8, crowd contribution patterns were similar to those seen in the crowdsourcing platform Zooniverse, with most crowd members only participating once. Hypothesis 9 was confirmed, showing that some crowd members completed a significantly larger portion of the work than others.

It was also found that for the participants involved in this study, they had a greater willingness to pay for the product they developed than individuals who had not worked on the project, confirming Hypothesis 11. Results also show that although crowd members were often frustrated with the collaboration process, they enjoyed being able to work with a large group of people to accomplish something. Results for Hypothesis 12 were inconclusive, and further research is needed to determine whether products developed through crowdsourcing have a lower development cost.

6.2.3 Contributions

The research presented in Chapter 3 has been published in the Journal of Computing and Information Science in Engineering (JCISE) [60].

In addition, best practices for MUCAD teams have been developed from the research presented in Chapter 4. Based on the findings presented, it is recommended that for best performance, MUCAD teams be organized with an appointed leader, and that this leader work with team members to complete the task. It is also recommended that a frame of reference be created by MUCAD team members to provide initial structure for their CAD model. Doing so will reduce confusion concerning the proper orientation and interfaces of the various model components, thereby reducing the amount of rework and corrections required throughout the modeling process.

6.3 Future Work

While significant progress has been made in understanding the benefits and challenges of MUCAD and crowdsourcing for product development, there are still many areas for future research. In order for the tools and methods discussed herein to be used in an industry setting, the following research should be completed.

For MUCAD teams it has been shown that multi-user teams communicate more than single user-teams, but future research could further explore whether this is causal or simply correlated with improved performance. Other studies could explore the benefits of MUCAD in design scenarios other than those tested in these studies. These could include early design/concept generation and design review scenarios. It has been shown that there are different modeling styles for single-user vs multi-user CAD and for high-performing vs low performing teams, but further research could expand the understanding of the ideal multi-user design style by repeating the experiments discussed here with a variety of CAD models, including large, complex parts and assemblies.

Further studies could also explore how leadership plays a role in long-term design scenarios. This could include multi-week design projects, where team members must use the CAD models in various stages of the design process. The role of leadership in non-collocated teams is also an important topic for future research. In the leadership experiments all team members were in the same physical location, and so the role or significance of a leader may change in situations where team members cannot interact face-to-face.

Many unanswered questions also exist for collaborative, crowdsourced product development. Several limitations of the current research need to be overcome in order to achieve more generalizable results. One major limitation of the study was the lack of design experts as participants. Future research should find ways to involve such individuals, as this will likely result in much more complete and usable product design. The website developed for the crowdsourcing platform, although sufficient for the exploratory studies conducted, will need to be developed to a more robust and user-friendly state, possibly through the integration of existing collaboration tools. Future studies could also test whether MUCAD can be successfully integrated with crowdsourcing. In this case, access to the CAD models would likely need to be restricted to a small subset of the crowd to avoid confusion. Future studies should also incorporate crowd members without an engineering or technology background, in order to understand how these types of individuals can best contribute to the product development process. Besides the phases of product development considered in this research, namely detailed design and consumer feedback, the value of crowdsourcing for other phases, such as prototyping and testing, can also be explored.

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APPENDIX A. CROWD DESIGN DELIVERABLES

This appendix contains the design deliverables created by crowd members during the Product Design Case Study. These deliverables include CAD models, an app design, requirements, and documentation.

A.1 CAD models and other designs

Figure A.1: CAD renderings of the frisbee tracker concept

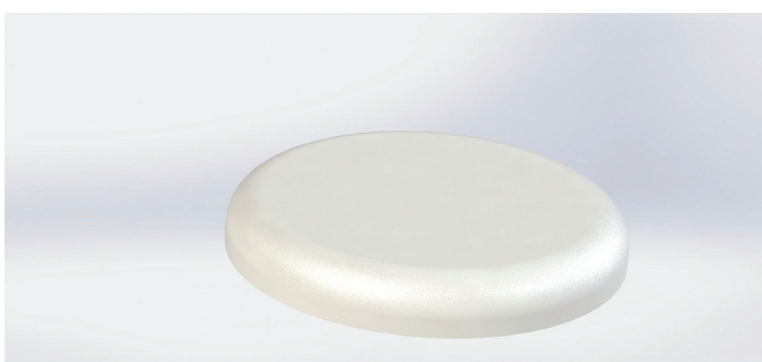


Figure A.2: Another CAD rendering of a frisbee

Figure A.3: Another CAD model of a frisbee

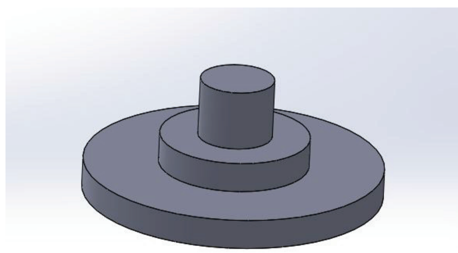


Figure A.4: A CAD model of a possible frisbee tracker

Figure A.5: A simple design for a frisbee tracking app

A.2 Requirements

Table A.1: The list of requirements created by the crowd

Requirements
Trackable by different devices
Not interfere with Frisbee flight
Must be able to easily remove from Frisbee
Low cost
Usable across Frisbee types
Attachment resilient to vibrations and shock
Lightweight
Reasonable battery life
Withstand the elements water, dirt, humid/arid climate
Attachment doesn't corrode over time

A.3 Documentation

This section includes three documents created by crowd members to selected design components. The documents are listed in order that they were created.

- Design Cost (version 1)
- Design Cost (version 2)
- Potential Parts List

Design Cost

Module - $5

http://www.fanstel.com/bt832-bluetooth-5-module/

Arduino Nano - $3

aliexpress.com/item/NANO-3-0-controlador-compatible-con-NANO-CH340-turno-USB-controlador-ninguna-CABLE-V3-0-NANO/32714947583.html

Adhesive - <$1 per device

http://www.skygeek.com/henkel-hysol-0151-50ml-83069.html?utm_source=googlebase&utm_medium=shoppingengine&utm_content=henkel-hysol-0151-50ml-83069&utm_campaign=froogle&gclid=CjwKCAiA47DTBRAUEiwA4luU2Wh0glbckdJ_EuZ02-JydjYnW-Mc6Q1UL0TroZmgW7QMiQmxnpJG0RoCt0QQAvD_BwE

Design Cost

On/off switch - $1

https://www.ebay.com/itm/Black-5-Pcs-M4-12mm-Waterproof-Momentary-ON-OFF-Push-Button-Round-SPST-Switch-/222391133288

Speaker, $.1-.5

https://www.alibaba.com/product-detail/Micro-Waterproof-Loudspeaker-Parts-Mylar-40mm_60698714157.html?spm=a2700.7724857.main07.1.79f91412XWKZcp&s=p

Batteries, $.1

https://www.alibaba.com/product-detail/CR2032-waterproof-battery-holder-with-wire_60111086563.html?spm=a2700.7724857.main07.314.50a51a41TCa4uB

Blue tooth Module - $5

http://www.fanstel.com/bt832-bluetooth-5-module/

Arduino Nano - $3

aliexpress.com/item/NANO-3-0-controlador-compatible-con-NANO-CH340-turno-USB-controlador-ninguna-CABLE-V3-0-NANO/32714947583.html

Pocket (Includes adhesive)- $1.09

https://www.4imprint.com/sampleitem/119373?gclid=Cj0KCQiAnuDTBRDUARIsAL41eDp4xsCIR1rSV6YeX0nRggs_nTRLAY16i58uF2E1Jv2Uoz0DJCqR3bIaAufKEALw_wcB&mkid=1pla-s119373&ef_id=UNtEzQAAXL9Z8vzL:20180205230918:s

Adhesive - <$1 per device

http://www.skygeek.com/henkel-hysol-0151-50ml-83069.html?utm_source=googlebase&utm_medium=shoppingengine&utm_content=henkel-hysol-0151-50ml-83069&utm_campaign=froogle&gclid=CjwKCAiA47DTBRAUEiwA4luU2Wh0glbckdJ_EuZ02-JydjYnW-Mc6Q1UL0TroZmgW7QMiQmxnpJG0RoCt0QQAvD_BwE

Potential-Parts List

This document is for keeping track of parts to be used in the Frisbee Tracker project. Please maintain formatting, update the changelog (see end of document) with each revision, and make sure to re-upload the updated document to the Crowd-Innovations website. Thanks!

Global Positioning System (GPS)

Currently, the team seems to have decided to steer clear of any sort of GPS functionality; however, if the team later decides to explore options relating to locating the frisbee, as opposed to simply causing it to beep or light up, GPS would be a viable option.

Bluetooth

Probably the best option for minimizing power consumption, Bluetooth will allow the frisbee tracker to connect to the user's cell phone (or remote, et cetera) to beep or flash a light or otherwise make its position obvious. As far as I am aware, Bluetooth cannot be used to determine location. Moreover, its range is limited to a couple hundred feet, and a device implementing Bluetooth without GPS would be working under the assumption that the user has a general idea of where the frisbee landed.

BT832F Long Range BLE 5 Module – $7.84

With an average range of 270 meters, this module looks promising. See datasheet for more information.

Microprocessor

The device needs a microprocessor. Originally, the team explored small microcontrollers, such as the PJRC Teensy and the Arduino Nano, but eventually decided that a custom PCB would be necessary to keep the size of the device to a minimum. What follows is a list of potential microprocessors, each with their own strengths and weaknesses.

ATMega 328P – $1.95

Arduino's bread and butter. The processor placed on Revision 3 of their classic board, the Arduino Uno, as well as the Arduino Nano. With GitHub user RocketScream's homebrew library, the chip can be placed into a simple low-power sleep mode to conserve power (see [github.com/rocketscream/Low-Power] for the open-source library). See the datasheet for more information.

Microcontrollers

If the team does revert to the concept of implementing a microcontroller, as opposed to designing a custom circuit, here are the microcontrollers originally explored: Arduino Nano, PJRC Teensy, Pinguino PIC32, TI Launchpad.

Adhesive

Either the tracker will be sold as a built-in part of a frisbee, or it will be sold independently and then attached by some adhesive. The adhesive route is a little more versatile, as it allows users to track their own frisbee instead of having to purchase another. Currently, the team seems to have settled on this concept.

Henkel Hysol 0151 Epoxy – $00.30 /mL

See datasheet for more information.

Other Hardware

From switches to battery compartments, this is the section for "everything else" that didn't quite fit under any of the categories above. Note, if you do add a category to this document, please check this section for components that might need to be migrated elsewhere.

CR2032 Waterproof Battery Holder – $0.10

See [alibaba.com/product-detail/CR2032-waterproof-battery-holder-with-wire_60111086563.html].

Hite Sound Waterproof Mini-Speaker – $0.50

See [alibaba.com/product-detail/Micro-Waterproof-Loudspeaker-Parts-Mylar-40mm_60698714157.html].

APPENDIX B. SURVEY QUESTIONS

B.1 MUCAD vs Single-user CAD Pre-Survey

This survey was used to organize teams as discussed in Section 3.1.3.

1. Have you ever used NXConnect?
2. How familiar are you with NX?
3. How comfortable are you using any other 3D CAD software?
4. Have you taken ME EN 172 or an equivalent introductory CAD course?
5. Have you taken ME EN 471 or an equivalent advanced CAD course?
6. Please list any other applicable 3D CAD experience. If you have no other CAD experience please respond "N/A".
7. Can you dedicate 6 hours (in three two-hour blocks) to participate in this study?

B.2 MUCAD vs Single-user CAD Post-Survey

This survey was given to multi-user and single-user team members as discussed in Section 3.1.3.

1. Enter your name (first and last)
2. How much do you agree with the following statement: "Participating in this competition helped me develop skills that will be beneficial in my education or career."
3. How much would you say you improved your understanding of CAD design principles?
4. Overall, how satisfied were you with your team?

5. Overall, how aware were you of your teammates' activities throughout the project?
6. In thinking about your team as a whole, how would you rate it in the following categories? [NX modeling skill]
7. In thinking about your team as a whole, how would you rate it in the following categories? [Communication]
8. In thinking about your team as a whole, how would you rate it in the following categories? [Leadership]
9. In thinking about your team as a whole, how would you rate it in the following categories? [Engagement (involvement, focus)]

Thinking of your team members, how would you rate them in the following categories:

10. Team Member [X]: Your level of interaction with this person during the competition
11. Team Member [X]: Your familiarity with this person before the competition]
12. Team Member [X]: Your familiarity with this person after the competition
13. Team Member [X]: NX modeling skill
14. Team Member [X]: Communication
15. Team Member [X]: Leadership
16. Team Member [X]: Engagement (involvement, focus)

17. Overall, how much did you enjoy the team project?
18. After participating in this competition, how familiar are you with NX?
19. I feel like I improved my understanding of how to use NX during this competition (Strongly disagree - Strongly agree)

20. I feel like I improved my CAD modeling skills during this competition (Strongly disagree - Strongly agree)
21. Would you say that you had a team leader?
22. If yes, how much do you feel having a leader helped your team productivity?
23. How much did you have a single leader on your team vs sharing leadership equally among team members?
24. How frustrated were you with the collaboration process?
25. What about the collaboration process was frustrating, if anything?
26. How much did you enjoy the collaboration process?
27. What about the collaboration process was enjoyable, if anything?
28. Give a rough estimate of how much time, in minutes, errors/bugs in the software cost you personally (not your team)
29. Can you think of a time when you caught someone else's mistake, or when someone else caught your mistake? If so, briefly describe what happened.
30. How frequently would you say you used undo?
31. If you used undo more or less frequently than you normally do, why was that? (why did you use it more or less frequently than you normally do?)
32. What, if anything, would you change about the software you used?
33. If this competition was performed again, what advice would you give to the researchers?
34. How many minutes early did you finish (if any)?

B.3 Design Style Survey

This survey was sent to BYU mechanical engineering alumni in industry as discussed in Section 4.1.3.

1. What is your name?
2. What company do you work for?
3. How many years of industry experience do you have?
4. In the past month, how often have you used 3D solid modeling CAD software?
5.

Refer to the images shown below while answering the following questions about modeling this part in CAD (see Figure B.1).

6. What would you choose as the initial feature of your CAD model? (This can be something other than the labeled features)
7. Why would you choose this as the initial feature?
8. Using the labeled engine block images above as a reference, list the steps you would take to model this part in CAD. Include in your description the features/operations that you would use to complete each step.
9. How did you decide on the modeling approach that you described in the previous question?

Imagine that you are modeling this part in a collaborative CAD environment where you are working with a team of engineers who are all working in the same part file simultaneously. You automatically receive each others' changes to the part in real time as you work. Answer the following questions in reference to this scenario.

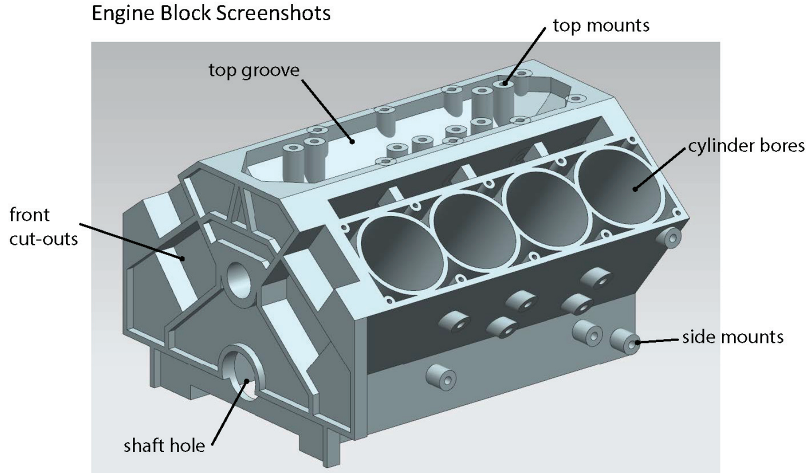
10. How would working in such an environment change your modeling style?
11. How comfortable would you be working in the environment described above?

12. Please explain your answer to the previous question

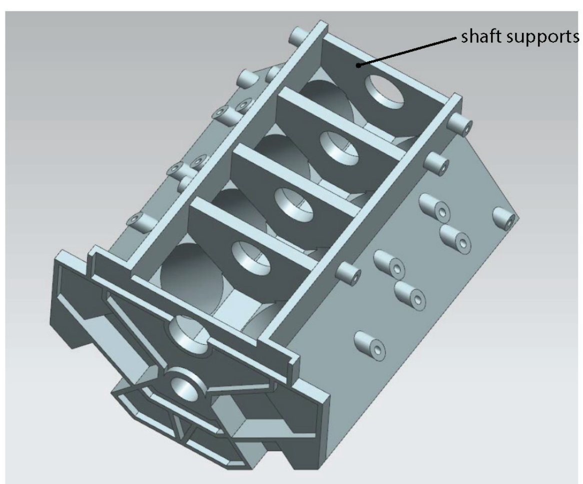
13. How much would knowing that others could see your work in progress negatively affect your inclination to work in a collaborative CAD environment?

14. Please explain your answer to the previous question

Engine Block Screenshots



Isometric view (left and right sides are identical)



Bottom view

Figure B.1: Engine Block images shown to Design Style survey respondents

B.4 Combined Factors Survey

This survey was given to participants of the Combined Factors experiment as discussed in Section 4.1.1.

1. Name
2. Team number
3. How difficult was working with your team to complete the task?
4. What was the most difficult thing about working with your team to complete the task?
5. How much did you enjoy working with your team to complete the task?
6. What was the most enjoyable thing about working with your team to complete the task?
7. How aware were you of your teammates' activities?
8. How efficient do you think your team was in completing the task?
9. How satisfied are you with your teams performance?
10. How did having someone more experienced or less experienced than you impact the effectiveness of your team?
11. How comfortable were you with other people seeing your work in progress?
12. If provided with this software in a work or class project setting, would you use it? (assuming it were bug free)
13. Please explain your answer to the previous question.

A different set of questions was given for each leadership style:
No Leader:

1. Would you say that your team had a leader?
2. If yes, how much did having a leader help your team accomplish the task?

3. If yes, who would you say was the leader?
4. If yes, what contributed to this person being the leader?
5. How much did you have a single leader on your team vs sharing leadership equally among team members?

Observer Leader:

1. How much did having a supervisor observe your team help your team accomplish the task?
2. What contributed to the supervisor being an effective leader?
3. What detracted from the supervisor being an effective leader?
4. How aware was the supervisor of your activities?
5. How aware was the supervisor of difficulties that you faced?

Participant Leader:

1. How much did having the leader work with you help your team accomplish the task?
2. What contributed to the team leader being an effective leader?
3. What detracted from the team leader being an effective leader?
4. How aware was the team leader of your activities?
5. How aware was the team leader of difficulties that you faced?

B.5 Crowdsourced Product Design Post-Survey

Note that the section headings listed below were not shown to the participants on the survey.

1. What is your name? (first and last)

B.5.1 Decision Making

The following survey questions were used to evaluate the crowd's decision making process as discussed in Section 5.2.2.

2. How extensively did the group look for information in making decisions?
3. How extensively did the group analyze relevant information before making a decision?
4. How important were quantitative analytic techniques in making decisions?
5. How would you describe the process that had the most influence on the group's decisions? (1 = Mostly intuitive, 7 = Mostly analytical)
6. In general how effective was the group at focusing its attention on crucial information and ignoring irrelevant information?
7. Were group members primarily concerned with their own goals, or with the goals of the organization?
8. To what extent were people open with each other about their interests and preferences in the decisions?
9. To what extent were the decisions affected by the use of power and influence among group members?
10. To what extent were the decisions affected by negotiation among group members?
11. How well was each implementation task done?
12. How important was each implementation task for its respective decision?

B.5.2 Leadership Emergence

13. Which individual do you think made the most valuable contributions to the group?
14. Which individual do you think had the most influence on the group's decisions?
15. Which individual had the greatest status (social respectability) in the group?

B.5.3 Awareness

16. How aware were you of other crowd members' activities throughout the project?

17. How aware were you of the current state of the design throughout the project?

18. How aware were you of what needed to be done throughout the project?

B.5.4 Website Interface

19. To what extent did the website facilitate or impede your collaboration with team members?

20. What feature of the website was most helpful to you as you worked on the project?

21. What changes would you request to make the website better facilitate collaboration and working on the project?

22. How often did you use the private message feature (accessed from the Messages link on the left side of the home page) to communicate with crowd members?

B.5.5 Willingness to Pay

23. If the project you worked on were fully developed and offered as a commercial product, how much would you be willing to pay for this product? (please put a single dollar value, not a range)

B.5.6 Collaboration Process

24. How frustrated were you with the collaboration process?

25. What about the collaboration process was frustrating, if anything?

26. How much did you enjoy the collaboration process?

27. What about the collaboration process was enjoyable, if anything?

B.5.7 Final Questions

28. Overall, how much did you enjoy working on the project?

29. How would you rate the quality of the work done by the crowd?

30. Any additional comments

B.6 Willingness-to-pay Survey

This survey was posted on Amazon Mechanical Turk as discussed in Section 5.1.5. Respondents were shown Figure 5.7 as a reference.

1. How much would you be willing to pay for this product? (Please give a single dollar value, not a range)

2. Please give your justification for the amount you are willing to pay.

3. What is your age?

B.7 Estimated Man-hours Survey

This survey was posted on Amazon Mechanical Turk as discussed in Section 5.1.5. They were shown a progress report consisting of the deliverable shown in Appendix A.

1. What is your best estimate for how many man-hours were spent on the work represented by the report?

2. Please provide your reasoning for the estimate you gave.

APPENDIX C. SELECTED SURVEY RESULTS

C.1 MUCAD vs Single-user CAD Post-Survey, Enjoyment and Frustration

MU or SU	How frustrated were you with the collaboration process?	What about the collaboration process was frustrating, if anything?
MU	2	Needed a planning session before starting. Some members were very indecisive.
MU	1	I think working and talking face to face for a least 5 or 10 minutes for every hour would really help out our effectiveness.
MU	3	Errors that kept popping up. Losing things that I had made because other people saved.
MU	1	NX bugs made collaboration frustrating. That's it, though.
MU	1	The frustration was mainly with the software. Sometimes it would not save correctly and then you were loosing pieces.
MU	2	The lag between updates made things difficult. Especially when you went back to the assembly and had 30-90 sec before anything could be done
MU	2	
MU	1	Just the time constraints. Sometimes someone would mess up your part, or vice versa :)
MU	0	If anything, it would just be some equipment difficulties with Skype
MU	1	The frustrating part was when someone would take responsibility for something but not be able to do it right away.
MU	0	
MU	1	just the buggy-ness of the program. also at the last minute an extrude went wrong and it would be nice if the graders just pretended the time ended 30 seconds earlier and it was just a sketch
MU	0	
MU	3	I just felt like my teammates didn't really know how to model and that if I had done the entire drill by myself I might have been able to get farther...
MU	2	I was frustrated with all the glitches in the software. The people where great.
MU	1	The frustrating part was that I couldn't tell if other team members were seeing the same thing that I was seeing so it took a lot of discussion to discover when someone went out-of-sync.
SU	2	nothing
SU	2	It was very hard to share dimensions among members of the team.
SU	1	Communication was a little bit sparse and poor communication was really the worst thing.
SU	4	There was a decent amount of time where I was just waiting for other people. It became especially frustrating because I had a teammate who was struggling and I couldn't help. I felt like turnbacks happened very often, and was the cause of the only thing (I think) wrong with the final model (the battery).

MU or SU	How much did you enjoy the collaboration process?	What about the collaboration process was enjoyable, if anything?
MU	3	It was neat to see the other team members' ideas and models.
MU	3	Learning from others and how they approached modeling. Seeing individuals styles
MU	2	
MU	4	It was nice feeling like a part of the team. We all could communicate audibly, and it was exciting.
MU	3	It was interesting to work with people on the same project even though they weren't in the same room. We all had our individual parts, but in the end came together to complete the whole thing.
MU	3	The process felt normal that having a single person model and everyone else watching or giving input.
MU	4	Everyone was very willing to take direction from each other so it made collaboration easy.
MU	4	Being able to play off our individual strengths. Those team members that may not have known how to do shell modelling could easily model the smaller less intricate parts.
MU	4	working with a team to model
MU	2	It was good to show that the tool was a way to help people who did not know the CAD system learn how to use it.
MU	3	I like how we can work on the same project at the same time.
MU	4	On engineering projects, I enjoy working with others and working on CAD this way was almost as good as if we were all sitting together (I did like how we could pass off parts to solve from us to someone else if they knew how to complete it)
SU	3	Everything went smoothly. We all picked the parts we were going to work on and then just did our own thing until it was time to assemble the whole drill. I felt like I could trust my team members with their parts and knew that if they had any questions or needed help they would ask.
SU	2	We didn't collaborate more than we needed to
SU	3	Screen sharing and voices was very helpful.
SU	4	Playful banter throughout.
SU	2	Not by yourself
SU	4	We had fun. We interacted to not only get the information we needed, but we kept it light too. This made the environment a lot less stressful and I felt it helped us to gain trust in each other. Also, it helped in that if anything went wrong, we could blame it on Fred.
SU	4	The constant communication and camaraderie that we built.
SU	2	Seeing others' modeling skills.
SU	2	Challenge of making different parts.
SU	3	For the most part, everything went smoothly, owing at large to being in constant communication via skype. I've worked with groups doing CAD that were far harder to bring together.

C.2 Crowdsourced Product Design Post-Survey, Enjoyment and Frustration

How frustrated were you with the collaboration process?	What about the collaboration process was frustrating, if anything?
A little	Nothing
A little	Firstly, there was no leadership and little assignment or delegation. Things felt pretty unorganized and I imagine there was a good deal of overlap, as well.
A lot	Trying to navigate to different pages.
A moderate amount	We relied a lot on the chat window, and it was hard to follow when everyone was talking at once and it was such a small window.
A moderate amount	I didnt really know if what i was doing was being repeated by another.
A moderate amount	It was hard to communicate with the whole group in the little group chat window. It was hard to know who was who and remember all of the strange names in that short time.
A little	It was just hard to do anything myself because I was keeping track of everyone else. It would be more effective to split into solid small groups and have them only work on one thing and then come together.
A moderate amount	The lack of being able to see the whole conversation in the chat window, and that it kept hoping to the bottom. And having to jump around to try to see how things were going in certain aspects
A moderate amount	That communication was so difficult while being important.
A moderate amount	It was hard to get anything done without any kind of leadership. If we had had more time we would have resolved into groups to work on different aspects of the project but as it was there was no clear direction or decision making.
A moderate amount	There wasnâ€™t a â€œbackâ€�button on several pages so I had to click back on the browser
A moderate amount	Lack of centrality made it a jiggling act to follow, with no clear direction other than that which I myself provided.
A little	It was too chaotic. There was no leader, no clear direction, and it felt like we were all pursuing our own agendas and not working together.
A lot	I spent a lot of time just trying to scroll up in the chat window so I didn't get much collaborating done.
A little	The website kept getting in the way. It was too hard to know what was being done and what needed to be done, and communication was too cumbersom

How much did you enjoy the collaboration process?	What about the collaboration process was enjoyable, if anything?
A moderate amount	Private message
A moderate amount	It was kind of fun to burn an hour racing through a novel project.
A little	Voting on polls, giving input and ideas.
A moderate amount	Talking with the other people.
A little	It was cool to work on a project with lots of people
A moderate amount	It was fun to work on a project with everyone and hear all of the design ideas while we worked from our own locations.
A moderate amount	Watching people work and think
A moderate amount	It was cool to see it happening and being in the middle of it. I know that if we had more time. and things were a little more simple we could have made something cool.
A moderate amount	Working together for a common goal.
A little	It was interesting to see other peoples ideas and opinions on how to solve a problem.
A moderate amount	See others inputs and their knowledge
A little	The concept is amazing and fun, though the collaborators in general were frivolous and unfocused. If done with more motivated subjects, the process would be much more productive and enjoyable.
A moderate amount	It was fun to see the product emerging from the chaos.
Not at all	just working with others I guess.
A great deal	The perple, we all treated eachother as equals and so there was free brainstorming with no real leader and no judgement. We were all just equals working together to finish a project
A little	I thought the idea was interesting.

C.3 Estimated Man-hours Survey Results

These are the results from the Estimated Man-hours Survey posted on Amazon Mechanical Turk. Respondents were asked to view a progress report showing the work accomplished by the crowd and then give their best estimate for how many man-hours were spent completing that work. They were also asked to provide their reasoning for the estimate they gave.

Table C.1: Estimated Man-hours Survey Results

ID	Estimated Man-hours	Reasoning for the estimate you given
1	20	It looks like few hours of brainstorming by a team of 5 and a day of report preparation by a volunteer.
2	4	It's not just writing the report but a fair amount of research was also made to write the report. The report itself isn't very detailed but there are several website links which shows what research was done. The research alone probably took up majority of the time. Writing the actual report doesn't look like it would take much time.
3	400	The engineering must have taken around this time to do the coding and hardware
4	40	It looked very in depth with research regarding the product.
5	16	It's not very detailed, and doesn't look very well put together.
6	24	This is all pre-planning and research on what current hardware components current exist that could be used.
7	20	This is my best guess based on the amount of information in the proposal. It seems like there is a good amount of research on the prices and needs of the device, but it's all just high level development at this point.
8	116	Cad work, product development, product design, materials research,
9	15	Since the tracking device is simple in design, I think that the team did not spend a lot of time on this project designing the device, which would have been the most complex part of the project.

10	4	It does not appear to be an insane amount of research necessary to look into alternative hardware solutions.
11	15	the report is not extremely lengthy, and is is presented in a very basic manner. It does not appear to have been thoroughly edited.
12	160	Because of the detail that went into it, I estimated it would take about a month assuming they worked only 40 hours a week
13	300	There was a decent amount of thought to everything that was in the pdf.
14	400	With all the brainstorming and researching technology/ideas. Also designing the technology and then prototyping and testing, and then later modifying the design and testing again until desired results.
15	320	8 hours a duy for 8 weeks
16	1000	Testing under many conditions 125 8hr days seem right.
17	1740	I Assume you have a 12-week project with 3 people working a 10-hour day. each person works five-day work week, 58 days are in 12 weeks. so 580 hours hours per person
18	4000	the CAD design and electronics integration likely took a team of a few people a couple of weeks to do
19	12	I think it took some time to come up with all the specifications.
20	50	product testing and development
21	500	Likely completed by more than one person, each of whom needed specific expertise and knowledge.
22	200	It appears the research took at least 1 full month or more to determine potential components.
23	40	The report contains only high level preliminary research and traces of concept description. There are 5 topics touched, 8 hours per.
24	3	The report has clean and neat appearance. The layout is very simple, nothing really pops out of the page except maybe the pictures. Overall not a bad presentation, i feel more effort could have gone into it.

25	1920	I work manufacturing and i did reports like this, i estimated 40 hours a week, with about 4 weeks in a month, and said about a years worth in time due to building, research, and other things that would take about a year to make a proper report thats been trsted after being built
26	60	Most of the time appears to have been spent in the parts list and prototype development. It's not easy working with components of that size, especially getting it all to work on a small battery for a decent amount of time. There was also considerable effort put into developing the app, which took some time as well.
27	120	Parts selection, circuit design, mounting techniques, frisbee flight reliability studies all take an enormous amount of time as does the trial and error phase.
28	40	The research for the the materials and technology; development of the PDF, and thought going into the phone app.

APPENDIX D. SCORING RUBRICS

The first scoring rubric was used by the panel of judges to evaluate the CAD models created by the four single-user teams and the four multi-user teams as discussed in Section 3.1.1.

The second scoring rubric was used by a panel of judges to evaluate the IBR models created by the six multi-user teams as discussed in Section 4.1.1.

TEAM CAD STUDY

RULES AND RUBRIC

- Teammates may only collaborate during project time (see study agreement).
- Teammates may not work face to face.
- Assemblies must be done in inches
- Each component must be at least one individual part in the assembly
- Extra points are not given for extra components (ex. Drill bits, missile launchers, multipurpose tool)
- Do not use the internet except for the given collaboration tools
- Extra points are not given for a rendering of the model.

COMPONENTS

	Nonexistent	Poor	Acceptable	Good	Great	Exceeds
Handle	0	6	12	18	24	30
Chuck	0	4	8	12	16	20
Battery	0	3	6	9	12	15
Trigger	0	2	4	6	8	10
Torque Control	0	2	4	6	8	10
Speed Switch	0	1	2	3	4	5
Direction switch	0	1	2	3	4	5
Level	0	0	1	2	3	3
Light	0	0	1	2	2	2

GENERAL

	Unacceptable	Poor	Acceptable	Good	Great	Exceeds
Overall look	0	3	6	9	12	15
Assembled	0	3	6	9	12	15
Fit together	0	4	8	12	16	20
					Total*:	150

*Minus 10 points for each created component that is not an individual part.

IBR Model Scoring Rubric

Team:

	Nonexistent	Poor	Acceptable	Good	Great
Blade	0	6	12	18	24
Center Hub	0	4	8	12	16
Bolt holes	0	2	4	6	8
Fillet	0	1	2	3	4
Total:					

Team:

	Nonexistent	Poor	Acceptable	Good	Great
Blade	0	6	12	18	24
Center Hub	0	4	8	12	16
Bolt holes	0	2	4	6	8
Fillet	0	1	2	3	4
Total:					

Team:

	Nonexistent	Poor	Acceptable	Good	Great
Blade	0	6	12	18	24
Center Hub	0	4	8	12	16
Bolt holes	0	2	4	6	8
Fillet	0	1	2	3	4
Total:					

Team:

	Nonexistent	Poor	Acceptable	Good	Great
Blade	0	6	12	18	24
Center Hub	0	4	8	12	16
Bolt holes	0	2	4	6	8
Fillet	0	1	2	3	4
Total:					

Team:

	Nonexistent	Poor	Acceptable	Good	Great
Blade	0	6	12	18	24
Center Hub	0	4	8	12	16
Bolt holes	0	2	4	6	8
Fillet	0	1	2	3	4
Total:					

Team:

	Nonexistent	Poor	Acceptable	Good	Great
Blade	0	6	12	18	24
Center Hub	0	4	8	12	16
Bolt holes	0	2	4	6	8
Fillet	0	1	2	3	4
Total:					